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Study on Efficiency of a Negative Pressure Irrigation System

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Abstract

In many areas of the world where water resources are limited, negative-pressure irrigation (NPI), a subsurface irrigation method, is utilized to boost water use efficiency. Negative pressure irrigation (NPI) consists of a water reservoir and a porous pipe that is buried in the ground. Negative pressure P_n is produced by lowering the water reservoir below the porous pipe. A soil column was made using seven rings of a PVC pipe, was filled with local sand and the porous pipe was inserted vertically in the soil column. One electric balance was positioned beneath the soil column, the other beneath the water reservoir. Between the reservoir and the porous pipe, water was pumped back and forth. The amount of water supplied (M_{sup}), soil water storage (M_{soil}), volumetric moisture content (Θ) in various layers, radial distances of wetting front were all measured for two different negative pressure -3 cm and -5 cm for three different time 8 hours, 24 hours and 48 hours. The experiment was phased into two stages. The primary stage was the measurement accuracy test which was done by covering the soil column to prevent evaporation loss. The secondary stage was the water balance test in which the evaporation loss was considered. The study shows that, volumetric water content increases with time and with increasing vertical distance from the top of the porous pipe. The water consumption efficiency rises as the negative pressure decreases and is always greater than 75%.

Keywords: *Negative pressure irrigation; Volumetric water content; Wetting front; Efficiency.*

1 Introduction

The most serious issue affecting agricultural production is drought, and most farmed regions of the world are experiencing an increase in the severity of this issue. So, the main goal of sustainable agriculture is to increase water production.(Mohammed et al., 2021) It is impossible to prevent water loss in irrigation systems due to evaporation, deep percolation below the root zone, and transportation of water from the source to the agricultural field. Under harsh weather circumstances like direct sunlight, high temperatures, and low humidity, it was shown that spray losses in a sprinkler irrigation system can reach up to 45%(Moniruzzaman et al., 2022). For nations like Saudi Arabia that have scarce water supplies and challenging external evaporation conditions, water-saving irrigation techniques are essential. Understanding the water dynamics during irrigation is crucial for determining the ideal technical parameters of any irrigation system, especially in light of climate change. Key factors in the design of a subsurface irrigation system are the size and distribution of the wetting front.(Cai et al., 2022) Since it allows for a direct water delivery to the root zone, negative pressure irrigation (NPI) is a very effective approach for conserving water(Bhople et al., 2014). Negative pressure irrigation (NPI) system is a kind of subsurface irrigation and is composed of a water reservoir and a porous pipe installed in soil. To create negative pressure, P_n, the water reservoir is positioned lower than the porous pipe. When the absolute value of the soil water matric potential (hereafter referred to as matric potential), $|\psi|$, is greater than that of the negative pressure in the porous pipe, $|P_n|$, water rises from the water reservoir to the porous pipe and then percolates through the porous pipe into the surrounding soil. On the other hand, when $|\psi|$ is less than $|P_n|$, the seepage ends naturally without the need for any external effort(Akhoond-Ai & Golabi, 2008). In comparison to conventional drip irrigation techniques, NPI can also lessen surface evaporation, runoff, and deep seepage loss during the growth season(Hsiao et al., 2007). When compared to drip irrigation, NPI's continuous and constant water supply has improved plant height, stem diameter, fruit output, and water use efficiency. Also, as NPI combines the delivery of water and fertilizer, it is suitable for vegetable production in solar greenhouses(Wang et al., 2019). Consequently, the aim of the present study is to investigate the efficiency of the NPI system with a vertically placed porous pipe at different negative pressures.

