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CONSTRUCTION OF A BIOGAS HEAT STORAGE GREENHOUSE ECOSYSTEM UNDER THE CONTEXT OF WATER POLLUTION RESULTING FROM LIVESTOCK BREEDING

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Abstract

Livestock farming in rural areas in Jilin Province is producing a huge amount of organic pollutants like livestock and poultry manure, of which, a large portion is directly dumped into the Yitng River, bringing serious harm to the environment. Taking Soonlng Village as an example, this paper investigates the environmental pollution caused by the livestock husbandry in this village and builds a biogas heat storage greenhouse ecosystem, which, by using solar energy to heat the biogas digester, not only supplies the necessary temperature for the ecological greenhouse, but also helps compost the soil in the greenhouse. The system model can avoid the direct discharge of livestock manure and aquaculture wastewater into rivers, and to a certain extent alleviate the pollution of surface water. The developed biomass energy can be used in the greenhouse, enabling farmers to get rid of the single corn planting mode and realize economic benefit increase and income, thus realizing the organic unification of environmental benefit, economic benefit and social benefit.

Keywords: livestock breeding, recycling, water pollution

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1. Introduction

In recent years, livestock and poultry farming pollution has become a major source of pollution in China, third only to industrial pollution and domestic waste pollution (Li et al., 2017). Take Soonlng Village in Jilin Province for example. The village is situated upstream of the Yitng River, where all 30 farmer households live by raising chickens, with an annual production of about 3.3 million chickens. Large-scale breeding of livestock and poultry produces a large amount of manure, leading to concentrated pollution that is difficult to dispose of. A large portion of such manure is directly dumped into the Yitng River, bringing serious harm to the environment (Bhattacharya et al., 1997). On the one hand, livestock manure and corn straw cannot be recycled and pollute the environment; and on the other hand, rural energy resources are in short supply, which is a common problem in rural areas in northern China (Edwin et al., 2010).

In recent years, the Chinese government has been stepping up efforts to protect the environment. With the introduction of the Hezhang system, it is no longer allowed to dump livestock waste directly on both sides of the river. Therefore, it is very necessary to develop an ecological model to free farmers from the single corn planting model to increase their economic benefits, and also to dispose of livestock and poultry manure and corn straw so as to maximize energy conservation and protect the environment (Hijazi et al., 2016; Himanen and Hänninen, 2011).

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This will be of great significance to the protection of urban and rural ecological environment and the development of modern agricultural industry and circular economy (Walekhwa et al., 2014).

2. Current status of water pollution

The sampling site is in a tributary flowing through this village upstream of the Yitng River (Zhao et al., 2016). There is a total of 9 surface water monitoring sites, as shown in Fig. 1, Soonlng Village is located at sampling site 7. Water was collected with clean mineral water bottles, and 2000ml of water was collected at each sampling point. Collect water sample as soon as possible analysis. The determination of total nitrogen content was determined by alkaline potassium persulfate digestion UV spectrophotometry, the determination of nitrate nitrogen content by UV spectrophotometry, the determination of ammonia nitrogen content by colorimetry, the determination of total phosphorus content by ammonium molybdate spectrophotometry, and the determination of chemical oxygen demand by rapid digestion spectrophotometry.

