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Air injection in Subsurface Drip Irrigation as an Efficient Method for Zucchini Production

Nermin HUSSEIN[a], **Shereen SAAD**[b], **Khaled REFAIE**[c], **Wael SULTAN**[a],
Mohamed GHONIMY[d*], **Ahmed ALZOHEIRY**[e]

[a]*Agricultural Engineering Research Institute, Agricultural Research Center, Dokki, Giza, EGYPT*
[b]*Physics and Chemistry Dept., Soils, Water and Environment Research Institute, Agricultural Research Center, Giza, EGYPT*
[c]*Application Dept., Central Laboratory for Agricultural Climate, Agricultural Research Center, Dokki, Giza, EGYPT*
[d]*Department of Agricultural and Biosystems Engineering, College of Agriculture and Food, Qassim University, P.O.Box 6622, Buraydah, Al-Qassim 51452, Saudi Arabia; Agricultural Engineering Dept., Faculty of Agriculture, Cairo University, Giza, EGYPT*
[e]*Department of Agricultural and Biosystems Engineering, College of Agriculture and Food, Qassim University, P.O.Box 6622, Buraydah, Al-Qassim 51452, Saudi Arabia; Department of Natural Resources and Agricultural Engineering, Faculty of Agriculture, Damanhour University, Damanhour, EGYPT*

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Corresponding Author: Mohamed GHONIMY, E-mail: *mohamed.ghonimy@agr.cu.edu.eg*
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ABSTRACT

Agriculture is a key pillar of the economy, constantly facing challenges due to population growth and climate change. Enhancing the sustainability and efficiency of crop production and improving water use efficiency are essential to evaluate air injection into subsurface drip irrigation system for zucchini production as efficient method for subsurface drip irrigation systems to improve water use efficiency (WUE), and zucchini production in heavy clay soils. Results showed that injecting air through built-in emitters using a compressor during the last third of the irrigation time maintained acceptable system performance, as measured by indicators like CV, qvar, and EU%. It also improved the physical properties of dry sieved aggregates and enhanced the availability of macronutrients, significantly improving and maintaining heavy clay soil, leading to a 27% increase in zucchini crop yields and 22% water savings compared to the control. Economic analysis indicated that air injection was a feasible option, increasing gross returns by 21% compared to the control, with a benefit-cost ratio of 2.3% for air injection versus 1.8% for the control.

Keywords: *Subsurface drip irrigation, Air-injection, Crop production, Water use efficiency*

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INTRODUCTION

Subsurface drip irrigation (*SSDI*) is recognized as one of the most efficient irrigation methods for enhancing water use efficiency *(WUE)*. By delivering small amounts of water at frequent intervals, *SSDI* minimizes water loss due to deep percolation, runoff, and soil evaporation, leading to better water and nutrient absorption by plants and improved *WUE*. However, temporary waterlogging within the root zone during and after irrigation can negatively impact root respiration, water and nutrient uptake, and overall plant growth. Irrigating with hyper-aerated or oxygenated water could help alleviate the adverse effects of waterlogging in the rhizosphere. Aerating soil by injecting atmospheric air through a subsurface drip irrigation system is believed to speed up water depletion from macropores and increase oxygen levels in the soil air. Oxygation is a technique designed to improve the efficiency of subsurface drip irrigation systems by injecting air directly into the crop root zone. This approach helps to balance aerobic and aquatic conditions in soils, particularly in heavy clay soils, to mitigate the adverse effects of inadequate soil aeration. Additionally, oxygation can boost crop yield and quality, especially for crops grown in heavier soils. The advantages are linked to the abundance of air in the rhizosphere and the higher level of dissolved oxygen in the water, which improves the absorption of nutrients by the roots. In addition, there are positive results in the irrigation system itself, such as a reduction in the formation of algae in the tubing due to the oxygen, and the suspension of solids due to micro bubbles, which reduces the possibility of emitter clogging (Essah and Holm, 2020). Achieving a harmonious equilibrium among the three soil phases, solid, liquid, and gas, is paramount for successful crop cultivation. The introduction of air through injection enhances the hydro-aerobic balance, particularly under conditions of frequent irrigation. Aerated *SSDI* has been shown to enhance yields and overall crop quality across various crops, including bell pepper (Goorahoo *et al.*, 2001), soybean (Bhattarai *et al.*, 2004), strawberry (Goorahoo *et al.*, 2007; Goorahoo *et al.*, 2008), melon (Goorahoo *et al.*, 2007; Goorahoo *et al.*, 2008), edamame (Bhattarai *et al.*, 2008), tomato (Goorahoo *et al.*, 2007), cotton (Bhattarai *et al.*, 2004; Pendergast *et al.*, 2014), pineapple (Dhungel *et al.*, 2012), sugar beet (Vyrlas *et al.*, 2014), potato (Shahien *et al.*, 2014), pumpkin, and lettuce (D'Alessio *et al.*, 2020). Continuous saturation of the root zone hampers effective root functioning due to the restricted diffusion of oxygen. It is postulated that the diminished oxygen concentration in the rhizosphere, particularly at the wetting front, significantly constrains the performance of *SSDI* crops under higher irrigation rates. Goorahoo *et al.* (2001) found that the average weights of aerated and non-aerated peppers were 103.7 grams and 99.4 grams, respectively. The aerated plants exhibited a 39% increase in weight compared to the non-aerated plants. Additionally, the aerated plants demonstrated a root weight increase of 17.53 grams, corresponding to a 54% rise over the plants receiving water only. Furthermore, the aerated plants displayed a stem and leaf weight increase of 68.98 grams. When sufficient water and food availability are given for both aerated and non-aerated plants, the air injection may be responsible for a larger percentage of the root mass in the aerated plants. Hussein (2015) observed that the injection of air through the Subsurface Drip Irrigation system during the final third of the irrigation period maintained all hydraulic parameters for the emitter within an acceptable range, resulting in an efficient system for crop yield, water conservation, and water use efficiency *(WUE)*. Refaie *et al.* (2019) indicated that air injection in irrigation systems can enhance aeration in the root zone, thereby enhancing the value of grower investments in subsurface drip irrigation techniques. Moreover, they noted that the increased yields and potential enhancement in soil quality associated with root zone aeration suggest that adopting subsurface drip irrigation-air injection technology primarily serves as a means to enhance carrot productivity. Dissanayake (2020) discovered that the aerated zone at a soil depth of 45 cm contained an equal or even higher level of soil oxygen than the non-aerated zone at a depth of 25 cm. Additionally, air injection reduced soil moisture content, likely attributable to increased root water intake due to enhanced root and soil respiration. Furthermore, it was found that air injection through *SSDI* positively influenced the growth parameters of corn and sugar beet crops. The drip irrigation system also exhibited more efficient water usage and conservation across various summer and winter crops (Essah and Holm, 2020).

