Effects of Alternate Moistube Irrigation on the Growth of Spinach (*Spinacia oleracea*) and Water Spinach (*Ipomoea aquatica*) under Controlled Conditions

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Abstract Moistube irrigation is a newly-developed irrigation technique that utilizes a semipermeable membrane to release water slowly and continuously into the plant root zone. Alternate Moistube Irrigation (AMI) is a combination of alternative irrigation and moistube irrigation. In order to investigate the effects of AMI on plant growth, greenhouse experiments were conducted on spinach (*Spinacia oleracea*) and water spinach (*Ipomoea aquatica*) plants at different time. We measured soil water content at a depth of 20 cm in the planting boxes, and also determined seed emergence rate, plant height, largest leaf area, fresh weight per plant, yield, and irrigation water productivity (IWP) for both spinach and water spinach. The results showed that the AMI treatments had significantly higher soil water content than the conventional surface irrigation control (CK). The emergence rates of spinach and water spinach were significantly higher in the AMI treatments than in the CK, and the plant height, largest leaf area, and fresh weight during the middle and late stages of spinach and water spinach growth were also significantly higher than those of the CK. Both spinach and water spinach grew well and produced high yield with high IWP under AMI with a high water head pressure of 1.5 m at tube spacing of 20 or 30 cm. We found that AMI with a suitable combination of head pressure and tube spacing can promote plant growth and increase yield and IWP under controlled conditions.

Key words Alternate Moistube Irrigation; Spinach; Water spinach; Soil moisture; Yield; Irrigation water productivity

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Shortage of freshwater resources has become a bottleneck that restricts agricultural development and global food security[1–3]. In order to alleviate the contradiction between limited arable land with a shortage of fresh water resources on the one hand, and the rise in world food demand on the other, many countries are actively developing water-saving irrigation methods[4–6]. At present, the effective irrigation area of farmland in China is 52%, of which the micro-irrigated area accounts for 12%. Micro-irrigation, represented by drip irrigation, is one of the best water-saving techniques for farmland irrigation[7–9]. The general drip irrigation system, in addition to water and energy consumption, needs to be equipped with electrical machinery, high-pressure pumps, control boxes, and other equipment in the irrigation system. Its popularity and application are limited in areas that are far away from water sources, that lack electricity, and that have complex topography. In this context, a new type of water-saving irrigation technology, known as Moistube Irrigation (MI), also called semi-permeable membrane irrigation, has been introduced in recent years to arid areas in China and abroad[10–11].

MI is a new irrigation technology that is similar to drip irrigation. However, instead of emitters, water is delivered from a semi-permeable membrane in the moistube tape depending on the applied pressure and the soil water potential of the surrounding soil. A moistube is a double-layer hose water supply device with a semi-permeable polymer membrane as its core material. The film thickness is the same as that of ordinary plastic film, with about 100 000 holes per square centimeter and a wall diameter of 10 – 900 nanometers. Nano-scale micro pores allow water molecules to pass through, while larger molecules and solids cannot. Membrane tubes function as semi-permeable membranes and have unidirectional permeability and osmotic pressure characteristics[12–16]. The outer membrane tube is a type of permeable high strength industrial non-woven sheath, which has the function of pressure resistance and protection. When the pipe is buried in the ground and filled with water, the water automatically moves out of the pipe, driven by the potential difference between the water inside and outside the film to achieve irrigation. MI takes advantage of the special properties of semi-permeable membranes to provide timely and sufficient water for crop root areas in a continuous flow manner, and the soil is constantly wet[5, 17]. The rate at which water is released through the nanopore membrane depends on the pressure applied to the system, and allows for easy adjustment of water release by simply changing the pressure[18]. The moistube discharge increases with increasing pressure, and the pressure discharge relationship follows a power function[11]. Because of the continuous irrigation with underground micro-slow-release, the deep seepage and surface evaporation are effectively controlled, resulting in clear water savings. In addition, the system only needs soil water with a low water pressure head and negative voltage potential to operate, thus saving energy. MI is gradually being promoted and adopted in China. For greenhouse-grown tomatoes, Xue *et al.*[19] found that MI had 13% higher water use efficiency than drip irrigation, while Lyu *et al.*[20] found that MI gave water savings of 38% compared

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to drip irrigation with mulch. The higher water use efficiency and water savings of MI compared to conventional drip irrigation can be explained by the fact that the former supply water is at 80% – 90% of field capacity, which is a form of deficit irrigation and thus improves crop water productivity and water use efficiency[21].