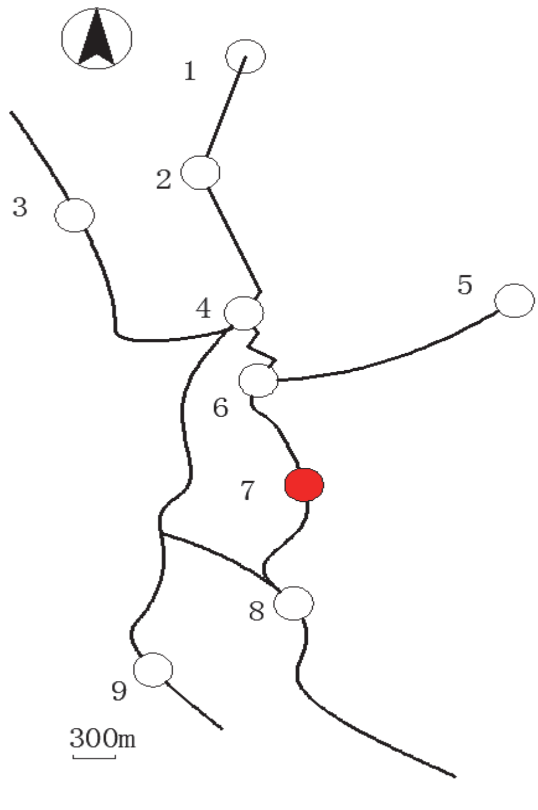

Fig. 1. Distribution of the sampling sites

It can be seen from Fig. 2 that at most sampling sites, the ammonia nitrogen content is ≤0.5mg/L, and that the nitrate nitrogen content is ≤1mg/L, which meet the surface water quality class II standard. Since sites 2 and 9 involve scattered pollution sources. Site 7 is the area polluted by the chicken farm, where the manure is directly discharged without any treatment, the area belongs to Class IV surface water quality. Because sampling point 6 has received field irrigation water and villagers' sewage, its ammonia nitrogen and nitrate nitrogen content are higher than other sampling points. The water flow at sampling point 8 is fast, and there are tributaries coming in, so the pollution is diluted.

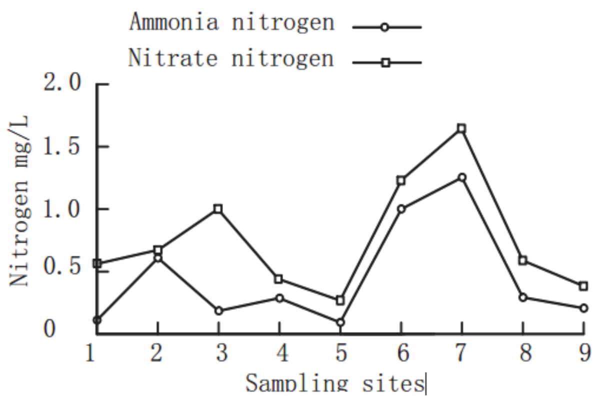

Fig. 2. Ammonia nitrogen and nitrate nitrogen contents in the water samples

Table 1 shows the contents of total N (total nitrogen), total P (total phosphorus) and COD in water samples. As can be seen from Table 1 that the pollution of total N is much more serious than that of ammonia nitrogen and nitrate nitrogen, especially at site 7, where the pollution far exceeds the limits of Class V surface water quality. Total nitrogen includes organic nitrogen and inorganic nitrogen compounds. The reason should be that the nitrogen in the animal excrement and the remaining feed exists in the form of organic nitrogen compounds; the content of total P at sampling site 7; the concentration of COD at sampling site 7 is as high as 1710 mg/L, far exceeding the limit of Class V surface water quality.

Table 2 shows the contents of heavy metals in poultry manure. The untreated poultry manure discharged into the environment can cause different degrees of pollution to the soil, water and crops. Long-term application of livestock manure to the soil can lead to accumulation of heavy metals in the soil and may also contaminate surface water and groundwater through leaching. The fertilizer application in the control soil was 2550 kg of compound nitrogen, phosphorus and potassium applied by 1hm^2, of which 1500 kg of base fertilizer was applied and 1050 kg of compound fertilizer was applied twice. The soil was cultivated by natural soil culture and non - protective rotation.

Heavy metal detection, soil digestion adopts Aqua regia +$HClO_4$ method, and the digested soil sample adopts ICP-MS for heavy metal content determination. Table 3 shows the contents of heavy metals and excessive contents in the soil by applying chicken manure.

Table 1. Total nitrogen, total phosphorus and COD content in the water samples

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Total N (mg/L)	5.12	5.22	5.1	3.11	0.46	7.89	13.4	0.91	1.81
Total P (mg/L)	0.17	0.16	0.15	0.27	0.06	0.58	1.22	0.13	0.08
COD (mg/L)	243	255	245	212	9.51	428	1716	18.2	22.1

Table 2. Contents of heavy metals in livestock manure (mg/kg)

Type	*Zn*	*Cu*	*As*	*Ni*	*Cr*	*Pb*	*Cd*	*Hg*
Pig manure	1769.2	1038.6	15.80	10.96	6.63	2.42	0.49	0.051
Chicken manure	379.9	273.9	5.06	5.51	7.11	4.89	0.73	0.051
Dairy manure	176.19	89.99	3.32	7.90	6.61	9.46	0.35	0.041

Table 3. Application of chicken manure to soil heavy metal content and excessive content