Cultivating zucchini holds significant importance in Egypt, both culturally and economically. This versatile crop is vital in Egyptian cuisine, featuring prominently in traditional dishes such as stuffed zucchini and vegetable stews. Beyond its culinary value, zucchini cultivation contributes to the country's agricultural sector, providing income for farmers and supporting local economies. Its export potential further enhances its economic significance as Egypt leverages its agricultural resources to generate revenue from international markets. Additionally, zucchini's resilience to drought conditions makes it a valuable crop in regions with limited water resources, contributing to food security and agricultural sustainability (Seleim *et al.*, 2015).Thus, the main objective of this research work was to evaluate air injection into subsurface drip irrigation system for zucchini production as efficient method for subsurface drip irrigation systems to improve water use efficiency *(WUE)*, and zucchini production in heavy clay soils. This objective was planned to be realized through the following stages:

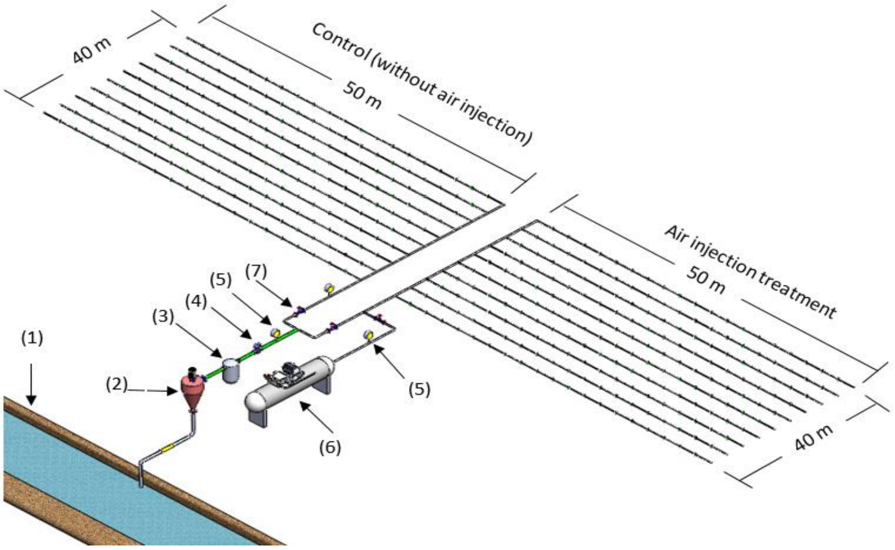
- Evaluating the impact of air injection through subsurface drip irrigation system on the hydraulic performance and system distribution uniformity.
- Evaluating the enhancement of soil properties with air injection.
- Effecting of air injection on the *WUE* and zucchini crop production in heavy clay soil.
- Assessing the Economic return of adding air injection in *SSDI* systems.

