Study on the intensified reduction of farmland non-point source pollution in winter using thermally insulated ecological shallow ditch

Y Yang\(^1\), C Liu\(^1,3\), Y Chen\(^1\), J Zhou\(^1\) and W Lv\(^1,2\)

\(^1\)College of Urban Construction, Nanjing Tech University, Nanjing 211800, Jiangsu Province, China  
\(^2\)Jiangsu Key Laboratory of Industrial Water-Conservation & Emission Reduction, Nanjing Tech University, Nanjing 211800, Jiangsu Province, China  
E-mail: yunduobai@126.com

Abstract. Ecological shallow ditch is one of the effective methods to improve non-point source pollution of farmlands. However, during winter when the temperature is low, the operation capacity of the common ecological shallow ditch (CESD) is not satisfactory. In the present study, a thermally insulated ecological shallow ditch (TESD) was constructed, and the pollutant removal efficiency of the two ecological shallow ditches (thermal-insulation type versus common type) was compared. The changes in the number of bacteria inside these two types of shallow ditches were studied, and the underlying mechanism was analysed. The results showed that the thermally insulated ecological shallow ditch could partly reduce the adverse effects of low temperature and keep the surface temperature above 10° C. After 18 days of observation in the winter, the removal rates of COD, TN and TP in the effluent were respectively 1.3 times, 2.5 times and 1.3 times higher than those of the common type, and the concentration of bacteria in each site was also higher for TESD. The oxygen content in the soil layer and filler layer in TESD increased. Moreover, TESD also demonstrated higher microbial activity and more active plant growth than the CESD.

1. Introduction

With gradual management of point source pollution, agricultural non-point source pollution has become the main pollution source of water eutrophication [1]. In China, more than 50% of the total nitrogen in lakes, such as Taihu Lake [2], Chao Lake [3] and Dongting Lake [4] has come from agricultural non-point source pollution. To note, not only China, but other countries have also been facing the same problem. For example, 60% of the total nitrate in the surface water of England and Wales [5] has come from agricultural non-point source pollution. The Loire River (France) [6] and the Indian River Lagoon [7] have the problem of water eutrophication, and the nitrogen there has mainly come from non-point agricultural pollution. Therefore, it can be seen that agricultural non-point source pollution control is currently an important concern in regard to environmental water treatment and needs to be controlled by effective treatment measures.

The agricultural non-point source pollution is mainly treated using source reducing technology and process interception technology [8]. The process interception technology includes constructed wetlands [9,10], paddy fields [10] and ecological shallow ditches [11,12]. They all belong to ecological technologies. Among them, the constructed wetlands and paddy fields are limited in
developed regions due to large occupied area. By contrast, the ecological shallow ditch transformed from farmland drainage ditch has good application prospects with the following advantages: small occupied area, simple running management, and low cost.

The ecological shallow ditch is composed of farmland drainage ditches, aquatic plants, microorganisms and soil. It can be used to degrade nitrogen, phosphorus and organic pollutants before the polluted water enters the downstream receiving water body. However, the efficacy of ecological shallow ditch, like other ecological treatment measures such as constructed wetlands, is affected by temperature and has poor running effects at low temperature during winter. Dong [13] studied the running effects of constructed wetlands under the influence of low temperature and found that the removal rate of COD and BOD decreased significantly in autumn and winter, and the removal rate of total nitrogen decreased to 49.8%. Chen [14] in a one-year study on the ecological shallow ditches found that the removal rate of total nitrogen in cold season (September to March) was only 25%-50% of that in warm season (April-August). At low temperatures, the growth and proliferation of microorganisms are affected. In addition, the growth and metabolism of aquatic plants become slower, and the rhizosphere is hypoxic, which imparts negative effects on pollutant removal [15]. Studies have shown that nitrification is inhibited when the temperature is lower than 10°C and denitrification becomes almost stagnant when the temperature is lower than 4°C, which affects the denitrification process [16].

