Effects of fertigation strategies on water and nitrogen distribution under water storage pit irrigation for orchards

Jingling Li*, Pan Chen, Xihuan Sun, Ping Liu

(*College of Water Resource Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China*)

Abstract: Water storage pit (WSP) irrigation is a simple and inexpensive technology suitable for orchards in semiarid and arid regions of North China. This study compared the effects of different fertigation strategies on water and nitrogen distribution, and ammonia volatilization. A fertigation experiment was conducted using a 30° wedge-shaped plexiglass soil container, which represents one-twelfth of the complete storage pit. The height of the container was 120 cm, and a plexiglass damper for simulating the zero flux plane of adjacent water storage pits was located at the 40 cm radius. Four fertigation strategies were used for WSP irrigation: solution application during the first half (N-W), the last half (W-N), the middle half of an irrigation cycle (W-N-W), and during the entire irrigation (N-N). Surface (SF) irrigation was used as a control treatment with solution application during the entire irrigation (SN-N). The experimental results showed that the soil water and ammonium contents at 0-10 cm soil depth under WSP irrigation were only 10.51% and 18.42% of those under SF irrigation, respectively. The cumulative NH_3 volatilization under WSP irrigation was 51.71%-68.72% lower compared with that under SF irrigation. The soil water distributions were similar for all four fertigation strategies. NH_3 volatilization mainly occurred at the pit wall interface, and cumulative NH_3 volatilization loss followed the trend N-N > W-N > W-N-W > N-W. Ammonium was adsorbed into the soil and thus mostly remained near the pit wall. Low concentrations of ammonium were found near the edge of the wetting zone under all strategies. Compared to N-W, N-N and W-N-W treatments, W-N treatment decreased the nitrate accumulation at 80-90 cm by 38.6%, 19.0% and 10.3%, respectively. The W-N strategy was suggested for minimizing potential nitrate leaching.

Keywords: water storage pit, fertigation, soil water, nitrogen distribution, orchards irrigation

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1 Introduction

Water shortage has become a serious global problem[1]. Approximately 70% of the North China (about 12 600 thousands hm^2), being a major agricultural region, is irrigated, accounting for over 70% of the total water supply in North China[2]. Irrigation water (more than 40% of farmland) in the region is originated from groundwater[3]. A study showed that the average water table in North China has decreased by approximately 0.7 m/year in the last 20 years; in addition, water shortage is aggravated by the excess exploitation of groundwater[4,5]. The water shortage in North China threatens the sustainability of agricultural development in the region.

Fruit trees have become a major economic crop in semiarid and arid areas of North China. In 2006, the area of orchards has reached 19×10^5 hm^2, which accounts for 1/3 in the world and represents more than sixfold increase in the past 25 years; furthermore, orchard production has reached 261×10^5 t, which accounts for 37% of the world production (China Rural Statistical Yearbook, 2007). Irrigation is necessary for fruit tree growth. The main irrigation method at present is still the conventional surface irrigation, which generates low water productivity[6]. Therefore, it is important for fruit trees in the water-saving research. Some water-saving irrigation technologies, such as drip irrigation, sprinkling irrigation, and other surface micro irrigation, have been employed in orchard regions because of their capacity to reduce soil evaporation, increase plant transpiration, reduce fertilizer pollution, and retain nutrients in the root zone[7–9]. However, the application of these technologies has a high initial investment, ranging between 1500-2500 US$/$hm^2$[10]. Hence, the expansion of micro technologies is limited in the vast rural region of North China.

Meanwhile, water and soil losses in North China are severe due to heavy rain and floods. For instance, the Chinese Loess Plateau is known for its serious water and soil loss problem[11]. Water and soil losses cause dry and poor soil, thereby endangering ecological environment and reducing land productivity[12,13]. Biological and engineering measures have been comprehensively applied to control water and soil losses since 1999. However, measures of control water and soil losses cannot overcome drought problems effectively. Thus, a new irrigation method that can solve water and soil losses and drought simultaneously in North China is needed.

To solve these problems simultaneously, water storage pit (WSP) irrigation has been introduced[14]. WSP irrigation is a simple and inexpensive technology that is suitable for orchards in semiarid and arid regions of North China. Sun[14] pointed out that pooling local rainfall in storage pits reduces runoff, water and soil losses, and

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Biographies: Pan Chen, PhD, Lecturer, research interests: porous media flow and mass transport, Email: chenpan@tyut.edu.cn; **Xihuan Sun**, PhD, Professor, research interests: water-saving irrigation theory and technology, Email: sunxihuan@tyut.edu.cn; **Ping Liu**, PhD, Associate Professor, research interests: water resources and environment, Email: liuping@tyut.edu.cn.