2 Experimental Method

Figure 1 shows the experimental setup at the laboratory. Seven rings (each measuring 0.03 meters in height and 0.30 meters in diameter) made up the PVC pipe soil column. Then, to maintain P_n constant, a Marriott tube was placed in a water storage tank. The reservoir and porous pipe were connected by a small pump that moved water back and forth between them. Under the soil column, the water supply tank, and the reservoir, respectively, two electric balances were positioned. The amount of water retained in the soil was measured using an electric balance that was positioned underneath the soil column, M_{soil} and the second balance was used to calculate how much water was supplied from the reservoir, M_{sup} simultaneously. Evaporation from the soil surface, M_{eva}, was given by subtracting M_{soil} from $M_{sup.}$

$$M_{eva} = M_{sup} - M_{soil}$$

The soil column was wrapped with plastic sheets to stop evaporation from the soil surface (measurement accuracy test) so that it would be simple to assess the measurement accuracy of M_{sup} and M_{soil}. As a result, the measurement accuracy for the simple water balance of M_{sup}=M_{soil} was assessed. The water balancing test was run for two distinct negative pressures (P_n= -.03m, -.05m) once the measurement accuracy was assured. Then at the end of the test M_{sup} and M_{soil} were measured and the dry soil around the wetted soil was removed by removing the pipe rings one by one. Finally, the wetted soil was collected in a heat -proof tray and the volumetric moisture content of the wetted soil, θ, was obtained. All data were measured at three elapsed time, t = 24, 48 and 72 hours.

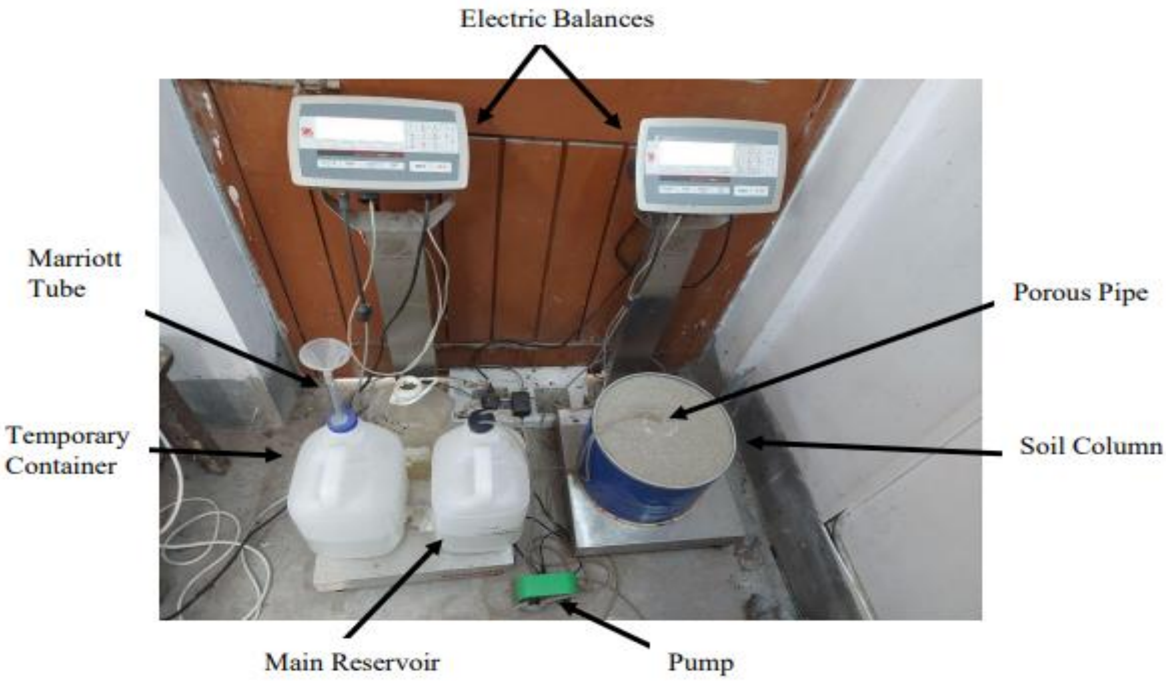

Figure 1: Image of the experimental arrangement at the laboratory.

3 Results and Discussions

In the following figures, volumetric water content increases with increasing vertical distances from the top of the porous pipe. On the other hand, volumetric water content decreases with increasing radial distance. In figure 2, It is seen that at highest radial distance 9 cm, volumetric water content is 0.04, which is less than the highest volumetric water content 0.067. In downward direction, water spreads faster than in radial direction.