MATERIALS and METHODS

Field experiments were performed during two summer seasons of 2022 and 2023, laboratory experiments at the National Irrigation Laboratory of Agricultural Engineering Research Institute (AENRI), Dokki, Giza, Egypt, field experiment was at special farm in Menoufia Governorate. Zucchini plants (Anglia variety) were sown between August 10 and 15. The plants were spaced 1 m apart between rows and 0.5 m apart within rows. They were planted in heavy clay soil (59.2% clay, 6.4% silt, and 34.4% sand) on a 4000 m² plot designated for crop cultivation. The planting was conducted manually to ensure proper placement and spacing of the seeds. Harvesting was performed manually between September 22 and October 15, at the optimal maturity stage, when the fruits reached the desired size and quality. The agricultural treatments for zucchini were based on the guidelines provided by Abdel Aal *et al.* (2019), which served as the reference for the crop management practices applied in the study. The subsurface drip line was installed at a 15 cm depth during the growing season. Fertilization and pest control operations were carried out on zucchini plants using the recommended doses of the Ministry of Agriculture and Land Reclamation. The daily irrigation requirements for the zucchini crop were determined based on data from the Central Laboratory for Agricultural Climate (C.L.A.C) under the Ministry of Agriculture and Land Reclamation for the study location, using the Penman-Monteith equation. The average estimated evapotranspiration *(ETo)* was used to calculate the daily water consumption. A compressor was used to deliver air through water in the built-in emitters. The compressor injects ambient air at the last third of irrigation duration, and the aerated water is injected into the plant root zone through the built-in emitters.

Components of Subsurface Drip Irrigation System

The experimental field's subsurface drip irrigation system (Figure 1) consisted of a pumping and control unit, including a water source supply, pumping unit, pressure gauge, non-return valve, media filter, control valves, pressure regulators, and an air injector unit. Water flows from the pumping unit to the main line made of UPVC with a diameter of 63 mm, and from there to a PVC sub-main line with a diameter of 32 mm. Then the water flows into the Lateral lines. The Lateral lines were 16 mm diameter low-density polyethylene (LDPE), with a 4 lph (at 1 bar operating pressure) built-in emitters, the distance between emitters 50 cm (Figure 2).



(1) Water source (2) Pump (3) Media filter (4) Pressure regulator (5) Pressure gauge
(6) Air compressor (7) Valve

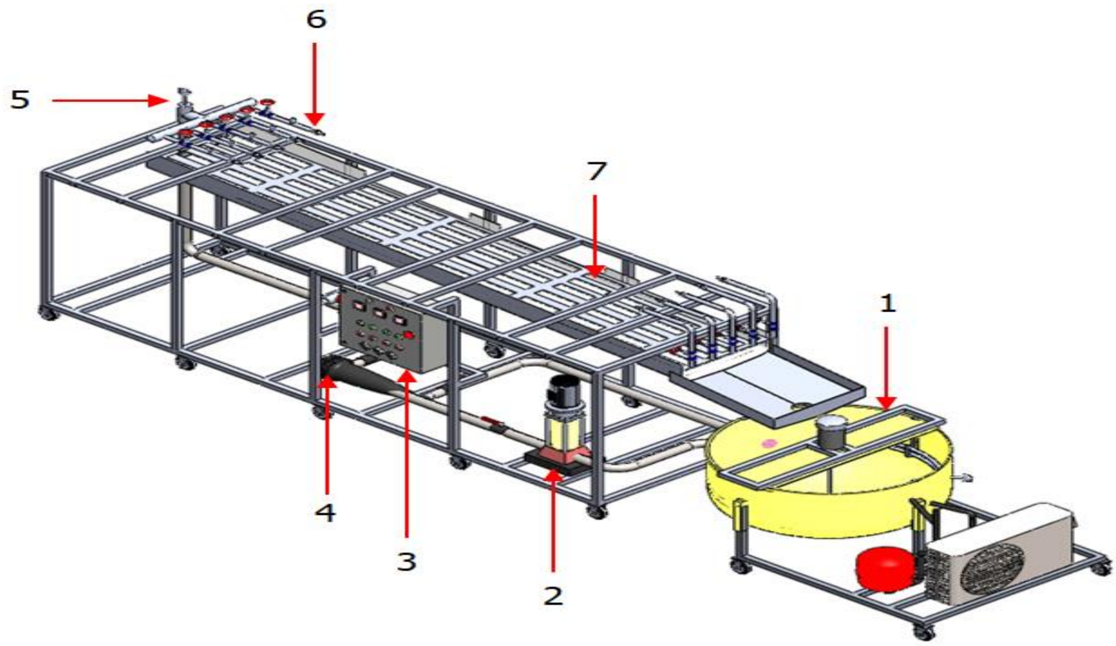
Figure 1. *Experiment design of subsurface drip irrigation system for control and air injection.*

Specification of emitter	
Average flow rates 8 lph /m at 1 bar	

Figure 2. *Built-in emitter.*

Hydraulic test bench

Figure (3) illustrates the components of the hydraulic test bench, used to assess the emitters hydraulic performance.