***Corresponding author: Jingling Li**, PhD, Associate Professor, research interests: efficient utilization of agricultural water and soil resources. Taiyuan University of Technology, 79 West Yingze Street, Taiyuan 030024, Shanxi, China. Tel: +86-13803454563, Email: lijingling@tyut.edu.cn.

drought effectively. Several studies focused on WSP irrigation in the past 15 years[15-18]. Nitrogen (N) is an important nutrient element for plant growth. However, excessive application and unreasonable management of nitrogen fertilizers cause nitrate leaching. Groundwater pollution is becoming a serious problem in North China because of nitrate leaching[19,20]. Therefore, the development of a reasonable irrigation management strategy for water and fertilizers is important to minimize nitrate leaching under WSP irrigation.

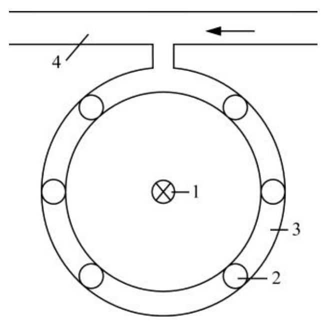
Fertigation is an economical, simple, and effective process of applying fertilizer through irrigation water[21]. In the past, fertigation was mainly used in micro-irrigation and sprinkler irrigation systems. Cote et al.[22] used the hydrus-2D model to simulate the nitrogen distribution of two fertigation strategies for drip irrigation. They concluded that solution application in highly permeable coarse-textured soils at the beginning of an irrigation cycle caused nitrogen accumulation above the soil profile and reduced nitrate leaching. By contrast, some researchers reported that solute application at the beginning of an irrigation event increased nitrate leaching. Gärdenäs et al.[23], Hanson et al.[24], and Zhang et al.[25] evaluated the effect of fertigation on nitrogen distribution for drip irrigation by the Hydrus 2D model. They found that fertigation events toward the end of the irrigation cycle reduced the potential for nitrate loss from the root zone. Bouwer et al.[26], Soroush et al.[27], and Šimůnek et al.[28] obtained the same conclusion for furrow irrigation through simulation. Li et al.[29,30] carried out indoor experiments to study the effects of fertigation on nitrogen distribution for drip irrigation. They reported that solute application at the middle half of the irrigation cycle was a good management strategy for drip irrigation. Li et al.[31] conducted field experiments using different fertigation strategies for tomato with drip irrigation. Their results showed that nitrogen solute application at the beginning of the irrigation cycle increased nitrate accumulation in the wetting front in comparison with other strategies. Considering nitrate leaching, apparent nitrogen recovery, and fertilizer use efficiency, they suggested solute application at the middle half of the irrigation cycle as the optimal fertilization strategy.

Therefore, it is clear that the fertigation strategies affect nitrogen distribution and potential nitrate leaching. To date, most studies have focused on soil water movement under WSP irrigation. However, the effect of different fertigation strategies on water and nitrogen distribution under WSP irrigation remains to be elucidated. Thus, the present study conducted indoor experiments and determined the effects of different fertigation strategies on the soil water content, nitrogen distribution in the soil profile, and ammonia volatilization under WSP irrigation. This study aimed to identify the optimum fertigation strategies for WSP irrigation, minimize potential nitrate leaching into groundwater, and provide a theoretical foundation for the field fertigation management of WSP irrigation.

2 Materials and methods

2.1 Brief introduction to WSP irrigation

WSP irrigation is a new irrigation technology that is suitable for orchards in North China. In this technology, several small cylindrical storage pits are dug along half radius of a tree canopy, and the water flows into the root zone soil through the storage pit wall. The field engineering of WSP irrigation is shown in Figure 1, includes water storage pits, circular furrow and pipeline (or field ridge).



1. Fruit tree 2. Water storage pits 3. Circular furrow 4. Pipeline

Figure 1 Field engineering of WSP irrigation

2.1.1 Pipeline (field ridge)

The pipeline is a field fixed channel that connects the irrigation main system to the circular furrow (No.3 in Figure 1). This channel is commonly set along a contour line and is located on the upper slope surface of tree rows. It helps intercept rainfall and drives water flow into the circular furrow by gravity.

2.1.2 Circular furrow

The circular furrow connects all water storage pits under a tree canopy. During irrigation, the water first flows into the circular furrow through the pipeline and then into all water storage pits. The circular furrow not only delivers water into the storage pits but also intercepts runoff. The circular furrow generally has a depth of 20 cm and a width of 25-30 cm.