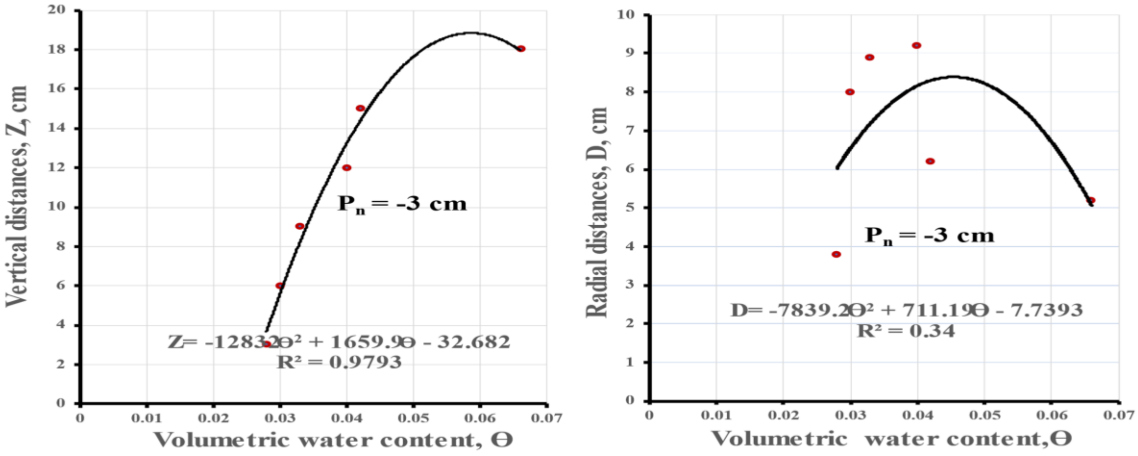

Figure 2. The variation between Volumetric water content, and vertical and radial distances around the porous pipe, P $_{n}$ = -3 cm, for time 8 hours

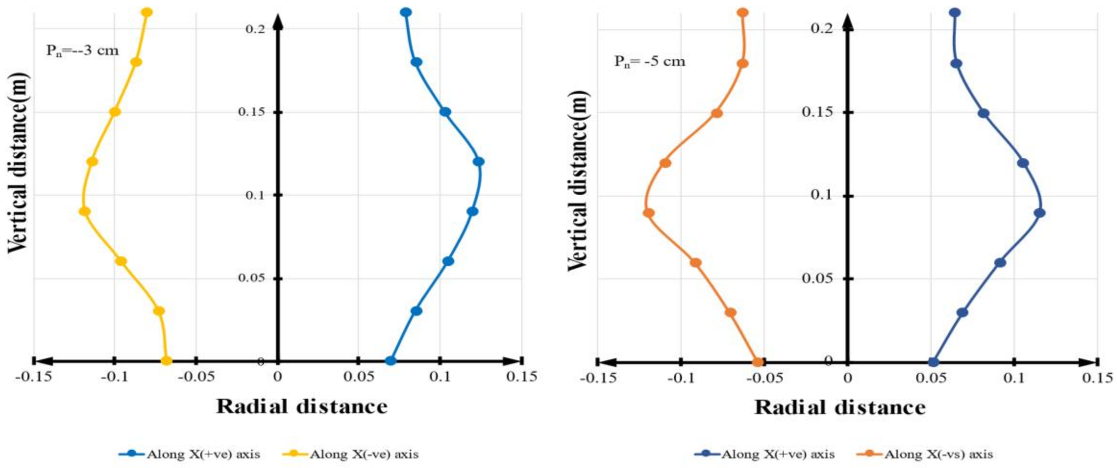

Figure 3. Wetting front measurement along X axis at P $_{n}$= -3 cm and -5 cm for 8 hours

The measurements of soil wetting front along both X axis and Y axis at P $_{n}$= -3 cm and P $_{n}$=- -5 cm are shown in the Figure 3.