The sampling point	*dispose*	*Cu*		*Zn*		*As*	
		Average ($mg \cdot kg^{-1}$)	*over standard rate(%)*	*Average ($mg \cdot kg^{-1}$)*	*over standard rate(%)*	*Average ($mg \cdot kg^{-1}$)*	*over standard rate(%)*
Soonlng Village	chicken manure	117.88	135.01	362.89	52.9	28.02	12.02
Soonlng Village	control soil	11.38	N	64.95	N	13.49	N

(N- Not overweight)

In the soil subject to long-term application of chicken manure from large-scale chicken farms in Soonlng Village, the contents of Cu, Zn and As are all higher than those in the control soil without manure application (exceeding the standard by 135%, 53% and 12%).

3. Building the biogas heat storage greenhouse ecosystem model

3.1. Biogas heat storage greenhouse ecosystem

The system consists of a solar collector system, a biogas digester warming system and a greenhouse soil heat storage alternating system, as shown in Fig. 3. The solar collector system can provide the temperature required for the normal operation of the greenhouse soil and biogas digester in winter; the biogas digester warming system consists of heat exchange tubes laid outside the biogas digester, in which the fluid convectively exchanges heat with the biogas digester wall to raise the temperature of the biogas digester; the soil heat storage alternating system has two layers of soil in the greenhouse, between which heat exchange tubes are laid. The upper layer is used for planting and the lower layer is used to make compost, and the two layers of soil are used in farming alternately.

The greenhouse is 20m long, 5 m wide. The lowest height in the north is 1.5m, and the highest height is 2m. There are two soil storage tanks (12 and 13) along the vertical height from the bottom in the greenhouse. The heat exchange coil (2) is installed between the soil storage tanks, which contains heat exchange tubes to heat the temperature inside the greenhouse. The positions of the upper and lower soil storage tanks can be interchanged so that the soil can be used alternately. The hot water flows out from the heat storage tank (11) into the greenhouse and the biogas digester in parallel for heat exchange to increase the soil temperature in the greenhouse and the fermentation temperature in the biogas digester (Buonomo et al., 2018; Engel et al., 2016; Pinel et al., 2011). The biogas generated in the biogas digester is collected in the gas collecting tank (9), and the heat is supplied to the greenhouse by the biogas lamp (7) at night to raise the temperature in the greenhouse.

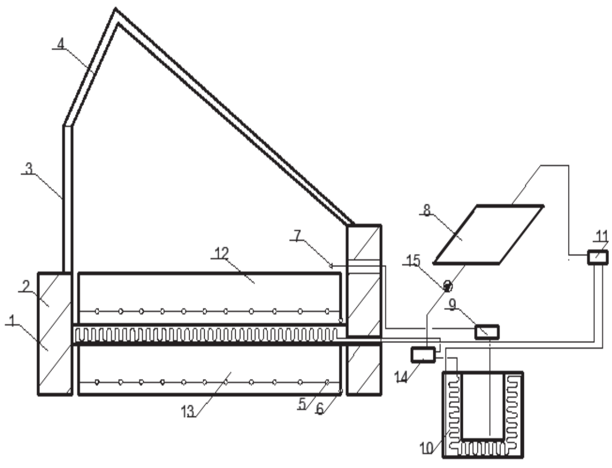

Fig. 3. Schematic diagram of the biogas heat storage greenhouse ecosystem model (1 is the wall self-insulation system; 2 are the heat exchange coils; 3 and 4 are the double-layer insulation films; 5 is the drain hole; 6 is the overflow hole; 7 is the biogas lamp; 8 is the solar collector plate, 9 is the gas collecting tank; 10 is the biogas digester, The outer side of the biogas digester is wrapped with heat exchange pipe to raise the temperature in the biogas digester; 11 is the heat storage tank; 12 and 13 are the alternating soil tanks; 14 is the heat pump; and 15 is the circulation pump)

3.2. Temperature field distribution of the biogas digester warming system

Soonlng village is located in the cold region of Northeast China. The biogas digester routinely built is greatly affected by the environmental temperature in winter, so it is difficult to maintain the optimal fermentation temperature, so the utilization rate of the biogas digester is very low in the winter in North China, and the production of gas stops for most of the winter. The biogas digester in this ecological mode is constructed of steel fiber reinforced concrete, outside which, the heat exchange tubes are laid. The circulating water is heated by the solar collector plate to exchange heat with the digester to increase the fermentation temperature in it (Brandl, 2006; Kezza et al., 2018). Fig. 4 describes the nephograms of the temperature field distribution of the biogas digester. It can be seen that after 3 days of heat exchange, the temperature in the biogas digester is stratified, forming three regions - high, medium and low temperature ones.