1	Water tank	500 l
2	Water left pump	5 m³ ·h-1 at 60 m left
3	Unit control	For control, the dimensions are 60 x 60 x 20 cm.
4	Filter	120 mesh
5	Heat sensor	
6	Outlets	1 inch
7	Water collection basin	From drip irrigation tested lines.

Figure 3. *Trickle hydraulic test bench.*

Experimental design and treatments

Evaluating the performance of built-in emitter

The flow rates of the emitters were measured across six operating pressures ranging from 0.6 to 2 bar. Flow rates were determined by weighing the water collected in a plastic cylinder over 6 minutes, timed using a stopwatch. All emitter flow rates versus pressure were evaluated via coefficient of variation *(CV)*, discharge variation (q_{var}), and emission uniformity *(EU)* according to ASAE (1996) and MSAE (2005) Standards.

Determining the effect of air injection on emitter hydraulic performance

The experiment included evaluating and comparing the hydraulic performance between the control (without air injection) and the air injection treatment using the above criteria. The treatment included air injection in the last third of irrigation.

Field experiment

To study the effect of air injection in heavy clay soil on crop production, water use efficiency *WUE*, and economic evaluation many variables, including, crop yield, total seasonal irrigation water, total annual costs were recorded for with each treatment. *WUE*, financial analysis measures of benefit-cost ratio *(BCR)*, and net return *(NR)* values were estimated. This data was then analyzed and compared to determine the economic return of air injection in subsurface drip irrigation.

Measurements and Calculation

Evaluation of the built-in emitters

Pressure-flow relationships

The emitter flow rate is typically defined by the relationship among flow rate, pressure, and an emitter flow rate exponent. The flow rate equation, widely used by researchers (Keller and Karmeli, 1974; MSAE, 2005), is derived from Equation (1):

$$q = kp^x \tag{1}$$

Where; q is emitter flow rate, lph; k is constant of proportionality that characterizes each emitter and compensates for units; p is the operating pressure, bar; and x is emitter flow rate exponent that characterizes the flow regime.

Equation (2) can be used to express the pressure influence on emitter flow rate variation (q_{var}) either directly as the average of the emitter flow rate or as a percentage of the flow rate change that takes place at the actual operating pressure and pressure of 1 bar with the same water temperature, divided by the flow rate at pressure of 1 bar.

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \times 100 \tag{2}$$

Where; q_{var} is the emitter flow variation, %; q_{max} is the maximum emitter flow, lph; and q_{min} is the minimum emitter flow, lph.

In general, the acceptable values of qvar were about from 10 to 20 %; and greater than 20% is not acceptable according to ASAE (1996).

Emitter manufacture's coefficient of variations (CV)

The manufacture's coefficient of variation *(CV)* indicates the unit-to-unit variation in flow rate for a given emitter. The emitter manufacture's coefficient, Equation 3, was calculated by measuring the flow rate from a sample of the new emitters as follows:

$$CV = {}^{s}/_{q_a} \tag{3}$$

Where; *CV* is manufacturer's coefficient of emitter variation; *s* is standard deviation of emitter flow rate rates at a reference pressure head, lph; and q_a is the average flow rate, lph.

Emission uniformity (EU)

Emission Uniformity *(EU)* is a measure of how evenly water is applied throughout a specified area. This measurement is essential for scheduling irrigations efficiently. *EU* is used to indicate performance for emitters. *EU* was calculated from Equation (4) according to Keller and Karmeli (1974).

$$EU = \left({}^{q_n}/_{q_a}\right)100 \tag{4}$$

Where; *EU* is the emission uniformity, %; q_n is average of the lowest 1/4 of the emitter flow rate, lph; and q_a is average of all emitter flow rate, lph.

Calculation of irrigation time

The irrigation time was determined based on the evapotranspiration (*ET*) data from the AENRI Weather Station. The following equations were used to calculate the irrigation time:

$$ET_c = K_c \times ET_o \tag{5}$$

Where; Et_c represents the evapotranspiration for the crop, mm day^{-1}; K_c is the crop coefficient values; and Et_o is the evapotranspiration, mm day^{-1}. All the Et_o calcaulation and the K_c values and the length of the growth periods were taken from the FAO 56 (Allen *et al.*, 1998).

$$App.Irri.Rate = \frac{Q}{S_m \times S_L} \tag{6}$$

Where; $App.Irri.Rate$ is the applied irrigation rate, mm h^{-1}; *Q* is the emitter flow rate, lph; S_m is the distance between emitters, m; and S_L is the distance between lateral, m.

$$Irri.Duration = \frac{ET_c}{App.Irri.Rate} \tag{7}$$

Where; Irri. Duration is the duration irrigation rate, h day^{-1}.