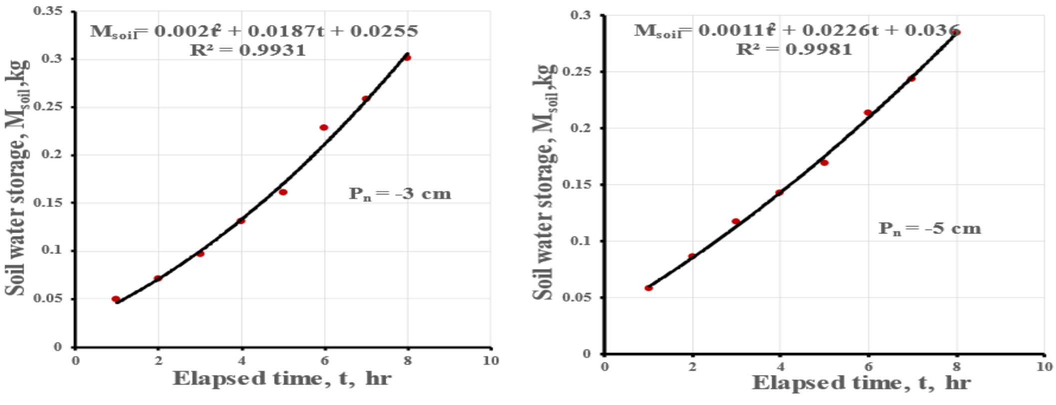

Figure 4**.** Soil water storage with respect to time at different negative pressure for time 8 hours

Figure 4 shows the amount of soil water storage for different time interval. Initially, M_{soil} increased remarkably with t. It is seen that at t = 8 hours for P_n= - 3 cm M_{soil} is 0.32 kg and for P_n = - 5 cm M_{soil} is 0.27 kg. So, When negative pressure decreases, soil water storage also decreases.
From the function of $\mathbf{M_{soil}= 0.002t^2 + 0.0187t + 0.0255}$ for P_n = - 3 cm and $\mathbf{M_{soil}= 0.0011t^2 + 0.0226t + 0.036}$ for P_n = - 5 cm, it is said that soil water storage decreases from higher negative pressure to lower negative pressure from P_n = -3 cm to P_n =- 5 cm. it has been showed a polynomial equation for that reason this variation of soil water storage and time has been occurred.

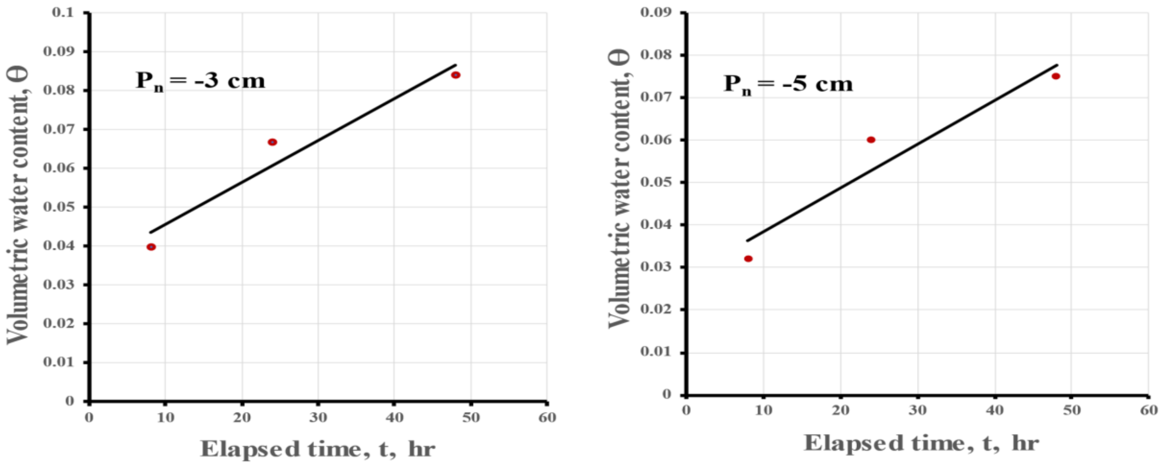

Figure 5. Variation of volumetric moisture content with time at two different negative pressure -3 cm and -5 cm

In Figure 5, volumetric moisture content is measured for time 8hours, 24hours and 48hours for negative pressure -3 cm and -5 cm. From the following graphs, it has shown that the volumetric moisture content increases with time at a constant negative pressure. For negative pressure -3 cm, volumetric moisture content at time 48 hour is 0.082, on the other hand, for negative pressure -5 cm, volumetric moisture content at time 48 hour is 0.076. So, volumetric moisture content increases with increasing negative pressure. Thus, higher negative pressure is good output for larger amount of storage of volumetric moisture content.

