Effects of the buried straw layer on soil water and nitrogen distribution under different irrigation limits

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Abstract: At present, water and fertilizer use efficiency is low in many cultivation areas in southern China. Studies show that the buried straw layer can effectively conserve water and fertilizer. To investigate the optimal irrigation upper limit above the straw barrier and its effect on soil moisture and nitrogen distribution, an indoor soil column experiment was conducted. Six treatments were designed consisting of two levels of straw layer i.e., (with and without buried straw layer at 25 cm depth), and three irrigation water upper limits i.e., (saturated moisture content (s), field water holding capacity (f), and 80% of field water holding capacity (0.8f) as the upper limit of irrigation). The result revealed that the buried straw layer can inhibit water infiltration and significantly increase the water storage capacity and water storage efficiency of 0-25 cm soil depth. Under the condition of no evaporation, when the upper limit of irrigation water does not exceed the field water holding capacity, the storage efficiency of 0-25 cm soil water reaches 89%-91% after 6 d. Moreover, a buried straw layer can inhibit the deep percolation of nitrate nitrogen and increase the amount of nitrate-nitrogen in 0-25 cm soil. The 80% field water holding capacity irrigation upper limit combined with straw interlayer treatment had a higher nitrate-nitrogen content in the 0-25 cm soil layer than other treatments. Therefore, 80% of field water holding capacity as the upper limit of irrigation combined with buried straw layer is the optimal strategy to conserve soil water and nitrogen in the upper soil profile.

Keywords: distribution of water and nitrogen, irrigation water levels, infiltration, water storage efficiency
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1 Introduction

Water and nitrogen are the two important factors affecting crop growth. At present, excessive application of water and fertilizer in many cultivated areas of south China to improve yield has led to problems such as low water and fertilizer utilization efficiency and crop quality degradation[1]. At the same time, fertilizers are lost into groundwater, resulting in non-point source pollution due to this excessive water[2,3].

Owing to the increase in vegetable cultivation area under the greenhouse year by year in China, the national demands have been touched by the quantity of supply line. For long, the target was to increase crop production of greenhouse vegetables by using land, fertilizers, and water resources to achieve the demands. But, the latest tendency demonstrates that the enormous rise in population has amplified the competition between land used for agricultural purposes and that for infrastructure, resulting in a considerable rise in greenhouse vegetable production. The vegetable growers use excess nutrients and water to enhance their crop yield within the limited availability of land resources which eventually outcomes in the wasting of nutrients and water and destroying the soil environment without a substantial increase in yield. Therefore, it is an urgent need to develop a reasonable irrigation system to save water and prevent non-point source pollution. Straw burial at a certain soil depth is a technique to form a straw isolation layer to inhibit water infiltration[4], and increase surface and soil water storage capacity[5,6]. Burying a straw layer at 25 cm soil depth can optimize water salt distribution[7-9], can effectively improve the water use efficiency (WUE) of vegetables[10-14], at the same time, can reduce nitrate-nitrogen leaching losses[15-17], and can help to achieve the effect of water and fertilizer savings. Therefore, straw application or deep burial measures can effectively conserve soil moisture and fertility. However, some studies have found that the moisture content of the soil above the straw layer exceeds a certain threshold, which will increase the infiltration, reduce the field water use efficiency[18], and increase the risk of non-point source pollution. If the soil moisture above the straw layer is controlled precisely, fertilizer and water can be held in the upper root zone above the straw layer to decrease percolation and fertilizer leaching[13,14]. Therefore, it is of great significance to find the appropriate upper limit of irrigation above straw separation layer and the distribution characteristics of soil water and nitrogen under straw separation conditions to improve soil water and fertilizer retention ability and control non-point source pollution. According to the current research, the previous research mainly used straw separation layer to inhibit the salinity of soil surface, but there are few researches on the appropriate moisture threshold above straw separation layer. Through indoor soil column simulation experiment, the effect of straw burial at a depth of 25 cm and different irrigation upper limits on the distribution of water and nitrogen in 0-25 cm soil layer has been studied. The study is expected to provide theoretical and technical support for the control

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of water and fertilizer under the condition of buried straw isolation layer.