At present, research on MI mainly focuses on conventional continuous irrigation. However, some studies have shown that compared with conventional MI, MI with an alternate watering interval of 2 d has a significant compensatory effect on tomato root absorbency, enhancing their ability to absorb soil moisture, and reducing water consumption and improving water use efficiency without significantly reducing fruit yield[22]. Attempts at alternate row irrigation or alternate furrow irrigation for some crops can be traced back to the 1970s, and since the 1990s, studies on the principle of plant root signaling under water stress have provided a theoretical basis for alternate irrigation[23-26]. At present, alternate furrow irrigation[27-30] and alternate drip irrigation[31-34] have been used on many crops. For example, the control of alternate root zone irrigation technology can reduce plant transpiration and soil water evaporation by alternately washing roots at some or all stages of crop growth while other root zones are under artificial water stress, thus saving water and improving water use efficiency. However, there are few studies examining the combination of MI and alternate irrigation.

In this study, the effects of Alternate Moistube Irrigation (AMI) on the growth of spinach (*Spinacia oleracea* L.) and water spinach (*Ipomoea aquatica* Forssk.) were determined in controlled greenhouse experiments. We used two head pressures (1.0 and 1.5 m) and two tube spacing (20 and 30 cm) to identify suitable alternate irrigation parameters. This work will enable an understanding of the application, design, and operational requirements of AMI systems.

Materials and Methods

Experimental details

The experiments were carried out in the plastic greenhouse of the College of Water Conservancy and Engineering, Taiyuan University of Technology, China (37°86′ N, 112°53′ E). The test site was located in a typical semi-arid region with a continental monsoon climate, annual average precipitation of 456.7 mm, and an annual average temperature of 9.56 ℃.

The equipment used in the experiment was an elevated water tank, a moistube pipe, a water delivery pipe, and a planting box (Fig. 1). The water tank with a floating ball valve was used to maintain a constant pressure head, and different pressure heads were produced by placing the water tank on adjustable height brackets. The moistube pipe was produced by Shenzhen Moistube Irrigation Co., Ltd. The inner diameter of the moistube pipe was 16 mm, and the wall thickness was 1 mm. The water delivery pipe was a black polyethylene (PE) pipe with an inner diameter of 16 mm. The planting box was 90 cm × 50 cm × 40 cm (length, width, and height), and was wooden with drainage holes at the bottom. Two moistube pipes were laid horizontally in a planting box, with a tube spacing of 20 or 30 cm, and were buried to a depth of 15 cm. The moistube pipes were connected to the elevated water tank by the water delivery pipe, and valves were installed to control the water supply for AMI. The water used was filtered urban tap water.

Spinach seeds were sown in the planting box on April 18, 2024, and the plants were harvested on May 24, 2024. Three rows of spinach with a row spacing of 15 cm were planted in each planting box, and the number of spinach seeds was equal in each row. There were 10 boxes of spinach grown in each treatment. Of them, three boxes of spinach were used to measure the yield at harvest, and no samples were taken during growth. The soil in the planting box was an organic nutrient soil produced by Hong Si Fang Gardening Co., Ltd. Soil bulk density was 0.75 g/cm^3, and the initial soil water content was 23.2%. The organic matter content of the soil was 25.6%, and the soil pH was 6.0.

Water spinach seeds were sown in the planting box on June 2, 2024, and the plants were harvested on July 8, 2024 using planting methods. Other conditions were the same as those for spinach.