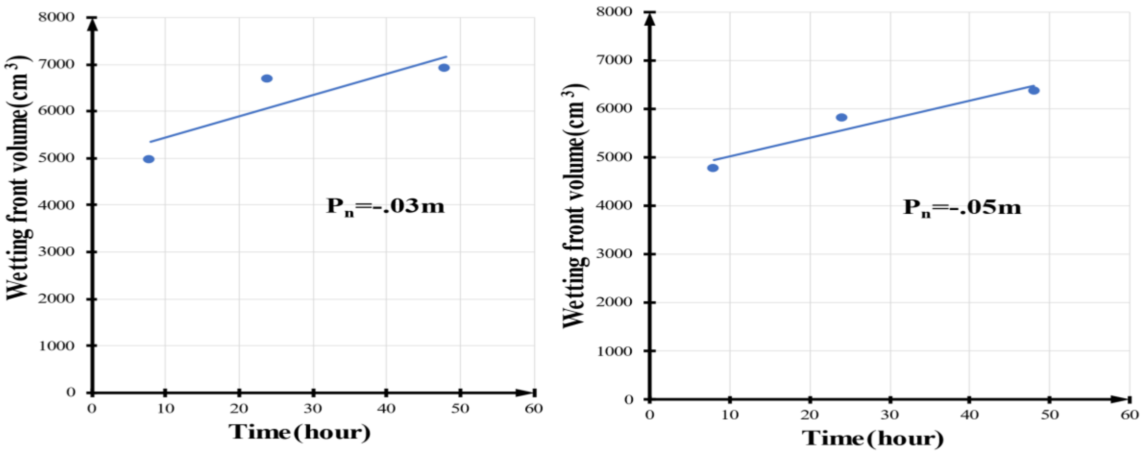

Figure 6. Variation of wetting front volume for 8h, 24h and 48h at P_n= -3 cm and P_n= -5 cm

In figure 6, we can see that the volume of soil wetting front increases with elapsed time at P_n= -3cm. Similar result is seen at P_n= -5cm. It can be said that, size of soil wetting front increases with the increasing value of negative pressure. This is because water spreads from high potential area to low potential area, and as the negative pressure increases, the difference between the water potential inside the soil and outside it becomes larger, causing more water to move into the soil. Also, when the values of wetting front volume at P_n= -3cm and P_n= -5cm are compared it is observed that wetting front volume increases with increasing negative pressure.

The efficiency of used water, E_f could be denoted as M_{soil}/M_{sup}. The following figures represent the variation of efficiency of used water for 8 hours, 24 hours and 48 hours.