The total yield per Fadden was calculated as follows:

$$Total\ yield\ per\ Feddan(kg/fed) = \frac{yield\ weight\ (kg) \times 4200}{sample\ area\ (m^2)} \tag{8}$$

Irrigation requirements were carefully calculated and applied to ensure efficient water usage, soil moisture within the active root zone was continuously monitored using a portable TDR device, ensuring optimal water management throughout the growing season.

Water Use Efficiency *(WUE)*

The *WUE* in this work was calculated for each treatment (Tolossa, 2021). This parameter can be used to compare between the studied treatment and control. The *WUE* for the tested treatments was calculated from Equation (8)

$$WUE = \frac{Y}{IRR} \tag{9}$$

Where; *WUE* is the water use efficiency, kg m^{-3}; *Y* is the total yield, kg ha^{-1}; and *IRR* is total amount of irrigation applied, m^3 ha^{-1}.

Soil physical and chemical properties evaluation

The physical and chemical properties of the soil were evaluated at the end of the experimental periods as follows:

Soil physical properties (Soil dry sieved aggregates)

Soil dry sieved aggregates were separated, using a sieve shaker with stacked and classify using equation (10) according to Richards (1954).

$$Dry\ sieved\ aggregates\ (\%) = \frac{Weight\ of\ each\ aggregate\ size\ fraction\ (g)}{Weight\ of\ soil\ (g)} \times 100 \tag{10}$$

Soil chemical properties

The available soil macro nutrients were measured; Nitrogen determined using Kjeldahl method described by FAO (1980), Phosphorus determined by a spectrophotometer according to Watanabe and Olsen (1965), and Potassium was using flame photometer, according to Page *et al.* (1982).

Economic return

Total annual costs

Total annual costs equal to renting farm for season, fertilizer, other chemicals, irrigation system cost installation divided into 5 years of use (construction elements of the subsurface drip irrigation system include outlets, regulators, laterals, manifolds, mainlines, fittings, and pumps), energy, workers salary through germination period and cultivation.

Net returns

Net returns are calculated by subtracting the estimated average annual costs *(C)* from the average annual gross returns *(B)*. To achieve the economic objective of maximizing net return, the system with the highest net return $(B - C)$ is considered the most effective based on the economic analysis.

Benefit-cost ratio (B/C ratio)

The Benefit/Cost ratio is calculated by dividing the annual benefits by the annual costs. When aiming to maximize return on investment, the system with the highest *B/C* ratio is considered the best choice according to economic analysis. It is common for one system to yield the highest net return while another achieves the highest *B/C* ratio (Khalifa, 2020).

$$Gross\ return\ (B)(\$) = Crop\ yield(ton/ha) \times Area(ha) \times Price(\$\ /\ ton) \tag{11}$$

$$Net\ return\ (B - C)(\$) = Gross\ return - Total\ annual\ costs \tag{12}$$

$$B/C\ Ratio\ (\%) = Gross\ return\ /\ Total\ annual\ costs \tag{13}$$

RESULTS AND DISCUSSION

Performance and Evaluation of the Built-In Emitters

It is necessary to evaluate the hydraulic performance of subsurface drip irrigation system. Thus, a test was run to evaluate the hydraulics of pressure-compensating emitter 4 lph flow rate with pressure rating of 0.6 to 2.0 bar. Figure (4) shows the average values of emitter flow rate for each pressure. The results clearly indicated that as the operating pressure increased, discharge of emitters is fixed. It's also clear that the flow rate coefficient *(k)* and emitter flow rate exponent *(x)* were 3.97, and 0.07 respectively.