2 Materials and methods

2.1 Site description

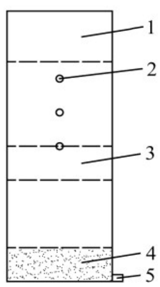
The study was carried out at a Water Saving Park of College of Agricultural Science and Engineering of Hohai University, Nanjing, PR China (31°95′N, 118°83′E), from April 17th to July 30th, 2019. The experimental soil had a bulk density of 1.34 g/cm^3, saturated soil moisture content of 43.7%, field capacity of 30.6%, and the initial amount of nitrate nitrogen was 1.4 mg/kg, which was determined by the use of phenol di-sulfonic acid spectrophotometric method[6,19].

2.2 Experimental design

The cylindrical PVC pipe columns were used for the experiment. The pots had 80 cm in height and 30 cm in diameter. Four sampling holes with a diameter of 2 cm were made around the first layer at a distance of 20 cm, 30 cm, and 40 cm, respectively, from the upper end of the column. A drain valve was provided near the bottom of the column. A 10 cm sand and gravel filter layer was laid at the bottom before soil loading. The soil with a bulk density of 1.34 g/cm^3 was layered above the gravel filter layer. When loading soil, the controlled depth was 10 cm each time. After compacting and combing the surface layer, the next layer was filled to ensure uniform contact with soil layer. A water storage height of 15 cm was reserved on the upper part of the soil column.

The dried rice straw was cut into 3-5 cm pieces using an isolation layer. From the gravel and sand filter layer to the place of 30 cm from the bottom of the soil column, 400 g was uniformly laid. After compaction, the straw layer was 10 cm thick making the straw density of 0.057 g/cm^3, and then the soil was filled 25 cm above the straw layer, thus the depth of straw burial was 25 cm. The upper reservation was the same as the treatment without straw.

Two factors were set in the experiment, namely the upper limit of soil irrigation above the straw barrier, and rice straw incorporation, with a total of six treatments. The straw factor was divided into two levels: with straw burial and no straw burial. The saturated moisture content (s), field water holding rate (f), and 80% of field water holding rate (0.8f) were set as three upper limits of irrigation. For T_1, T_3, and T_5 treatments, buried straw layer was incorporated, for T_2, T_4, and T_6 treatments, straw layer was not used. The detail of treatments is presented in Table 1. Each treatment was repeated three times. The experimental pot is shown in Figure 1.



1. Reserved height 2. Holes for taking the soil samples 3. Buried straw isolation layer 4. Gravel and sand filter layer 5. Drain valve

Figure 1 Setup of experimental pot

For a one-dimensional infiltration test, the mass concentration of urea in infiltration water was set at a rate of 0.48 g/L for all the treatments. After irrigation, the soil column was covered with a plastic film to prevent evaporation. The irrigation amount and fertilizer amount are listed in Table 1.

Table 1 Experimental design and treatments detail

Treatments	Irrigation upper limit/L	Urea/g	Straw interlayer
T_1	10.4	5	Yes
T_2	10.4	5	No
T_3	7.3	3.5	Yes
T_4	7.3	3.5	No
T_5	5.8	2.8	Yes
T_6	5.8	2.8	No

2.3 Soil sample collection and determination methods

Soil samples were taken at the interval of 2 d, 4 d, and 6 d after irrigation, through the sampling hole to ensure that the sampling position was not repeated. The sampling position was 5 cm, 15 cm, and 25 cm away from the soil table. After the end of infiltration, soil samples were taken from 0-5 cm, 5-15 cm, and 15-25 cm soil depths, respectively. The moisture content of soil sample was measured by gravimetric method, and the nitrate content was measured by spectrophotometer.

The water storage efficiency S (%) was calculated by the following equation.

$$S=(\mathrm{VT}-V_0)/\mathrm{VI}\times 100\% \quad (1)$$

where, VT is the total amount of water stored in the soil layer 0-25 cm below the soil surface after the treatment of infiltration, L; V_0 is the initial water content of the soil layer 0-25 cm before irrigation, L; VI is the total amount of irrigation water for each treatment, L.