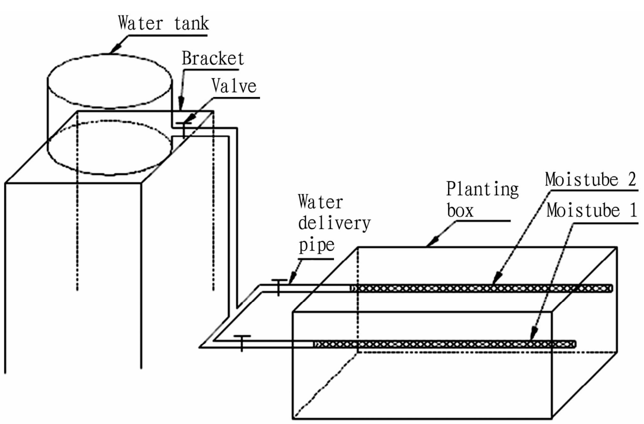


Fig. 1 Experimental equipment and planting system design

Treatments and measurements

Treatments in the experiment consisted of the factorial combinations of (i) two head pressures of 1 m (H1) and 1.5 m (H2), and (ii) two tube spacing of 20 cm (S1) and 30 cm (S2). Conventional surface irrigation was used as the control (CK). Before sowing, both moistube pipes were placed in a planting box supplied with sufficient water to ensure soil moisture for seed germination in the H1S1, H1S2, H2S1, and H2S2 treatments, and an equal volume of water was supplied to the planting box for the CK by conventional surface irrigation. After sowing, one of the moistube pipes was used to supply water for 4 d. It was then stopped, and the other moistube pipe was used to supply water for the following 4 d. Both pipes were used to alternate the water supply, changing every 4 d, and the irrigation volume was recorded and calculated. The planting box for the CK was irrigated at 08:00 every day with an irrigation volume equal to the average outflow of one moistube pipe under the H1 and H2 head pressures. Soil water content at a 20-cm depth in the planting boxes was determined by a drying method during the growth of spinach or water spinach in which the soil water content was measured at three points randomly selected from each row, and the average values were obtained from all nine points in the three rows. The emergence rates for spinach and water spinach were calculated at 8 d after sowing (DAS). Plant height, largest leaf area, and fresh weight per plant for spinach and water spinach were determined during growth, and yield (fresh weight) was measured at harvest. The largest leaf area was determined by the paper cut-out weighing method. In specific, the largest leaf blade was traced onto a piece of A4 paper and cut out. The paper leaf was then weighed and compared to the weight of the whole sheet of paper, and the ratio was used to calculate the leaf area. We also calculated irrigation water productivity (IWP), which is defined as the yield produced per unit of irrigation water used.

Data analysis

Analysis of variance was performed to determine the effects of AMI on soil water content, emergence rate, plant height, largest leaf area, yield, and IWP of spinach and water spinach using Tukey's Honest Significant Difference (HSD) test. The notations a and b are used in Fig. 3 and Fig. 4 to indicate a significant difference at $P < 0.05$. Statistical analysis was performed using IBM SPSS Statistics version 20.0 (IBM Corporation, Somers, New York).