2.1.3 Water storage pits

The storage pits, each with a diameter of 25-30 cm and a depth of 40-60 cm, are dug along half radius of a tree canopy. The bottom of each pit is impermeable, thereby reducing water deep percolation. The storage pits function in temporary water storage and water irrigation.

2.2 Soil samples

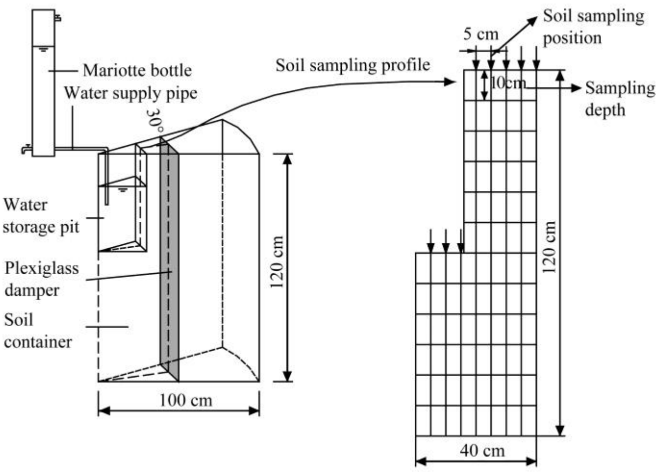
Silty loam was used in the experiments. Soil samples were collected from 20-120 cm depth of a field in Chai Village, Taiyuan, Shanxi Province, China (37°56′N, 112°28′E) and then passed through a 2 cm sieve. The soil samples featured with initial volumetric water content of 0.031 cm^3/cm^3, field capacity of 0.32 cm^3/cm^3, saturated volumetric water content of 0.47 cm^3/cm^3, initial ammonium nitrogen and nitrate nitrogen contents of 3.14 mg/kg and 4.27 mg/kg, respectively, and pH 7.42. The soil particles comprised 238 g/kg sand, 679 g/kg silt, and 83 g/kg clay on average.

2.3 Experimental design

Figure 2 shows the indoor equipment used in WSP irrigation, including a soil container, water storage pits, a mariotte bottle, a water supply pipe, and a plexiglass damper. The soil container is a 30° wedge-shaped plexiglass with a height of 120 cm and a radius of 100 cm. The main root system activity layer of fruit trees in arid and semiarid regions exists in the 20-120 cm soil layer[32,33]. The water storage pit is located into the angle of the soil container with a height of 60 cm and a radius of 16 cm. The bottom of the storage pit is impermeable. Lubricating grease fills the gaps between the side walls of the storage pit and the soil container, thereby avoiding preferential flow into the gap. The mariotte bottle is a plexiglass cylinder with an inner diameter of 9 cm and a height of 50 cm. The device maintains a constant water level during water infiltration. The water supply pipe is a plastic flexible hose connecting the mariotte bottle with the storage pit. The plexiglass damper simulates the zero flux plane when the wetting front is connected to each other between adjacent water storage pits[34]. The 30° wedge-shaped container was assumed to represent one-twelfth of the complete cylinder for WSP irrigation. This assumption was verified by Wang et al.[35], who investigated the influence of the angle of the wedge-shaped container on water and solute movement, and indicated no significant difference between 15° and 90° wedge containers.

According to the application order of the fresh water (W) and nitrogen solution (N) during an irrigation event, four fertigation strategies were used for WSP irrigation: (1) N-W (solution was applied during the first half of an irrigation cycle), (2) W-N (solution was applied during the last half of an irrigation cycle), (3) W-N-W (solution was applied during the middle half of an irrigation cycle), and (4) N-N (solution was applied during the entire irrigation). A conventional surface (SF) irrigation in which solution was applied during the entire irrigation (SN-N) was used as a control treatment. The total volume of applied water and solute was the same in all treatments.

During the experiment, a completely mixed air-dry soil was filled into the soil container with every 5 cm, which helped obtain a constant soil bulk density of 1.35 g/cm^3. The irrigation water volume and urea solute were 7 L and 4900 mg N, respectively. The water level in the storage pit was kept at 20 cm below the soil surface during constant water level infiltration, which can simulate the circular furrow in the field. Volatilized ammonia was collected using the venting method[36], and two layers of phosphoglycerol-soaked sponges (2 cm thickness) were placed at the top of the water storage pit and topsoil for absorbing vaporized ammonia. Sponge samples were collected daily in the first week and then every 2-3 d. Soil samples were collected at a 5 cm radial interval and 10 cm vertical interval 24 h after the irrigation completed (Figure 2).