The upper part is the low temperature region, with the temperature being between 280k and 290k. In the middle is the medium temperature region, with the temperature being about 300 k, and the part near the wall surface of the biogas digester is the high temperature region, with the temperature reaching 310k; after 7 days, the temperature field in the biogas digester tends to be steady, but the high temperature region is further expanded - 3/4 of the area reaches a temperature of 310 k or more. In order to truly and effectively measure the changes of temperature field, temperature measurement points were set in the bottom wall and side wall of the biogas digester body, in the inner part along the center and radius direction, in the middle and lower parts, in the bottom, middle and top layers of biogas digester, and in the center and side walls of each layer. Experiments using self-made copper - constantan thermocouple measuring temperature, and combined with precision of 0.1 °CWJK-E multipath data acquisition instrument, automatically and regularly read, record and store temperature data.

By using the TFX1020P - type superacoustic wave flow meter measures the flow quantity of thermo-engineering in the system. Fig. 5 shows the temperature measured inside and outside the biogas digester for 15 days in January, the coldest month throughout the year. Through actual measurement, it is found that when the biogas digester was heated by a solar collector, the temperature of the biogas slurry significantly increased and reached an average of 23.77°C.

On January 15, when the outdoor temperature dropped to minus 23°C, the temperature of the biogas slurry could still reach 23°C, fully meeting the normal working temperature of the biogas digester. By adjusting the temperature of the heating system, the temperature of the fermentation liquid in the pond was increased, so that the biogas digester could be fermented at high temperature in winter.

3.3. Soil heat storage alternation

There are two soil storage tanks along the vertical height at the bottom in the greenhouse. The upper tank is used for plantation, and the lower one is used for composting. The composting experiment is to add corn straw to chicken manure to make compost, and compare this scheme with the one with the addition of activated sludge.