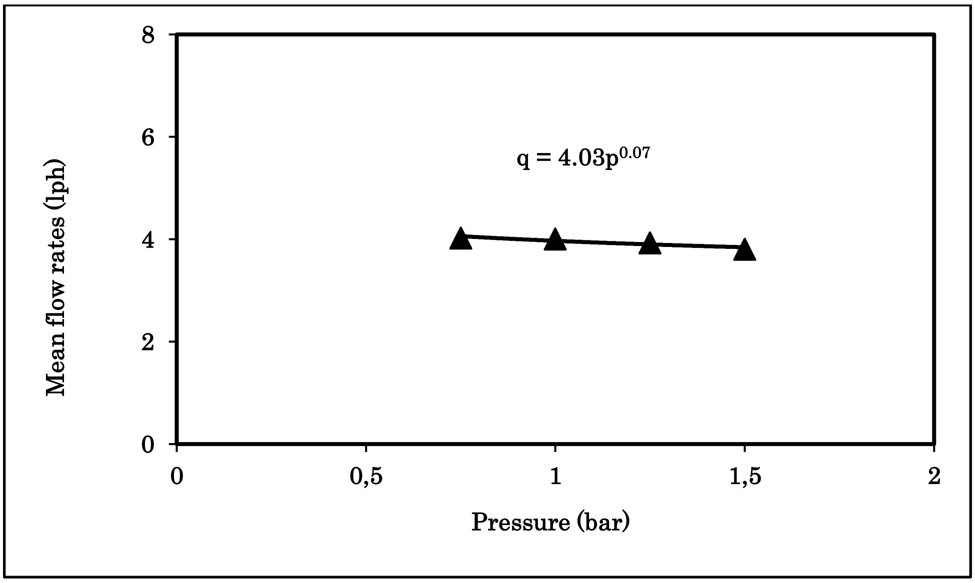


Figure 4. *Performance curves of the experimental emitter sample (built-in 4 lph-50 cm).*

Evaluation of the impact air injection in the last third of the Irrigation through subsurface drip irrigation system on the hydraulic performance and system distribution uniformity and comparison with control.

Figure (4) and Table (1) show that there is a close relationship between emitter flow rates and pressure. By comparing the evaluation results with the results of the control, the results showed that there is no significant difference between the injection treatment in the last third of the irrigation time and the control, because the points maintain all their acceptable hydraulic properties without being negatively affected by the air injection. The values of all parameters injecting air in the last third of irrigation duration q= 3.91 lph, CV= 2.26% were excellent according to ASAE standard, EU = 97.44% were excellent according to ASAE standard. q_{var} =10.71% was acceptable according to ASAE standard. This result agrees with of

Hussein (2015). Thus, adding air during the subsurface drip irrigation system has a positive effect in maximizing the benefit from the subsurface drip irrigation system, especially for crops that depend for their growth on aerobic bacteria, as well as in flooded lands that need to change and improve the structure and increase the amount of oxygen in them, thus improving the management of the system.

Table 1. *The impact of air injection by air compressor through subsurface drip irrigation system on the hydraulic performance and uniformity distribution.*

Treatments	**Water flow rate, lph**	**CV, %, at 1 bar**		***EU*, %**		**q_{var},%**	
	Mean	Value	ASAE standard	Value	ASAE standard	Value	classification
Control	4.03	2.26	Excellent	97.18	Excellent	11.15	Acceptable
Air injection	3.91	2.26	Excellent	97.44	Excellent	10.71	Acceptable

CV= Manufacture's coefficient of variation, *EU*= Emission uniformity, q_{var}= Emitter flow variation

The effect of air injection on the water use efficiency and plant performance in a heavy clay soil

The average results of two seasons of zucchini crop that were grown using air injection in subsurface drip irrigation showed a significant increase in yield compared to the control found that air injection in the last third of the irrigation increased the zucchini yield by 27% compared with control. Total yield (ton ha^{-1}) was 19.05 with air injection and 15 ton ha^{-1} with control. The applied water (m^3 ha^{-1}) with air injection was 1152.4 in comparison Control which was 1476.2 m^3 ha^{-1}. This means that there was water saving in case of using this method of 22%. The water use efficiency (Table 2) under air injection resulted in 16.53 kg m^{-3}, but with Control, it was 10.16 kg m^{-3}. This result agrees with Goorahoo *et al.* (2001); Bhattarai *et al.* (2008); Shahien *et al.* (2014); Refaie *et al.* (2019).

Table 2. *Average water use efficiency and Zucchini yield under air injection and control treatments.*

Treatments	**IRR, m^3 ha^{-1}**	**Y, ton ha^{-1}**	***WUE*, kg m^{-3}**	**Increasing in *WUE*, %**
Control	1476.2	15.00	10.16	38.54
Air injection	1152.4	19.05	16.53	

Y= Zucchini yield, *IRR*= total amount of irrigation applied, *WUE* = water use efficiency.

Effect of air injection on physical and chemical properties of heavy clay soil:

Soil physical properties (Soil dry sieved aggregates)

The results of the soil dry sieved aggregates at the end of the experimental practices with and without air injection show a change in the aggregates distribution by air injection indicate to an improvement of heavy clay soil physical properties by changing the arrangement of soil aggregates which improves soil structure. While Table (3) shows, there was a decrease in the large macro-aggregates that have diameters from 2 to 10 mm which distributed to a small macro-aggregate (2 to1, 1 to 0.5 and 0.5 to 0.25 mm) resulted in relative increase of these aggregates diameters, also micro-aggregates that less than 0.25 mm were decreased comparing to the absence of air injection. That can contribute in alleviating compaction impacts create pathways for air, water, nutrients and allow roots elongation to reach its need while, air, water, earthworms, microbes, roots and seeding have trouble moving through heavy clay soil, so crop yields suffer.