Note: The soil profile by the long dotted line represents sampling profile. The sampling position in the profile were set at a 5 cm radial interval and 10 cm vertical interval.

Figure 2 Scheme of experimental equipment for WSP irrigation

2.4 Analytical methods

Soil pH was determined in a 1:5 soil/water suspension by using a pH meter[37] (PHS-3E, Leici, China). The saturated water content and field capacity were tested using the cutting ring method[38], respectively. The soil water content was measured in accordance with the oven-dried method for 6-8 h[37]. The ammonium content was extracted with a 2.0 mol/L KCl solution in a 1:10 soil/solution ratio, passed through a filter, and then measured by a UV spectrometer at 625 nm[37] (5100B, Yuanxi, China). The nitrate-nitrogen content was measured with a double wavelength UV spectrometer[39] (5100B, Yuanxi, China). The sponges were immersed in a 1.0 mol/L KCl solution and then shaken to analyze ammonium content. The distribution of soil particle size was analyzed in a 0.5 mol/L $Na_2C_2O_4$ solution by using the hydrometer method[37] and then soil texture was determined according to the USDA textural soil classification, in the classification system, the particles size for sand, silt and clay are >0.05-2.0 mm, 0.002-0.05 mm and <0.002 mm, respectively.

3 Results and discussion

3.1 Effects of fertigation strategies on soil water content

Figure 3 shows the contour plots of soil gravimetric water content in 24 h when the irrigation was completed for the four fertigation strategies under WSP irrigation and one control treatment (SN-N) under SF irrigation. For the WSP irrigation, the contour plots were similar for the four fertigation strategies (N-W, W-N, W-N-W, and N-N). The water content gradually decreased far away from the center of 60 cm soil depth and 16 cm radial distance, and the wetted region extended to 40 cm radially and 90 cm vertically. The maximum water content was found near the bottom of the water storage pit with 60 cm depth. The water content was mainly distributed in the middle-deep soil layer, and the water content in the topsoil was lower than that in the other layers. The change range of soil water content was 8.44%-23.05% for all fertigation strategies in the experiment. The effects of the four fertigation strategies on soil gravimetric water content were limited because the water movement in the unsaturated soil was mainly driven by the soil-water potential gradient, which is mainly composed of matric and gravitational potentials. The effect of solute potential, which is caused by solution concentration on water movement, was weak in all fertigation strategies. These findings are consistent with the results reported by Gardenas et al.[23] and Zhang et al.[25]. Compared with that under WSP irrigation, the contour value of water content gradually decreased with soil depth for the SN-N treatment under SF irrigation. In addition, the vertical water movement was limited to about 50 cm depth under SF irrigation, and this value was smaller in vertical depth than that under WSP irrigation for the same water volume application. This result can be attributed to the deeper infiltration interface in the vertical direction under WSP irrigation than under SF irrigation. Furthermore, the soil water content was mainly distributed in the topsoil layer, and the water content range in wetted volume was 12.25%-25.47%.

The ratios of soil water content to total water applied at different depths for the five treatments are shown in Table 1. The ratio of soil water at 60-70 cm depth was relatively higher than that of other depths for all fertigation strategies under WSP irrigation and accounted for about 16.8% of the total water volume. The average water content in the 0-10 cm topsoil was low, i.e., only 10.51% of that under SN-N, and accounted only for 2.24% of the total. The soil evaporation depends on factors such as surface water content, crop type, soil characteristics and meteorological conditions, the relative soil evaporation declines with the decreasing of soil water content at the soil surface when other conditions are the same[40,41]. The results indicate that the distribution benefits the deep root system and reduces the surface soil evaporation under WSP irrigation. Moreover, the average soil water contents for all treatments were not significant (p>0.05).