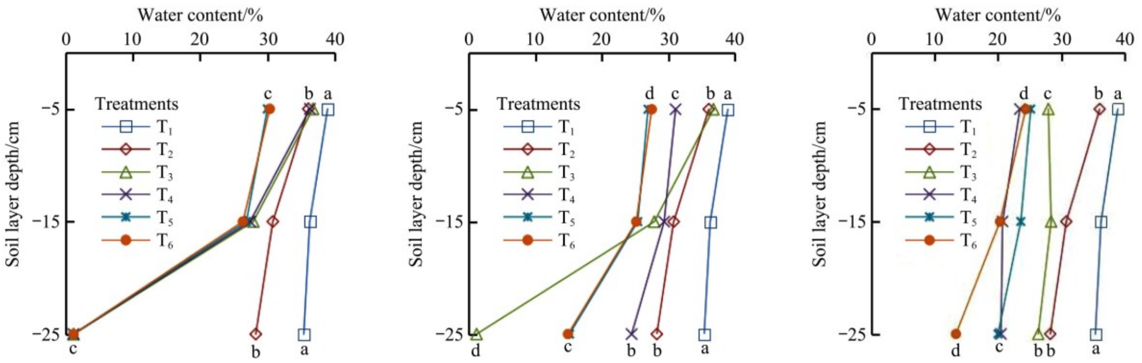
2.4 Data analysis

The analysis of varience was done using SPSS and graphs were created using Microsoft Excel. Mean values of each treatment were compared when significant differences were detected at the significant level of $p\leq 0.05$.

3 Results

3.1 Effects of different treatments on soil moisture content

Figure 2 shows the changes in soil moisture content under different treatments over time. It can be seen from Figure 2 that after 2 d of infiltration, when the upper limit of irrigation water was the unsaturated moisture content, each treatment had not infiltrated to 25 cm, and this interval layer had no significant influence on soil infiltration and moisture content. When the upper limit of irrigation water reached saturated moisture content, the partition layer significantly increased the soil moisture content of the upper 0-25 cm soil layer, which improved the water retention capacity of the soil. After 4 d of infiltration, the difference in the water content of each layer in T_1 and T_2 treatment increased; the water content of each layer in T_3 treatment was higher than that in T_4 treatment, and there was still no significant difference between T_5 and T_6 treatment. After 6 d of infiltration, the difference of moisture content between T_1 and T_2 treatment and T_3 and T_4 treatment was more significant, and the moisture content of each layer in T_5 treatment was higher than that in T_6 treatment. Under the same upper limit of irrigation water, the moisture content of 0-25 cm soil layer with straw treatment was significantly higher than that without straw treatment, indicating that the straw separation layer could increase the retention time of soil water above the separation layer and inhibit the infiltration of soil water in the upper layer. The higher the upper limit of irrigation, the faster the infiltration rate, and the more obvious the difference of moisture content with or without straw separation treatment. Therefore, the difference between straw barrier layer and irrigation upper limit can have a significant influence on soil water distribution.



a. 2 d after irrigation b. 4 d after irrigation c. 6 d after irrigation

Note: Mean values of each treatment were compared when significant differences were detected at the significant level of $p \leq 0.05$.

Figure 2 Water distribution in 0-25 cm soil layer for different treatments.