In order to improve the operation effect of ecological shallow ditches in winter, a thermally insulated ecological shallow ditch (TESD) was constructed in the current study to compare with the common ecological shallow ditch (CESD). The removal effects of pollutants and the concentration of interior bacteria in TESD and CESD were compared and analyzed. From the above-mentioned comparation, the operation effects and mechanisms of TESD in strengthening the reduction of agricultural non-point source pollution in winter were analyzed. The current research results should act as reference for other studies on enhancing the ability of ecological shallow ditches in controlling agricultural non-point source pollution in winter.

2. Materials and methods

2.1. Experimental set-up and operation

As figure 1 shows, the ecological shallow ditch was constructed with PVC sheet. Along its height, the ditch was divided into soil, filler and cushion layer from top to bottom. The soil layer was the planting area, and its thickness varied with different plants, ranging from 150 mm to 250 mm. The filler layer was filled with volcanic rock (particle size: 20 mm-30 mm) and its thickness was 300 mm. The cushion layer was filled with gravel (particle size: 20 mm-40 mm) and the thickness was 150 mm. To prevent any mixing, the ecological shallow ditch was separated by earthwork cloth between each layer.
Along the length, the ditch was divided into three compartments of length 1.0 m each with PVC sheets. From left to right, rohdea, canna and calamus were planted in sequence. Under proper lighting and irrigation conditions, these plants were cultivated for 40 days and grew well.

In winter, the ecological shallow ditch was processed with heat preservation to construct the TESD: (1) A foam pad with thickness 40 mm was pasted around the ditch and the outer surface of its bottom. (2) Bamboo sticks were fixed around the ditch and then covered with thick white transparent film (not shown in figure 1). The film was 1.5 m above the surface of the ditch. The gap between the film and the ground was compacted with wood. (3) When the daily temperature was higher (12 o'clock at noon), the film was opened to breathe in the ditch, and it was covered again at 3 o'clock in the afternoon.

Figures 1 and 2 show the ecological shallow ditch (white transparent agricultural film is not shown) constructed to reduce agricultural non-point source pollution during winter. Water sample ports were set at the bottom of the filler layer in each compartment. From left to right, there were three water sample ports numbered in the order 1#, 2#, 3#. To study the insulation effect in winter, the water samples collected from the three sampling ports were mixed in equal amounts. A small space was partitioned using a porous separator in the top right corner of each compartment for sampling plant roots, soil, and fillers conveniently.

Another ecological shallow ditch, the CESD, was constructed similarly as mentioned above but without any insulation set up. To compare with the prepared TESD, water and bacterial samples were also collected from the CESD in the same fashion as that for the TESD.

2.2. Water sampling and analysis
According to the concentration of pollutants in the paddy field water on the second day after application of base fertilizer, wastewater samples that simulated farmland surface runoff were prepared. In the wastewater sample, chemical oxygen demand (COD) was 139 mg/L, total nitrogen (TN) was 118 mg/L, ammonia nitrogen (NH\textsubscript{3}-N) was 9.2 mg/L, and total phosphorus (TP) was 2.1 mg/L.

Next, simulated wastewater (0.30 m\textsuperscript{3}) was added to TESD for static test. During the test, no supplying and draining occurred from the TESD and CESD. Samples were collected from three sampling ports every 72 hours, and three water samples were mixed in equal amounts. Six batches of water samples in total were obtained and stored in the refrigerator. The same method was used to collect water samples from the CESD. Within 24 hours, COD was measured using the potassium dichromate method, TN by the alkaline potassium persulfate digestion-UV spectrophotometric method, NH\textsubscript{3}-N by the Nessler's reagent colorimetric method and TP by the ammonium molybdate spectrophotometric method.