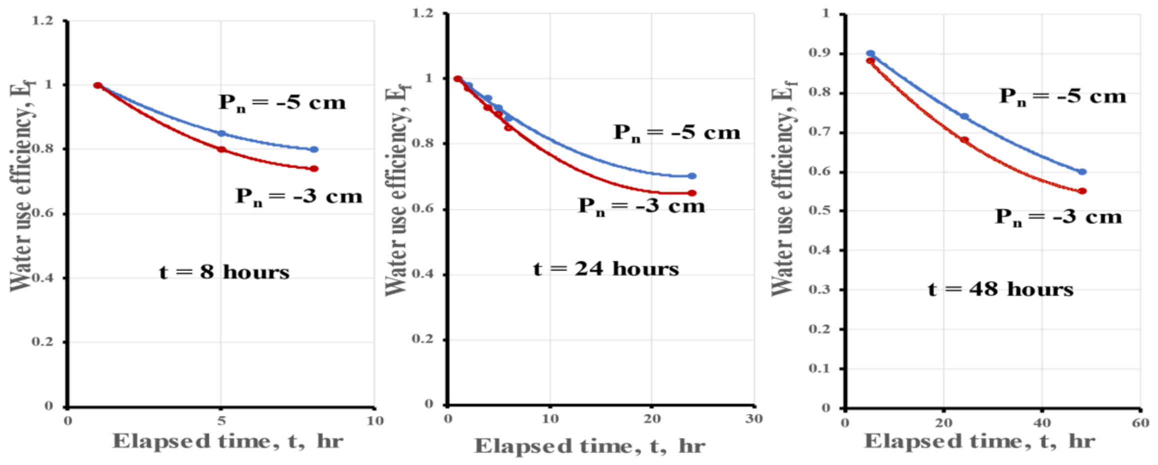

Figure 7. Water use efficiency with respect to time at P_n=-3 cm & -5 cm for 8 hours, 24 hours and 48 hours

In figure 7, all the graphs displaying that E_f is decreasing with increasing of negative pressure. This is because when the soil water potential becomes more negative, soil water bounds more tightly to soil particles, that causes difficulty to plant roots for extracting water.

4 Equations

Calculation of Volumetric Moisture Content of Soil
Volumetric moisture content can be measured by Gravimetric method. It is expressed as,

$$(1)\quad \Theta = \frac{\text{Volume of water}}{\text{Volume of soil}}$$

$$\text{Hence, } \Theta = \frac{\frac{\text{Mass of water}}{\text{Density of water}}}{\frac{\text{Mass of soil}}{\text{Bulk density of soil}}} * 100$$

Calculation of bulk density of soil:

$$(2)\quad \text{Bulk density, } \rho = \frac{\text{Mass of soil}}{\text{Volume of soil}} = \frac{25}{\pi*(0.2)*0.2*0.21} = 947.35 \text{ kg/m}^3$$

$$(3)\quad \text{Volumetric moisture content, } \Theta = \frac{\frac{\text{Weight of can+wet soil} - \text{weight of can+dry soil}}{\text{unit weight of water}}}{\frac{\text{weight of can+dry soil} - \text{weight of can}}{\text{Bulk density of soil}}}$$

$$\text{Volumetric moisture content, } \Theta = \frac{\frac{82.22-81.24}{1000}}{\frac{81.24-47.95}{947.35}} = 0.028$$

Table 1. Volumetric moisture content measurement at different layer of soil column and at different radial distances at P_n = -3 cm for time 8 hours

Negative pressure, cm	Layer of soil column, cm	Radial distances from porous pipe, cm	Weight of can, kg	Weight of can + wet sample, kg	Weight of can +dry sample, kg	Volumetric moisture content, Θ
	1	3.80	47.95	82.22	81.24	0.028
	2	8.00	50.39	86.84	85.72	0.030
-3	3	8.88	47.25	100.20	98.42	0.033
	4	9.20	44.88	95.61	93.56	0.040
	5	6.20	48.18	110.34	107.81	0.042
	6	5.20	45.18	117.11	112.43	0.066

5 Conclusions

Under constant air temperature and humidity, the experiment was conducted using a porous pipe placed in soil column and a reservoir to investigate the wetted soil in NPI system. Measurements of the supplied water, soil water storage, evaporation, wet soil surface, and volumetric water content around the porous pipe were measured for three different time intervals of eight hours, twenty-four hours, and forty-eight hours at two different negative pressures of three and five centimeters, respectively.

The following are the study's major conclusions:

- The volumetric water content rises with increasing vertical distances from the top of the porous pipe.
- Volumetric water content decreases with increasing radial distances.
- Increase of negative pressure increases the size of soil wetting front.
- Soil water storage increases when negative pressure increases.
- Soil water storage increases with increasing time intervals.
- Volumetric water content increases with time at a constant negative pressure.
- Volume of soil wetting front increases with elapsed time and with the increasing value of negative pressure.
- As evaporation occurs, the efficiency of used water decreases when time interval increases.
- The efficiency of used water, decreases with increasing negative pressure.

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