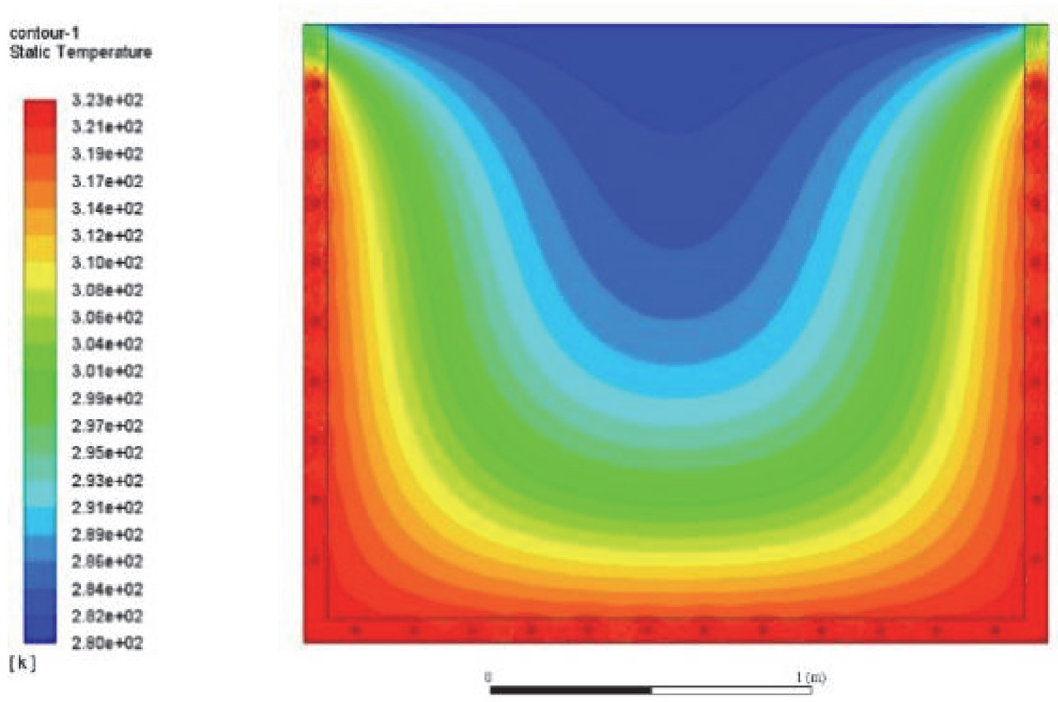

Fig. 4. 3d image of heat exchange thermal fields

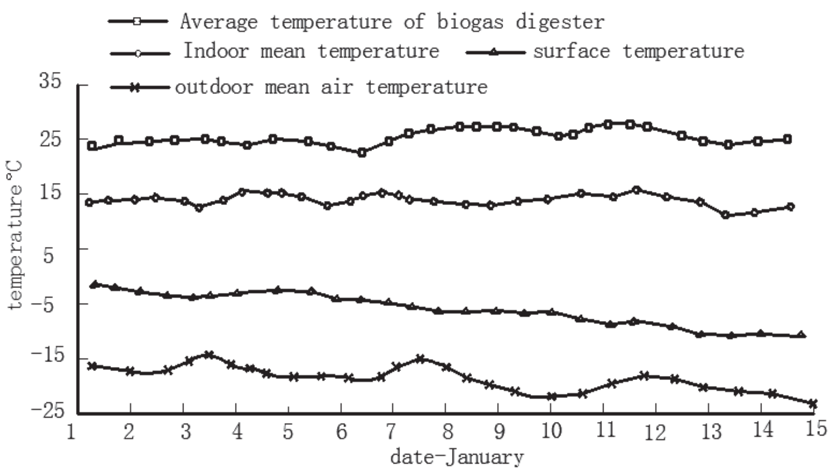

Fig. 5. Temperature measured inside and outside the biogas digester

Table 4. Basic properties of aerobic compost materials

Material	*pH*	*H_2O (%)*	*organic matter (%)*	*TC (%)*	*TN (%)*	*C/N*	*TP (%)*	*TK (%)*
straw	6.22	11.69	80.5	43.14	0.85	50.75	0.37	0.16
chicken manure	6.81	77.09	56.1	39.83	4.02	9.908	2.48	0.98
sludge		84.67	49.7	25.30	4.64	5.45	0.6	1.80

The ambient temperature is 25°C. The basic properties of aerobic compost materials are shown in Table 4, The aerobic compost simulation experiment was conducted from early July to mid-august in the alternating soil tanks 13 of the insulated greenhouse for 49 days. The experimental composting schemes are shown in Table 5.

During the simulation of aerobic composting, compost indicators were monitored, mainly including: core temperature of the reactor, pH, water content, organic matter, TC, TN, TP, TK. P H was determined by electrode method. Observed temperature change at the same time, when the core temperature reaches 55^0C to 60 ^{0}C should be double stack. Other indexes were sampled and tested every 5 days.

Table 5. Experimental composting schemes

No.	*Material mix*	*Mass ratio*	*C/N*	*H_2O(%)*	*pH*
1	Chicken manure: straw	71.43:28.57	26.3	64.5	5.75
2	Chicken manure: straw: sludge	64.94:25.97:9.09	26.3	66.6	5.73

Total organic matter was determined by potassium dichromate oxidation method, TC was measured by Muffle furnace high temperature burning method, TN was measured by Kjeldahl method, TP by molybdenum antichromatism method, and TK by atomic absorption spectrophotometer. Fig. 6 shows the temperature changes during composting. It can be seen that the aerobic composting of corn straw and chicken manure are divided into three stages. During the heating stage, the temperature of the composite rose to 45°C on day 21; during day 21-35, the composite was in the high temperature stage, where the temperature was maintained at 45-50°C; after day 45, it entered the maturity stage, where the temperature gradually decreased to the room temperature and tended to be consistent with the ambient temperature. The composite with the addition of sludge was increased to 45°C as early as day 7, and the temperature remained at 45°C during day 7- day 21. After day 35, the temperature of the composite tended to be consistent with the ambient temperature, without obvious changes, indicating that it was completely mature. The temperature of the composite with sludge increased faster than that of the composite without sludge, and the temperature of the composite with sludge was slightly higher than that of the composite without sludge during the decomposing process, indicating that the sludge can accelerate the decomposing of the aerobic compost of chicken manure and shorten the decomposing time. Fully fermented compost can be used as biological organic fertilizer to effectively control the environmental hazards of non-point pollutants in livestock and poultry manure.