2.3. Bacterial sampling and counting
The bacterial samples of the roots, soils and fillers in the TESD and CESD were collected separately: about 80.00 g of roots were cut out from each plant and sterilized scissors were used to cut up and mix them evenly; about 80.00 g of soils from each compartments and about 100.00 g of volcanic rocks...
from each filler layer were collected, and sterilized mortar were used to mill and mix them evenly for subsequent tests. The location of each sampling point is shown in Table 1. Three batches of samples from the TESD and CESD were obtained, and the interval between each batch was 72 hours.

| Sample name  | Depth (mm) |
|--------------|------------|
| Rohdea roots | 50         |
| Canna roots  | 100        |
| Calamus roots| 100        |
| Soils        | 50         |
| Fillers      | 350        |

| Table 1. Location of each sampling point. |

Plant roots, soils and volcanic rocks, each of weight 10.00 g were added to 100 mL sterile water with glass beads. Then, they were shaken in a biological shaker at 200 r•min⁻¹ for 30 minutes, followed by dilution by 10⁴, 10⁵, 10⁶ and 10⁷ times in turn to prepare the bacterial suspensions. Then, appropriate amounts of mediums were added to 0.5 ml of each bacterial suspension to prepare plate culture mediums. These plate culture mediums were cultured for 72 hours.

The characteristics of the bacterial colonies were observed visually, while the microbial morphology in the culture mediums was observed by a digital biological microscope. The number of bacterial colonies was counted by the counter method, and the concentration of bacterial was calculated.

3. Results and discussion

3.1. Thermal-insulation effect in winter

The ecological shallow ditch with heat preservation by the method mentioned above has demonstrated good thermal-insulation effect. Table 2 compares the surface temperature of TESD and CESD in winter. The result showed that after heat preservation, the surface temperature increased by about 10°C.

| Types | surface temperature / °C |
|-------|--------------------------|
| CESD  | 0                        |
| TESD  | 12-13                    |

3.2. The pollutant removal effect

Figure 3(a) shows a comparison of COD removal rate change over time between TESD and CESD. The COD removal rates for both TESD and CESD increased steadily with time, and this increase was faster at the early stage corresponding to the time 72 h, 144 h, and 216 h. However, the COD removal rate of TESD was significantly higher than that of the CESD. At 432 h, the COD removal rate for TESD was about 65%, which was 1.3 times higher than that for the CESD. The COD removal rate of CESD was approximately 48%.

In winter, the temperature of CESD was about 0°C for a long time. The plant was mainly dormant, it stopped growing, and its roots were deprived of oxygen. The concentration of dissolved oxygen in water and soil layers reduced, and the metabolism of microorganism became slow. Both these factors resulted in a decrease in the COD removal rate [17]. On the other hand, the surface temperature of TESD was above 10°C. The ability of the soil and filler layer to become enriched with oxygen was strengthened. At the same time, the plant root system relatively developed and the plant growth remained active. These factors increased the number of microorganisms and enhanced their activity. As a result, the ability of the microorganisms in degrading organic pollutants also enhanced.
The changes in TN removal rate for TESD and CESD are shown in figure 3(b). Large differences can be observed between the two curves. In CESD, the TN removal rate was low, 22% at 432 h, with some fluctuations during the test. By contrast, the TN removal rate showed a steady rise over time for TESD, and it was about 54% at 432 h, which was about 2.5 times higher than that for CESD.

The form of nitrogen in the ecological shallow ditch mainly comprised organic nitrogen (urea), ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, nitrous oxide and dissolved nitrogen. The removal mechanism of nitrogen is complicated and mainly occurs through volatilization, soil adsorption, denitrification, plant root absorption and microbial nitrification.

When the temperature was around 0°C, the plant growth became static, and the number of microorganisms greatly reduced. When the temperature was lower than 12°C, primarily the activity of nitrifying bacteria decreased significantly [18]. Furthermore, when the temperature was lower than 0°C, the activity of the denitrifying bacteria was terminated. These factors certainly affected the removal of TN adversely [18-20]. The surface temperature of TESD was mainly above 12°C; therefore, the absorption capacity of plant roots and the nitrogen removal effect of the microorganisms remained active.