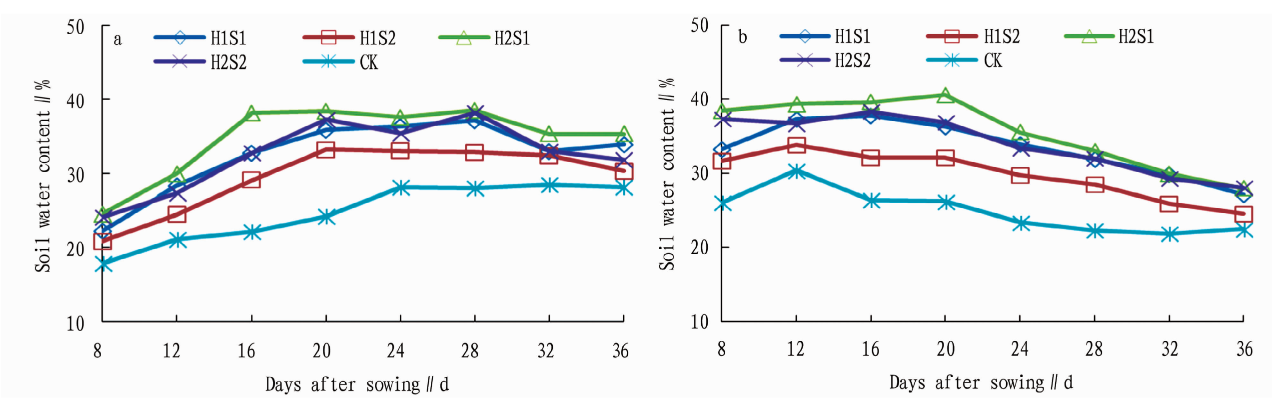
Results and Discussion

Soil water content

The change in soil water content at a depth of 20 cm in the planting boxes during the growth of spinach and water spinach plants is shown in Fig. 2. As spinach growth progressed, soil water content for all the treatments increased slightly, although the changes were minimal. At 12 – 32 DAS, soil water contents were significantly higher for the AMI treatments than for the CK ($P < 0.05$). Soil water contents were also higher for the H1S1, H2S1, and H2S2 treatments compared to H1S2, and there was no significant difference in soil water contents among the H1S1, H2S1, and H2S2 treatments.

During the growth of water spinach plants, soil water contents for all treatments decreased slightly with minimal change. At 8 – 32 DAS, soil water contents were significantly higher for the AMI treatments compared to the CK, soil water contents were higher for the H1S1, H2S1, and H2S2 treatments than for H1S2, and there were no significant differences in soil water content among the H1S1, H2S1, and H2S2 treatments.

Wang et al.[35 – 36] reported that the 20-cm-depth soil water content in planting boxes during the growth of pepper or large leaf chrysanthemum plants under AMI was higher than it was for conventional surface irrigation. The same result was observed in this experiment. Li et al.[37] examined the effects of head pressure on the growth of tomatoes in a greenhouse were using MI, and the results showed that head pressure significantly affected soil moisture content and the size of the wetting zone. They also showed that soil moisture content under MI was higher than that under drip irrigation, and that MI formed a continuous and stable water environment in which the crop could grow. In our experiment, when the tube spacing was 30-cm (S2) under AMI, the soil water content was higher at the H2 head pressure (1.5 m) than at the H1 head pressure (1 m), which showed that with the increased tube spacing, the higher head pressure could ensure a higher soil water content.