3.2 Influence of different treatments on the amount of infiltration

The water storage condition after 6 d of infiltration of 0-25 cm in each treatment is listed in Table 2. It can be seen from Table 2 that the water storage capacity of T_1, T_3, and T_5 treatments with buried straw layer is 40.7%, 24.5%, and 15.4% higher than that of T_2, T_4, and T_6 treatments without straw separation layer respectively ($p<0.05$), indicating that under the same irrigation upper limit condition, straw separation layer can reduce water infiltration and significantly increase the water storage capacity of straw upper layer. In the straw burial treatments, the water storage efficiency of T_1 treatment was 16.9% and 19.2% lower than that of T_3 and T_5 treatments, respectively, ($p<0.05$), indicating that under the condition of straw burial, the water storage efficiency of low-irrigation upper limit treatment above the straw separation layer was significantly improved. The water storage efficiency of T_3 and T_5 was close to 90%, but not significant. The reason is that under the condition of low irrigation upper limit, the upper soil of straw separation layer is clay. Under the same water potential, the moisture content of straw separation layer was lower than that of clay. However, the capillary pore of straw layer was underdeveloped, and the water conductivity was low under the condition of low water content, which reduced the water flux through soil-layer interface, inhibited the soil water infiltration above straw separation layer, and improved the water storage efficiency. The above results also showed that even if the upper limit of irrigation was controlled at the level of field water holding rate under normal irrigation, straw separation could significantly reduce the water migration to the deep layer and improve water retention performance of soil.

Table 2 Water storage status of different treatments after infiltration for 6 d

Treatments	Irrigation upper limit	Water storage capacity	Water storage efficiency	Infiltration rate
T_1	10.4	7.46^a	72.1^c	27.9^b
T_2	10.4	5.30^c	51.3^d	48.7^a
T_3	7.3	6.45^b	89.0^a	11.0^d
T_4	7.3	5.16^c	71.2^c	28.8^b
T_5	5.8	5.29^c	91.3^a	8.7^d
T_6	5.8	4.59^d	79.2^b	20.8^c

As can be seen from Table 2, the infiltration rate of irrigation water from 0-25 cm soil layer under T_3 treatment was 28.8% after 6 d of irrigation without partition. However, it was 11% in the interval treatment, which was significantly different from the T_4 treatment. This is consistent with the change in soil water content mentioned above. It shows that the straw separation layer has the effect of restraining deep percolation.

The multi-factor analysis of variance (Table 3) showed that the difference between straw separation layer and irrigation upper limit had a significant impact on water storage and water storage efficiency ($p<0.05$), and combined with the *F*-value table, it could be seen that straw separation layer had a greater impact on water storage and water storage efficiency than the upper limit of irrigation.

Table 3 *F* value for regression analysis by SPSS

Treatments	Water storage capacity	Water storage capacity
S	53.75*	134.70*
W	19.89*	96.98*
S×W	15.80*	3.03

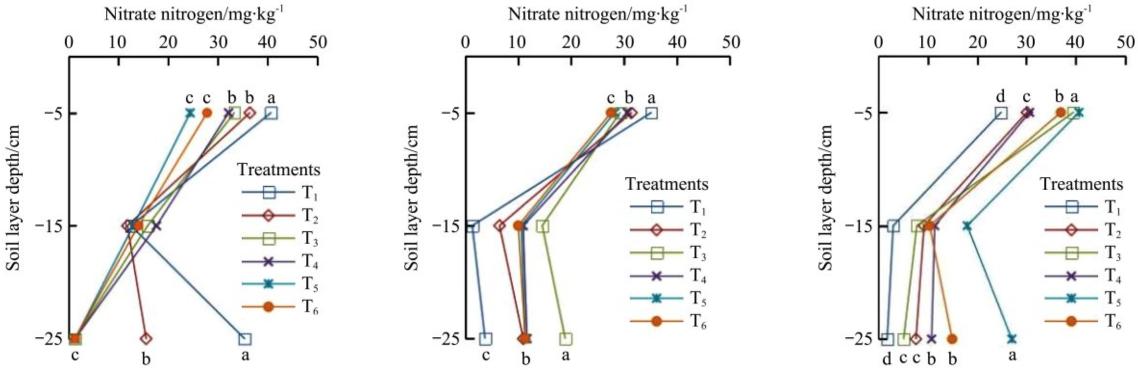
Note: * means the difference is significant. S means straw interlayer; W means upper irrigation limit.