Figure 3(c) shows the changes in NH₃-N removal rates over time in TESD and CESD. The NH₃-N removal rates in TESD and CESD fluctuated greatly during the test period. Overall, the NH₃-N removal effect in TESD was significantly better than that in the CESD.
The removal mechanism of NH$_3$-N is similar to that of TN. NH$_3$-N is mainly removed via volatilization, soil adsorption, plant root absorption, microbial nitrification and denitrification. Therefore, the removal effect was greatly affected by the absorption capacity of plant roots and the activity of the microorganisms. During a sampling period of the test (144 h, 216 h in figure 3(c)), the NH$_3$-N removal rate decreased, which could be related to the conversion process of organic nitrogen. The NH$_3$-N is an intermediate product when organic nitrogen transforms to inorganic nitrogen.

The changes in TP removal rates in TESD and CESD are shown in figure 3(d). The removal rates of TP in both TESD and CESD increased steadily with time, and it increased faster at the early stage corresponding to the time of 72 h, 144 h, and 216 h. The TP removal rate for TESD was higher than that for CESD. At 432 h, the removal rates in TESD and CESD were about 44% and 33%, respectively. The removal rate of TP in TESD was about 1.3 times that in CESD.

TP was mainly removed by the absorption of soil and plant root and biological phosphorus removal, so its removal effect was related to the state of plant roots and microorganisms. The roots of TESD were more developed than that of the CESD, and its absorption capacity for phosphorus was stronger. The phosphorus-accumulating bacteria have the ability to remove phosphorus. The growth rate of Phosphorus-accumulating bacteria is inhibited at low temperatures, but relatively low temperature has little effects on the removal of phosphorus than nitrogen [15]. Therefore, due to the above two reasons, at low temperatures 8°C-9°C, the CESD still showed a relatively stable phosphorus removal capacity.

3.3. Comparison of bacterial concentrations between TESD and CESD

The results of the total bacterial concentration in roots, soils and fillers in TESD and CESD are shown in figure 4. It can be seen from the figure that in CESD, the total bacterial concentration in roots showed a downward trend, while it increased slightly in the soil and was relatively stable in the fillers. In TESD, the total bacterial concentration in the roots showed an upward trend while it was relatively stable in soils and fillers. Generally, the total bacterial concentration was higher for all parts of the TESD than those of the CESD. The average bacterial concentration of the three batches in roots of TESD was 2,573,000 ORG/GM, which was significantly higher than that of the CESD. The average concentration in CESD was 2,265,000 ORG/GM.

![Figure 4. Comparison of bacterial concentration in different sites of TESD and CESD.](Image)
In CESD, as the temperature decreased, the plant growth gradually became static, the root activity decreased, respiration weakened, and the bacteria in the roots gradually began to die due to lack of favourable growth conditions\cite{21,22}. By contrast, the total number of bacteria in the soils and fillers were low and did not change too much because the nutrients in water were not the limiting conditions for bacterial growth. The surface temperature of TESD was kept above 10°C, and the plant could continue growing. In addition, the activity of the root zone restored, the bacteria in it proliferated, and thus the bacterial number increased. Studies had shown that the removal of nitrogen, phosphorus and organic matter has an obvious relation with the microorganisms in the plant roots\cite{21,23}.

The total concentration of bacteria in roots was the highest, ranging from 1,968,000 ORG/GM to 2,653,000 ORG/GM, followed by soils with concentration of 118,000 ORG/GM to 173,000 ORG/GM for both the TESD and CESD. The total concentration in the fillers was the least with 17,500 ORG/GM to 25,000 ORG/GM for both the TESD and CESD. The total number of bacteria was distributed in such way that it was related to the background concentration of total bacteria and the plant biomass in plant roots, soils and fillers at the early stage of construction\cite{22,24}.

4. Conclusions

- In winter, the insulation measures maintained the surface temperature of TESD above 10°C. After observation for 18 days, the removal rates of COD, TN, and TP in TESD were respectively 1.3 times, 2.5 times, and 1.3 times than that of CESD. The plant growth remained active, the capacity of enriching oxygen in soils increased, and the ability of microorganisms to degrade organic matter also enhanced.
- The total bacterial concentration of roots, soils and fillers in TESD was higher than that of CESD. Moreover, for TESD, the greatest number of bacteria was found in the roots. Because the surface temperature of TESD was kept above 10°C, the plants there could continue to grow.

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