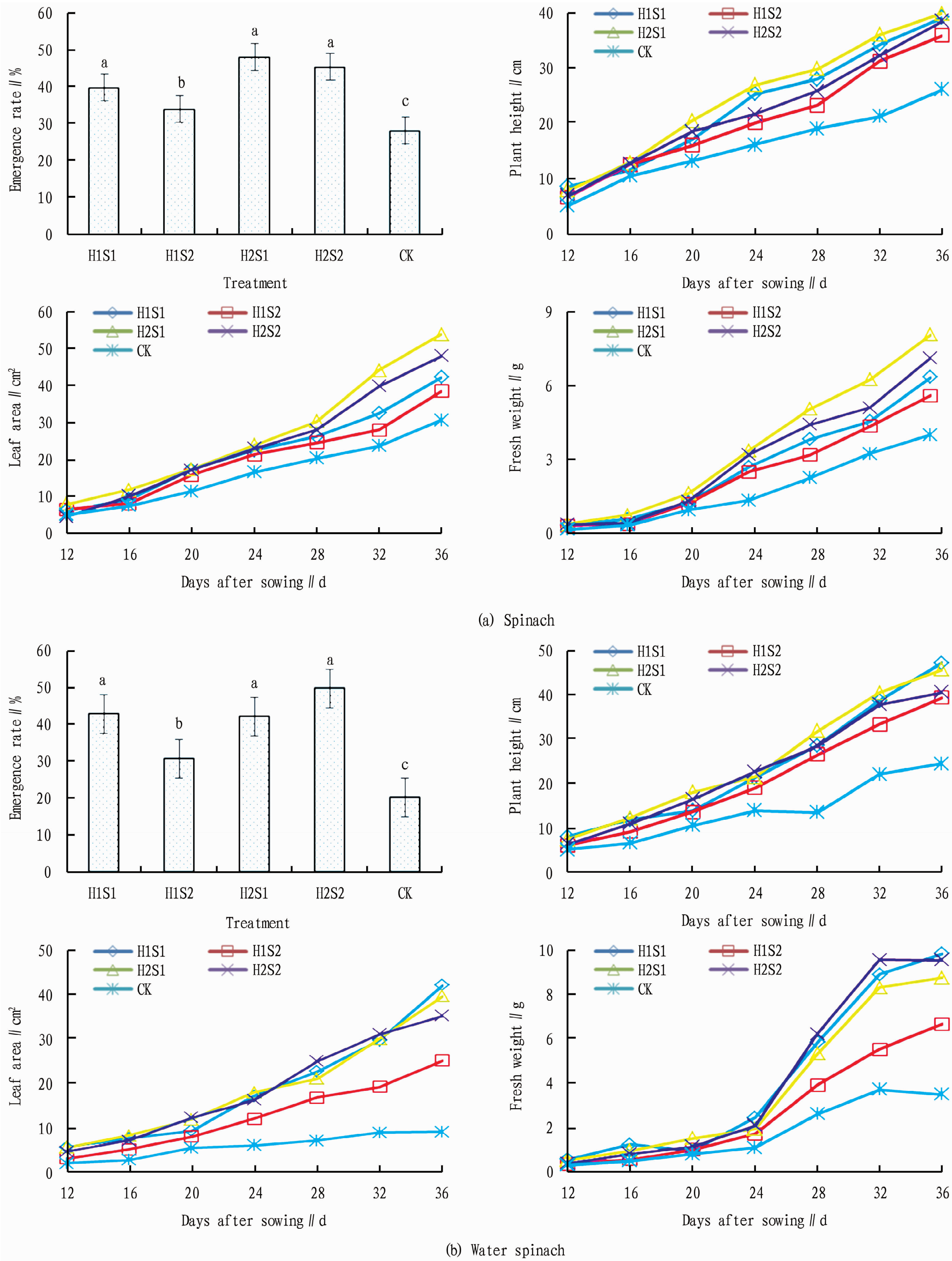
a. Spinach; b. Water spinach.

Fig. 2 Soil water content for spinach and water spinach grown in the greenhouse in planting boxes with AMI

Emergence rate, plant height, leaf area and fresh weight

As shown in Fig. 3(a), the emergence rates of spinach seeds at 8 DAS were ranked in the order H2S1 > H2S2 > H1S1 > H1S2 > CK. Emergence rates for the H2S1, H2S2, and H1S1 treatments were significantly higher than those for H1S2 and the CK, and the rate for H1S2 was significantly higher than it was for the CK. At 12 – 36 DAS, the plant height, largest leaf area, and fresh weight per plant for spinach increased gradually during the growth process. The plant heights and largest leaf areas were significantly greater for the AMI treatments than for the CK at 20 – 36 DAS. Fresh weight per plant increased slowly from 12 – 20 DAS with no significant differences among all the treatments, but it increased quickly from 20 – 36 DAS, when fresh weights were significantly higher in the AMI treatments than in the CK.

As shown in Fig. 3(b), the emergence rates of water spinach seeds at 8 DAS were ranked in the order H2S2 > H1S1 > H2S1 > H1S2 > CK. Emergence rates were significantly higher in the H2S2, H1S1, and H2S1 treatments than in the H1S2 treatment



The lowercase letters a and b indicate significant differences ($P<0.05$) based on Tukey's Honest Significant Difference (HSD) test.