3.3 Effects of different treatments on nitrate-nitrogen distribution

Figure 3 shows the change of nitrate-nitrogen under different treatments. It can be seen from Figure 3 that the infiltration peak reached the position of the separation layer 2 d after irrigation under T_1 and T_2, and the nitrate-nitrogen content of the soil layer above the separation layer was $T_1>T_2$ (Figure 3a). When the infiltration time was extended to 4 d and the wetting pattern of each treatment reached the straw layer and the upper limit of saturation was reached, the nitrate-nitrogen content in the topsoil (5 cm) showed $T_1>T_2$, while the middle and lower layers (15 cm and 25 cm) showed $T_1<T_2$. When the upper limit of irrigation water was lower than saturation, the nitrate-nitrogen content of field water holding rate treatment was $T_3>T_4$, and, T_5 and T_6 treatment showed no significant difference (Figure 3b). After 6 d of infiltration, the overall nitrate-nitrogen content in T_5 and T_6 treatments was higher, and T_5 treatment was significantly higher than other treatments. When the upper limit was the field water holding rate, the nitrate-nitrogen content in the T_3 treatment was higher than that in T_4. At the saturated water content, the straw separation capacity was lower, T_1 treatment was significantly lower than T_2 treatment, and the leaching loss was noticeable.

Figure 4 shows the nitrate-nitrogen content of soil in 0 to 25 cm (above the straw layer) after 6 d of infiltration. It can be seen from figure 4 that the nitrate nitrogen amount in the treatments had a relation of $T_5>T_6>T_3>T_4>T_2>T_1$. It implies that with the reduction of the upper limit of irrigation, soil nitrate-nitrogen content increased. In the case of field water holding rate and 80%

field water holding rate, straw layer treatments increased the soil nitrate-nitrogen content. When the irrigation upper limit was lower than the moisture rate (T_5 and T_6), the soil nitrate-nitrogen content at 0-25 cm was higher, although the fertilizer rate was lower than the former, the amount of nitrate-nitrogen was significantly higher than saturated moisture content (T_1 and T_2), nitrate-nitrogen in T_6 had no significant difference with that of T_3 and T_4, but T_5 had significantly higher nitrate-nitrogen contents when compared with that of T_3 and T_4 and T_6. The results show that inhibition of infiltration is an effective means to reduce nitrate leaching loss. Especially at the lower irrigation limit, the effect was more noticeable.



a. 2 d after irrigation b. 4 d after irrigation c. 6 d after irrigation

Figure 3 Nitrate nitrogen distribution in 0-25 cm soil layer for different treatments

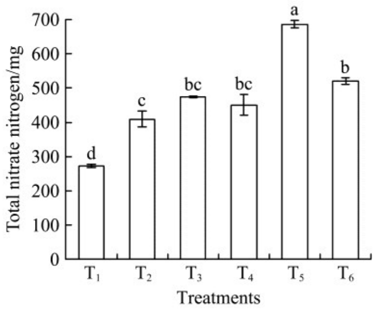


Figure 4 Nitrate content in 0-25 cm soil layer after 6 d for different treatments

4 Discussion

Soil water infiltration is mainly related to the structure, morphology, and geometry characteristics of soil pores, while layered heterogeneous soil has a difference in pores structure compared to homogeneous soil, which is expressed as a capillary obstruction at layered boundary[20], thus affecting soil water distribution. Straw layer is buried at a certain depth underground. Due to the existence of buried layer, homogeneous soil is stratified. The air in the pores of the separation layer cannot be discharged completely or the infiltration surface is too late to be discharged[21]. The experimental study found that the buried straw layer could significantly improve the water storage efficiency above the straw layer under different irrigation upper limit treatments. Similar results have also been confirmed by Zhao et al.[22]. It can be seen that the straw separation layer can effectively inhibit water infiltration, reduce deep infiltration, and improve water use efficiency.