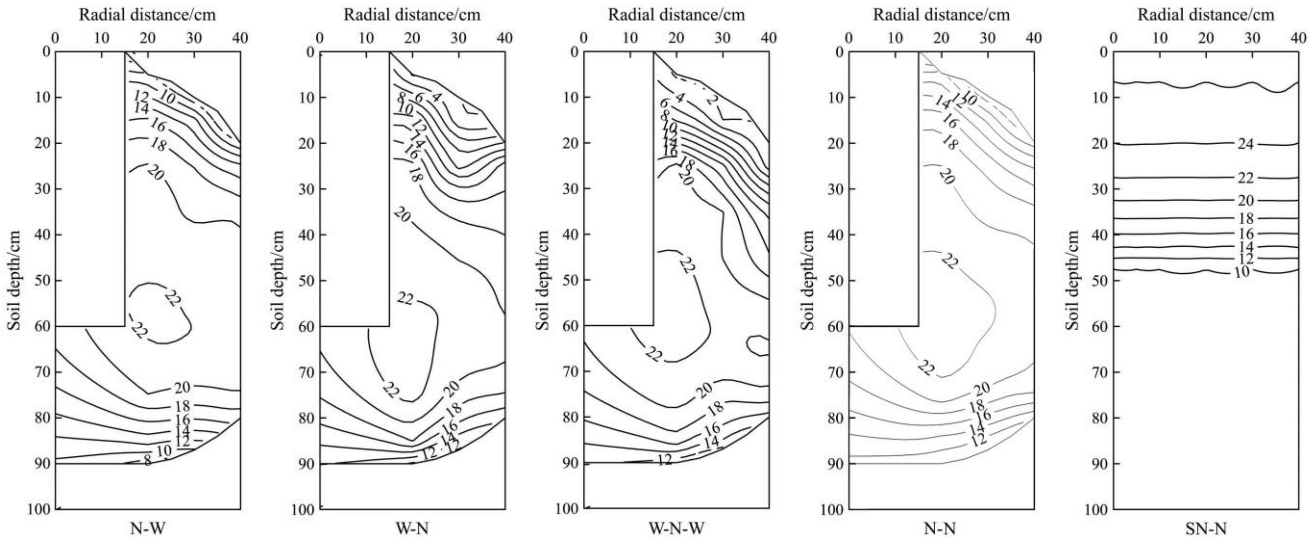


Figure 3 Contour plots of soil gravimetric water content (%) in 24 h after irrigation

Table 1 Summary of the ratios of soil water content to total water applied at different depths

Treatments	Soil depth/cm								
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
W-N	0.02	0.055	0.091	0.129	0.139	0.144	0.166	0.155	0.101
N-W	0.021	0.058	0.104	0.125	0.136	0.141	0.167	0.151	0.097
W-N-W	0.024	0.052	0.096	0.128	0.133	0.143	0.170	0.152	0.102
N-N	0.023	0.06	0.110	0.126	0.135	0.142	0.168	0.152	0.084
SN-N	0.304	0.287	0.229	0.125	0.055	0.000	0.000	0.000	0.000

3.2 Effects of fertigation strategies on NH_3 volatilization

The curve diagram in Figure 4 shows the NH_3 volatilization rate for the four fertigation strategies and one control treatment. Under WSP irrigation, two interfaces (pit wall and topsoil) were observed for NH_3 volatilization. As shown in Figure 4, the NH_3 volatilization rates for all treatments gradually increased and then decreased with time after fertigation. The NH_3 volatilization rates peaked near the seventh day and followed the trend SN-N > N-N (pit wall) > W-N (pit wall) > W-N-W (pit wall) > N-W (pit wall) > all strategies (topsoil). About 15 d after fertilization, the NH_3 volatilization rates were smaller. That is, the NH_3 volatilization rates under SF irrigation increased compared with those under WSP irrigation possibly because of the higher ammonium concentration in the topsoil under the former irrigation than the latter. Previous studies[42,43] showed that topsoil ammonium was the source of NH_3 volatilization; therefore, the concentration of topsoil ammonium directly affected the NH_3 volatilization rate. For example, Peng et al.[44], Wang et al.[45], and Rochette et al.[46] reported that the NH_3 volatilization rate was closely related to soil ammonium concentration. Furthermore, NH_3 volatilization occurred through the pit wall under WSP irrigation regardless of the fertigation strategy. The NH_3 volatilization from the pit wall significantly differed among the four strategies but did not significantly change in the topsoil. The NH_3 volatilization rate from the pit wall was lower after the N-W strategy compared with the other strategies because of the lower ammonium concentration near the pit wall.

Figure 5 shows the effect of different fertigation treatments on cumulative NH_3 volatilization. Cumulative NH_3 volatilization gradually increased with time for all fertigation treatments. The trend of cumulative NH_3 volatilization loss under the five treatments was SN-N > N-N > W-N > W-N-W > N-W, which accounted for 0.49%, 0.23%, 0.19%, 0.17%, and 0.15% of the total nitrogen applied throughout the experiment, respectively. Clearly, the NH_3 volatilization loss from urea accounted for approximately 0.1%-35% of the N applied in indoor and field crop planting