Table 3. *Air injection techniques effect on distribution fraction (%) of soil dry sieved aggregates.*

Treatments	Dry aggregates diameter, mm						
	10-2	2-1	1-0.5	0.5-0.25	0.25-0.125	0.125-0.063	<0.063
Control	43.16	18.56	19.34	11.72	4.47	2.55	016
Air injection	58.41	11.94	12.16	8.85	5.85	2.62	0.17

Soil chemical properties

Figure (5) shows an increase in available macronutrients N, P and K with air injection. The amount of available nitrogen increased from 94.1 ppm for the control treatment to 116.4 for the air injection treatment, K values increased from 60.8 ppm for the control treatment to 80.2 ppm for the air injection treatment, and P values increased from 4.1 ppm for the control treatment to 6.2 ppm for the air injection while that avoid the loss of N converted to gases by the denitrification and also oxygen has a dramatic impact on microbial activity and rate of decomposition of nutrients, releasing K on exchange sites of the clay and P from its unavailable compounds while, many nutrients can be in soluble form and easy to plant uptake by roots of crops in case of air condition (Refaie *et al.,* 2019).

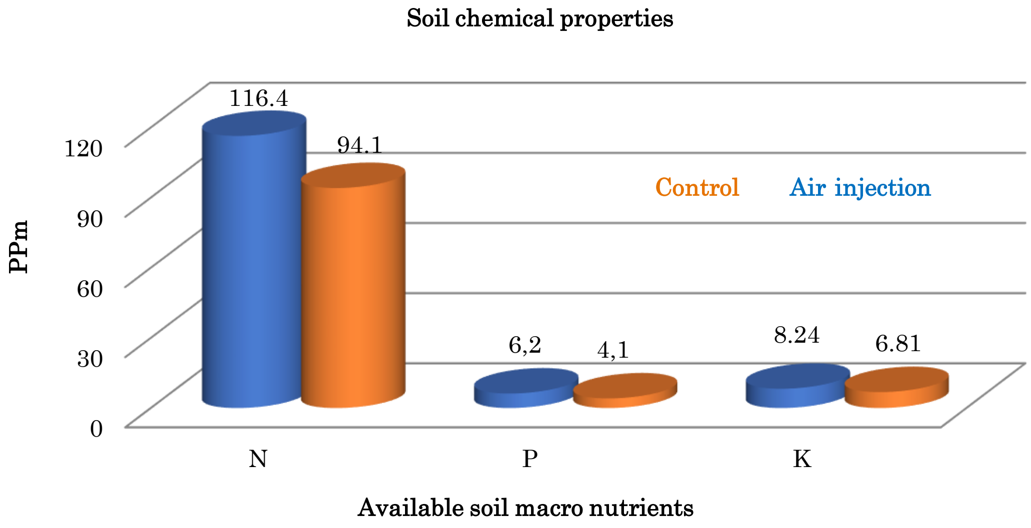


Figure 5. *Air injection techniques performance on available soil macronutrients.*

Economic return of air injection through subsurface drip irrigation system

The following parameters were taken as an economical evaluation in case injecting air through drip irrigation system the following items were the major item in economic analysis:

1. Gross return LE and $,
2. Net return LE and $ and,
3. Benefit-cost ratio (*B/C* ratio).

Table (4) shows the gross return, net return, and benefit-cost ratio (*B/C* ratio). It's clear that the gross return of air injecting treatment was 72000 LE (4161.9 $) compared with the control treatment (without air injecting) which was 56700 LE (3277.5 $). The gross return of air injection increased by 21% compared with control treatment (without air injecting). While the net return of air injecting was 40695 LE (2352.3 $) compared with the control treatment (without air injecting) which was 25395 LE (1467.9 $). Furthermore, the benefit-cost ratio of air injection stood at 2.3%, surpassing the 1.8% of the control treatment. Economic analysis, which included criteria such as the benefit-cost ratio (B/C) and net return values (*B-C*), indicated that air injection represented a viable economic option.