When the moisture content of the planned wetting layer does not exceed the field water holding rate, the soil water will be retained as capillary water without deep percolation. However, due to the uneven distribution of planned wetting layer moisture content, even if the planned wetting layer average reaches the field water holding rate, the subsoil moisture content s exceeds the field water holding rate due to the existence of soil gravity potential, so deep leakage is bound to occur (such as T_4 treatment). On the other hand, even if the field water holding rate is not exceeded, infiltration may still occur due to the higher upper soil moisture content and water potential after irrigation (such as T_6 treatment). This test is done by the saturated moisture content, water-holding capacity in the field, and 80% of field capacity rate of irrigation water cap, respectively to simulate flood irrigation, normal surface irrigation, and water-saving irrigation, the study found that in the irrigation upper limit is not greater than the water-holding capacity in the field, the same irrigation conditions set the layer separation treatment of water in irrigation efficiency can reach 89% after 6 d (T_5) to 91% (T_3), the upper limit of water saturation moisture content was high. This is because compared with the general soil, straw has developed non-capillary macro-pores, and capillary porosity is lower. When the upper soil moisture content of straw was low, or when the water supply was insufficient, under the same soil water potential, the water content of straw was also lower, and the water flow rate was lower than that of soil. As a result, more irrigation water was stored in the upper soil. However, in the case of higher water content, macro-pores were filled with water to rapidly increase their water conductivity, resulting in more percolation. Therefore, the upper storage efficiency of saturated water content irrigation was lower than the treatment of field water holding rate and 80% field water holding rate, which has also been stated Lu et al.[23] It can also be seen that whenever the upper limit of irrigation water was lower than the water holding rate in the field, the straw burial treatment effectively improved the water storage efficiency above the buried straw layer.

One of the main factors of nitrate-nitrogen leaching is excessive irrigation[24], and soil texture[25]. In this study, it was found that the nitrate-nitrogen content in the upper soil decreased with the increase of the upper limit of irrigation water, which could be due to the loss of nitrate-nitrogen with water during infiltration process[26]. Similar results have also been reported by Dang et al.[27] on the influence of irrigation water on nitrate-nitrogen content. The nitrate-nitrogen content in the upper layer of straw separation treatment (T_3 and T_5) was higher than that in the straw-free treatments (T_4 and T_6). The straw layer changes the soil texture in the soil profile, inhibits the infiltration of irrigation water, and reduces nitrate-nitrogen leaching, which could be the possible reason for higher nitrate contents in the upper layer, hence it can play a certain role in fertilizer conservation. In our findings, 80% of field water holding capacity under buried straw layer had higher nitrate-nitrogen content, and saturated moisture content upper limit of water combined with straw layer had lower nitrate nitrogen content. This might be due to lower content of moisture compared to the field water holding capacity rate. Although the straw separation layer improves the moisture content, the nitrate nitrogen is mostly stored above the straw layer due to less water infiltration. The saturated moisture content of irrigation upper limit leads to increase soil humidity, and sets up the straw barrier to further improve the upper soil moisture content, even if the fertilizer rate is high. The higher moisture promoted the nitrate nitrogen leaching, and more water infiltration, resulting in a lot of nitrate nitrogen above the isolation layer and decreasing the nitrate migration from the upper soil layer. Therefore, the upper limit of irrigation should be set below the field water holding rate in order to improve the ability of buried straw layer to conserve fertilizer and water.

5 Conclusions

Straw separation treatment can significantly improve the soil moisture content above the separation layer and the water storage after the end of infiltration. After 6 d of infiltration, the water storage of T_1, T_3, and T_5 treated with straw layer was 40.7%, 24.5%, and 15.4% higher than that of T_2, T_4 and T_6 treated without straw separation. When the upper limit of irrigation is set below the field water holding rate, the water storage efficiency of the upper soil layer can be significantly improved. Especially in the buried straw treatment, the water storage efficiency of T_3 and T_5 treatment reached 89.0% and 91.3%, significantly higher than T_1 treatment. Setting 80% field water holding rate, the upper limit of irrigation water combined with straw separation treatment not only has the highest water storage efficiency but also can effectively inhibit the deep nitrate-nitrogen leakage of soil and increase the nitrate-nitrogen above the separation layer, therefore, it can be used as the optimal water-saving and fertilizer protection measure.

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