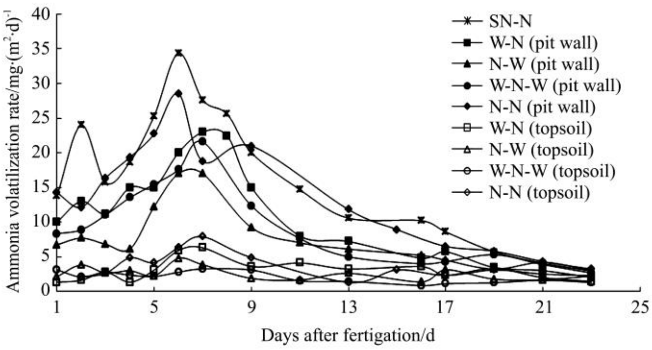


Figure 4 Curve diagram of NH_3 volatilization rate for different fertigation treatments

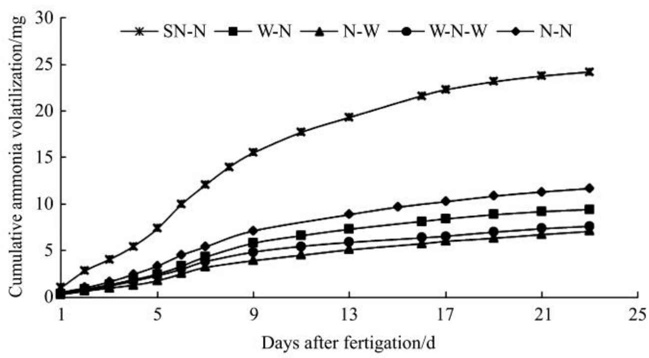


Figure 5 Curve diagram of cumulative NH_3 volatilization for different fertigation treatments

experiments[47]. Compared with that under conventional SF irrigation, fertilizer application under WSP irrigation reduced NH_3 volatilization by 51.71%-68.72% because of the deeper scope of the latter than the former[45]. Among the four fertigation strategies, N-W generated the smallest NH_3 volatilization loss.

3.3 Effects of fertigation strategies on soil ammonium nitrogen

The contour plots in Figure 6 show the distribution of ammonium nitrogen content under the different treatments. As shown in Figure 6, the peaks of ammonium nitrogen were only slightly affected for all strategies under WSP irrigation. The peaks of ammonium content occurred in the immediate vicinity of the pit wall, and no accumulation was observed near the edge of the wetting zone due to soil adsorption. However, a slight ammonium movement was observed when the solution was applied during the first half and in the middle of an irrigation cycle. This result may be ascribed to the fresh water which was applied after fertigation[48]. However, the effect on the peaks of ammonium nitrogen was not significant for all fertigation strategies (p>0.05). Hanson et al.[24] used Hydrus 2D to simulate the distribution of soil nitrogen using a urea-ammonium-nitrate fertilizer under drip irrigation, concluded that ammonium was distributed around the drip line because of absorption for all fertigation scenarios, although urea moved readily with the irrigation water. Our findings are inconsistent with those of Li et al.[30] and Hanson et al.[24]. For the SN-N control treatment, the ammonium content was mainly distributed on the soil surface.

Table 2 shows the ratios of ammonium content to the total ammonium content under the different treatments. For WSP irrigation, the ammonium ratio at 0-10 cm depth was lower than that of other depths. The average ammonium concentration under the four strategies was 5.62 mg/kg, which was only 18.42% of SN-N at 0-10 cm depth. As expected, the NH_3 volatilization rate from topsoil was larger under SF irrigation than under WSP irrigation. The average ammonium concentration of the infiltration interface of the pit wall at 20-60 cm depth followed the order N-N > W-N > W-N-N > N-W. The same trend was observed for the NH_3 volatilization rate from the pit wall in the four fertigation strategies.