Table 4. *Economic return of air injection and control treatments through subsurface drip irrigation system.*

Treatments	Gross return, LE ($)	Net return, LE ($)	*B/C* ratio, %
Control	56700 (3277.4 $)	25395 (1467.9 $)	1.8
Air injection	72000 (4161.9 $)	40695 (2352.3 $)	2.3

B/C= benefit-cost ratio

The findings of this study revealed that introducing air into the drip line did not impact the hydraulic performance of the emitters. The T-test analysis indicated no significant differences between the air injection treatment and the control group. This lack of distinction could be attributed to the similar behaviour of the air injected into the lines compared to water flowing in the lines, particularly considering the pressure-compensating type of the emitter used. While the results showed a slight reduction in emitter flow rate with air injection treatments, this was likely due to a less dense water-air mixture in these instances rather than a change in emitter performance. The reduced density of the water-air mixture led to less water accumulation from the same volume passing through the emitter compared to the control treatment, resulting in a lower emitter flow rate. The method of determining emitter flow rate by collecting and weighing the flow mass over time is what caused the observed differences in flow rate between treatments. This is consistent with the findings of Li *et al.* (2023). The results of the crop yield and the total seasonal irrigation water (*SIW*) shows a decrease in the *SIW* while increasing the yield for the air injected treatment when compared to the control treatment. The decrease of the *SIW* is due to the slight decrease in the emitter flow rate and the increase in yield may be due to the fact that the heavy clay soils induces hypoxia in the rhizosphere through air purge, which limits root respiration and growth as well as microbial respiration (Chen *et al.*, 2010), particularly in heavy clay soils (Midmore *et al.*, 2007). Airiation was proposed as a promising method that can alleviate hypoxia effects on a variety of crops to improve their performance (Bhattarai *et al.*, 2006; Bhattarai *et al.*, 2008). Airiation can improve and maintain heavy clay soil to enjoy benefits clay offers for healthy plants while air can effect positively on soil reactions and in turn many soil properties as enhancing biodegradation of organic practices within the aggregates which the vital cementing agent for micro- aggregates to become macro-aggregates contribute to improving soil structure and lead to better water infiltration, better aeration and better nutrition (Zhang *et al.*, 2022). Airiation improved soil oxygen content and soil respiration in root zone, which was beneficial for plant growth and yield in wheat, rice, and pineapple (Chen *et al.*, 2010). Plant growth and development necessitate the presence of oxygen in the rhizosphere; it is involved in several processes, including carbohydrate metabolism and nutrient uptake by roots (Makita *et al.*, 2015). Because of the treatment's increased yield and decreased water supply, the *WUE* of the air injection treatment was significantly higher than that of the control treatment. The results are in accordance with Abuarab *et al.* (2013) how reported moer leaf area faster grain filling and less maturation time for corn plant when using ariation in subsurface drip irrigation lines. Zhang *et al.* (2023) also reported a higher *WUE* for tomato plants under oxygenated drip irrigation in heavy clay soils. The availability of soil nutrients increased with the air injection treatment. Soil airiation impacted microbial activity and nutrient decomposition rate, releasing from its unavailable compounds on exchange sites of the clay. This agrees with Refaie *et al.* (2019) who concluded that many nutrients can be in soluble form and easy to plant uptake by roots in case of airiation condition. The economic analysis shows that even though the cost of aeration was higher because of the need to an air compressor and the extra cost of energy required for its' operation the extra revenue added by the increase in the crop productivity covered the extra costs and allowed for more profit as shown from the increase of the net return and the higher benefit-cost ratio of the air injection treatment.

CONCLUSION

Integrating air injection into subsurface drip irrigation *(SSDI)* systems has proven to be a cost-effective method for enhancing vegetable production, particularly in heavy clay soils. This approach offers several advantages, including improved water use efficiency, increased crop yields, and enhanced soil properties compared to conventional irrigation methods. By introducing atmospheric air into the soil through *SSDI* systems, issues such as waterlogging in the root zone are mitigated, resulting in better root respiration, improved nutrient uptake, and overall enhanced plant growth. The benefits of air injection were especially evident in zucchini cultivation, where significant increases in yield and water conservation were achieved. Furthermore, from an economic standpoint, the use of air injection systems contributed to higher gross and net returns for farmers, along with a favorable benefit-cost ratio. These results highlight the effectiveness and sustainability of air injection in modern agricultural practices.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

The authors declare that the following contributions are correct.
Nermin Hussein: Contributed equally to various roles including setting research goals, development of methodology, performing the experiments, analyzing data, and writing the artical.
Shereen Saad: Contributed equally in various roles including setting research goals, development of methodology, performing the experiments, analyzing data, and writing the artical.
Khaled Refaie: Contributed equally in various roles including setting research goals, development of methodology, performing the experiments, analyzing data, and writing the artical.
Wael Sultan: Contributed equally in various roles including setting research goals, development of methodology, performing the experiments, analyzing data, and writing the artical.
Mohamed Ghonimy: Contributed equally in various roles including setting research goals, development of methodology, performing the experiments, analyzing data, and writing the artical and also coordinated the activities with the co-author.
Ahmed Alzoheıry: Contributed equally in various roles including setting research goals, development of methodology, performing the experiments, analyzing data, and writing the artical.

ETHICS COMMITTEE DECISION

This article does not require any Ethical Committee Decision.

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