Fig. 3 Seed emergence rate, plant height, leaf area, and fresh weight for spinach and water spinach grown using Alternate Moistube Irrigation (AMI)

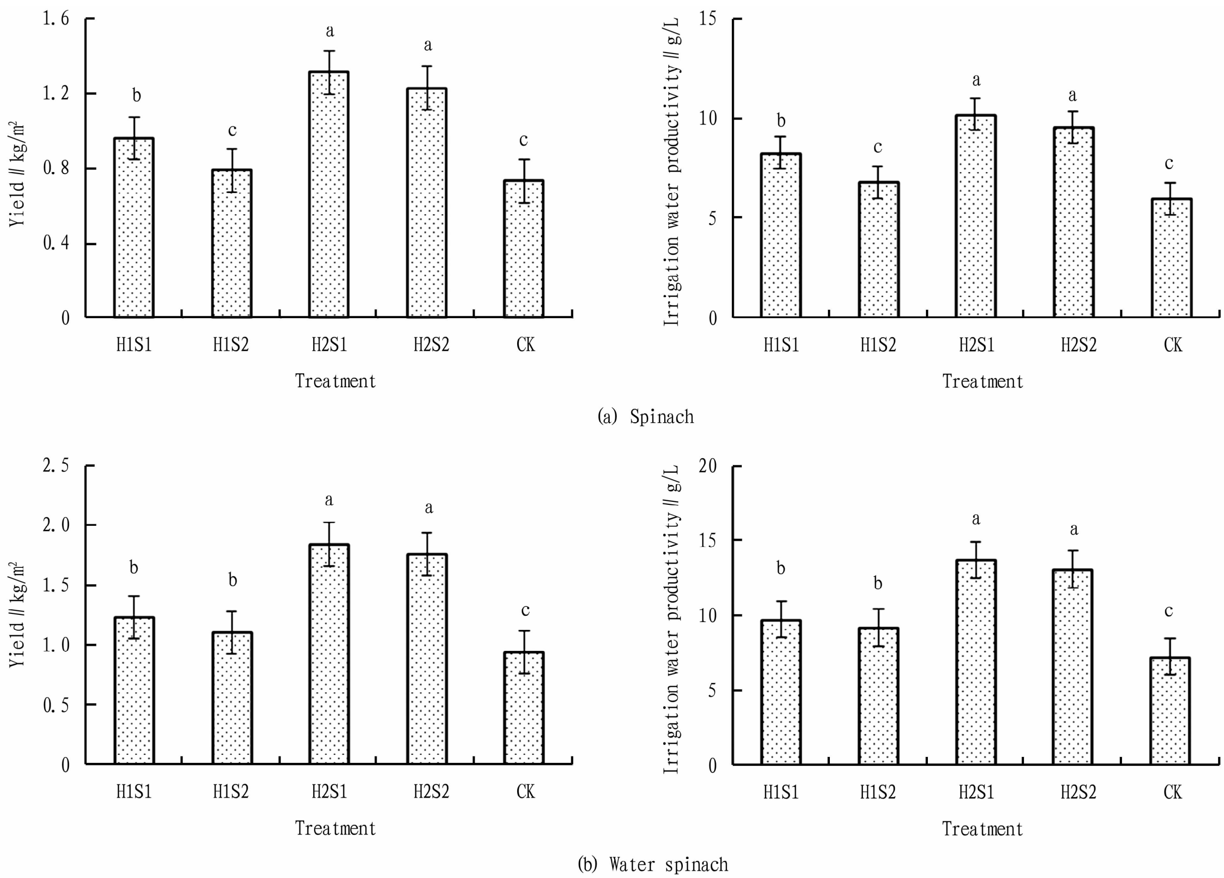
and the CK, and emergence was significantly higher in H1S2 than in the CK. At 12 – 36 DAS, the plant height, largest leaf area, and fresh weight per plant for water spinach increased gradually as the growth process progressed. Plants were taller in the AMI treatments than in the CK at 12 – 20 DAS, and were significantly taller in the AMI treatments than for plants in the CK at 24 – 36 DAS. The largest leaf areas were greater in the H1S1, H2S1, and H2S2 treatments than in H1S2 and the CK, and the largest leaf area was greater in the H1S2 treatment than in the CK. At 24 – 36 DAS, the largest leaf areas in the H1S1, H2S1, and H2S2 treatments were significantly different compared to H1S2 and the CK, and also in H1S2 compared with the CK. There were no significant differences in the largest leaf area among the H1S1, H2S1, and H2S2 treatments. Fresh weight per plant increased slowly from 12 – 24 DAS with no significant differences among all the treatments, but it increased rapidly from 24 – 36 DAS, and was significantly higher in the H1S1, H2S1, and H2S2 treatments compared to H1S2 and the CK, and fresh weight per plant was also significantly higher in the H1S2 treatment than in the CK.