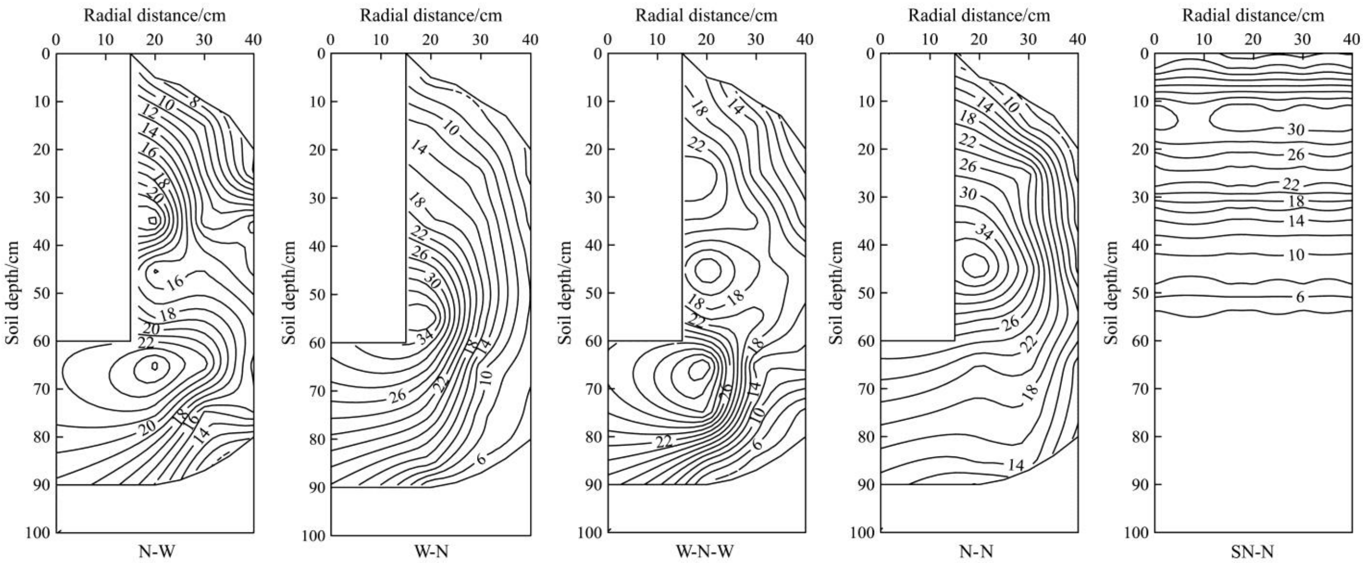


Figure 6 Contour plots of ammonium nitrogen (mg kg^{-1}) for different treatments

Table 2 Summary of the ratios of soil ammonium content to total ammonium nitrogen in wetted volume at different depths

Treatments	Soil depth/cm								
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
N-N	0.032	0.063	0.113	0.136	0.216	0.143	0.131	0.123	0.044
W-N	0.027	0.062	0.092	0.114	0.153	0.224	0.167	0.127	0.034
N-W	0.033	0.067	0.101	0.123	0.104	0.123	0.244	0.145	0.059
W-N-W	0.036	0.086	0.111	0.127	0.120	0.150	0.212	0.118	0.040
SIN-N	0.239	0.311	0.215	0.142	0.093	0.000	0.000	0.000	0.000

3.4 Effects of fertigation strategies on soil nitrate nitrogen

The contour plots in Figure 7 show the distribution of nitrate-nitrogen content under the different treatments. All fertigation strategies generally caused nitrate accumulation along the periphery of the wetted soil volume, with little or no nitrate nitrogen in the vicinity of the pit wall. As shown in Figure 7, the range of low nitrate concentration in the vicinity of the pit wall was larger under the N-W strategy than under the other strategies. The more fresh water applied at the end of an irrigation, the more nitrate accumulated at the 40 cm radial distance because nitrate was easily to move and leach. For example, the nitrate content at 40 cm radial distance in the N-W treatment was 241.86 mg, which was 12.54%, 28.23%, and 26.30% higher compared with those in the N-N, W-N, and W-N-W treatments, respectively. Meanwhile, the accumulation in the vertical wetting front was larger in the N-W treatment than in the other treatments. These findings are supported by the results of Soroush et al.[27] and Zhang et al.[25] Thus, we can infer that the probability of nitrate leaching is high when fresh water is applied at the last half of an irrigation event. For the SN-N treatment, we found the same accumulation in the wetting front.

Table 3 shows the ratios of nitrate content to the total nitrate contents in the different treatments. The ratio was smaller at 30-70 cm depth than at the other depth regardless of the fertigation strategies. The highest ratio of nitrate content occurred in the 80-90 cm wetting front, and it followed the order N-W > N-N > W-N-W > W-N. For example, the total nitrate content at 80-90 cm depth increased by 25.41%-31.05% in the N-W strategy compared with the other strategies. These results indicate that solution application during the first half of an irrigation event increases the probability of nitrate leaching. Cote et al.[22] employed Hydrus 2D to simulate nitrate movement and reported that nitrate leaching was reduced after the solute application because capillarity was the main driving force controlling solute movement with dry soil. This force causes the upward movement of nitrate solute from the drip emitter and reducing nitrate leaching. In the present experiment, the soil used was very dry, with an initial volumetric water content of 0.031 cm^3/cm^3. However, in the N-W strategy, the accumulation was higher in the deeper wetting front. These differences may be ascribed to the different textures of the soil samples used. Whereas compared to N-W, N-N and W-N-W treatments, W-N treatment decreased the nitrate accumulation at 80-90 cm by 38.6%, 19.0% and 10.3%, respectively. Thus the groundwater was less likely to be contaminated by nitrate nitrogen with nitrogen fertilizer solution application at the end of irrigation.

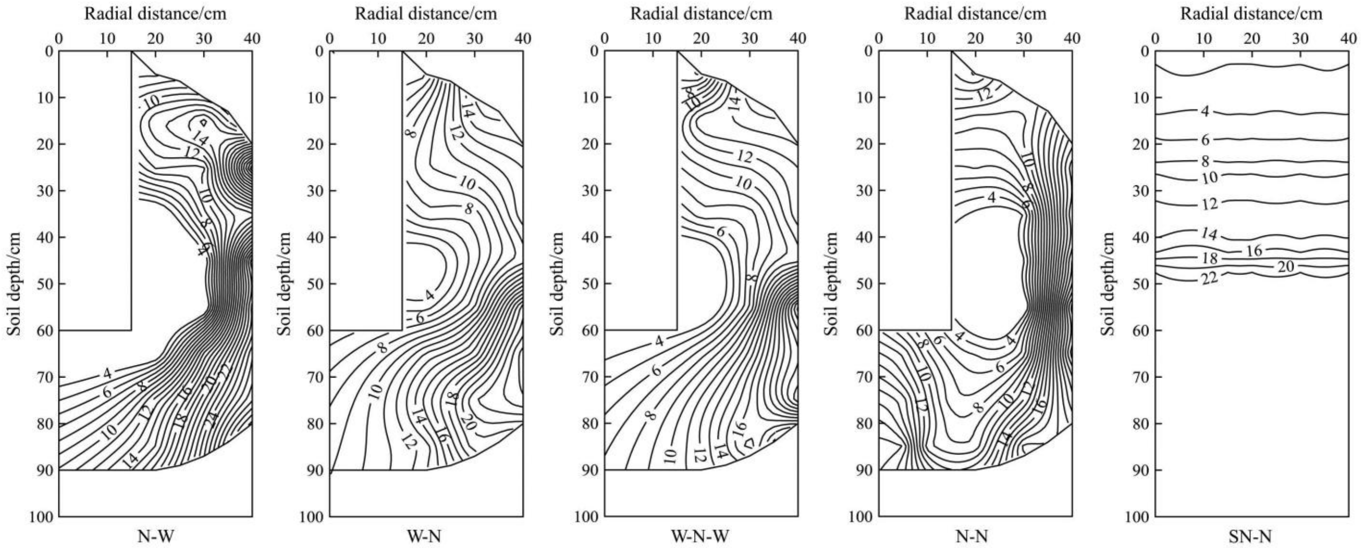


Figure 7 Contour plots of nitrate nitrogen (mg kg^{-1}) for different treatments

Table 3 Summary of the ratios of soil nitrate content to total nitrate content in wetted volume at different depths

Treatments	Soil depth/cm								
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90
W-N	0.101	0.131	0.117	0.073	0.032	0.056	0.089	0.185	0.214
N-W	0.083	0.136	0.121	0.063	0.013	0.051	0.030	0.155	0.349
W-N-W	0.098	0.160	0.123	0.078	0.026	0.043	0.053	0.179	0.239
N-N	0.110	0.147	0.136	0.075	0.018	0.046	0.044	0.159	0.264
SN-N	0.000	0.035	0.235	0.338	0.393	0.000	0.000	0.000	0.000

4 Conclusions

The contents of water and ammonium at 0-10 cm depth under WSP irrigation were low, i.e., only 10.51% and 18.42% respectively of surface (SF) irrigation, whereas those in the middle-deep soil layer were relatively higher. The average cumulative NH_3 volatilization under WSP irrigation was only 28.83% of SF irrigation, and WSP irrigation showed 51.71%-68.72% reduction of NH_3 emission in the present study.

The soil water distributions were similar in the four strategies, and the effect of the fertigation strategies on soil water content was not significant. NH_3 volatilization mainly occurred through the pit wall interface, and the cumulative NH_3 volatilization loss followed the trend N-N > W-N > W-N-W > N-W, which accounted for 0.23%, 0.187%, 0.17%, and 0.154% of the total nitrogen applied. Ammonium was adsorbed into the soil and thus mostly remained near the pit wall. Low concentrations of ammonium were found near the edge of the wetting zone under all strategies. Nitrate accumulated in the wetted front, and higher nitrate accumulation occurred at 80-90 cm depth than the other depths. The accumulation of nitrate at deeper wetting front followed the order N-W > N-N > W-N-W > W-N. Applying the solution at the last half (W-N) of a WSP irrigation event reduced the probability of nitrate leaching.

Acknowledgements

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