Wang *et al.* [38] reported that large leaf chrysanthemum grown using AMI showed a growth advantage compared to conventional surface irrigation, and the plant height, stem diameter, and fresh weight per plant grown under AMI were higher than those grown using conventional surface irrigation. In our experiment, the emergence rate, plant height, largest leaf area and fresh weight per plant for spinach and water spinach grown under AMI were higher than for plants grown using conventional surface irrigation.

Yield and irrigation water productivity

As shown in Fig. 4(a), spinach yield and IWP (irrigation water productivity) were ranked in the order of H2S1 > H2S2 > H1S1 > H1S2 > CK, and both were significantly higher in the H2S1 and H2S2 treatments than in H1S1, H1S2, and the CK, and they were significantly higher in the H1S1 treatment than in H1S2 and the CK. There were no significant differences in either yield or IWP for water spinach between the H2S1 and H2S2 treatments, or between H1S2 and the CK.

As shown in Fig. 4(b), the yield and IWP for water spinach were ranked in the order of H2S1 > H2S2 > H1S1 > H1S2 > CK. They were both significantly higher in the AMI treatments than in the CK, and were significantly higher in the H2S1 and H2S2 treatments than in H1S1 and H1S2. There were no significant differences in the yield or IWP for water spinach between the H2S1 and H2S2 treatments, or between H1S1 and H1S2.



The lowercase letters a and b indicate significant differences ($P < 0.05$) based on Tukey's Honest Significant Difference (HSD) test.

Fig. 4 Yield and IWP for spinach and water spinach grown in a greenhouse with Alternate Moistube Irrigation (AMI)

Previous experiments have shown that for pepper, yield and IWP were higher for plants grown under AMI than for those grown using conventional surface irrigation, and this was also the situation for large leaf chrysanthemum. In pepper, the yield and IWP were higher with a head pressure of 1.0 m compared to a head pressure of 1.5 m, while for large leaf chrysanthemum, the yield and IWP were higher for plants grown using a head pressure of 1.5 m compared to those grown with a head pressure of 1.0 m. The reason for this is that pepper consumes more water than large leaf chrysanthemum, and the high soil water content under the higher head pressure could meet the needs of pepper. In our experiment, both spinach and water spinach preferred the higher head pressure due to high soil water content no matter whether the tube spacing was 10 or 20 cm under AMI.

Conclusions

In this study, the effects of head pressure and tube spacing on the growth of spinach and water spinach plants grown using AMI were studied in greenhouse experiments. The results showed that the AMI treatments had significantly higher soil water contents at a depth of 20 cm in the planting boxes compared to the CK. The emergence rates of spinach and water spinach seeds were significantly higher in the AMI treatments than they were in the CK. In the middle and later stages of spinach and water spinach growth, the plant heights, largest leaf areas, and fresh weights in the AMI treatments were significantly greater than in the CK. The yield and IWP of spinach and water spinach were significantly higher in the H2S1 and H2S2 treatments than in the H1S1 and H1S2 treatments and the CK. Both spinach and water spinach grew well and produced high yield with high IWP under AMI at the higher H2 head pressure regardless of whether the tube spacing was S1 or S2.

AMI is a new water-saving irrigation method, and with a suitable combination of head pressure and tube spacing, it can promote plant growth and increase yield and IWP. Further investigation of the effects of AMI on plant growth and yield needs to be conducted under field conditions.

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