4. Results and analysis

4.1. Improvement of soil quality

This section compares the contents of organic matter, total nitrogen, rapidly available phosphorus and rapidly available K (potassium) in the soil of the greenhouse before and one year after the implementation of the biogas heat storage greenhouse ecosystem model, with the comparison results shown in Fig.7.

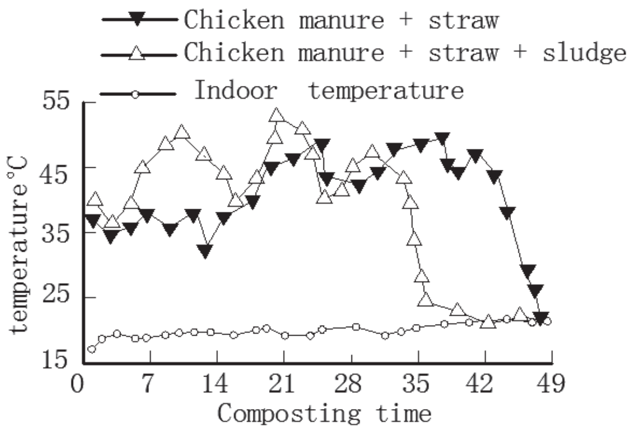

Fig. 6. Temperature changes during composting

In Fig.7, I represents the Level I standard for soil nutrients. It can be seen that the average content of rapidly available K in the soil one year later was 6.2 times the original one, an increase of 260.2 mg/kg. The average content of rapidly available P was 8 times the original one, an increase of 79.6mg/kg. The average content of rapidly available K in the greenhouse soil was 55% higher than the Level I soil nutrient standard, and the average content of rapidly available P in the soil was higher than the Level I soil nutrient standard double. It can be seen that the use of biogas residue and slurry increased the total nitrogen content in the greenhouse soil by 45% compared with the ordinary soil, and that the organic matter content was increased by 2.5 times, one year later.

As the biogas residue and slurry contains a large amount of soil nutrients including organic matter, total nitrogen, rapidly available P and rapidly available K and little iron, manganese, copper, zinc, lead, mercury and arsenic, it is very helpful to reducing the consumption of fertilizer, increasing soil nutrients, improving soil quality and increasing agricultural production in rural areas.

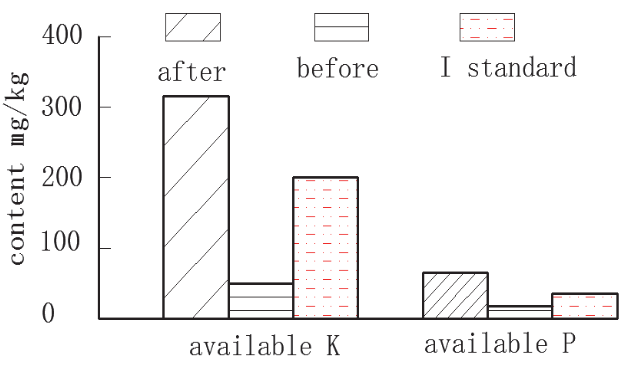

Fig. 7. Rapidly available K and rapidly available P in the soil

4.2. Improvement effects on the river water quality

The COD, NH_3-N and TP concentrations at sampling site 7 in the river were measured one year after this model was implemented and then compared with those a year ago, as shown in Fig.8, where NH3-N is expressed in 0.1mg/L and TP in 0.01mg/L, and V represents the Level V water quality standard. It can be seen that, one year after this model was implemented, the average concentrations of various pollutants in the river at sampling site 7 were significantly decreased. Among them, the concentration of COD decreased from 1710mg/L to 25.09mg/L, which met the Class V water quality requirement; the concentration of NH_3-N decreased from 1mg/L to 0.61mg/L, and the concentration of TP decreased from 1.2mg/L to 0.18mg/L, which both met the Class III water quality requirements. After applying the ecological model, farmers used dry cleaning of chicken manure, using a small amount of water to wash chicken manure. After flushing, the water is put into the soil of chicken manure for compost, or into the biogas digester for fermentation. This method reduces the discharge of livestock and poultry excrement and flushing waste water, improves the living environment of farmers and solves the problem of river pollution. The quality of the river has been greatly improved.

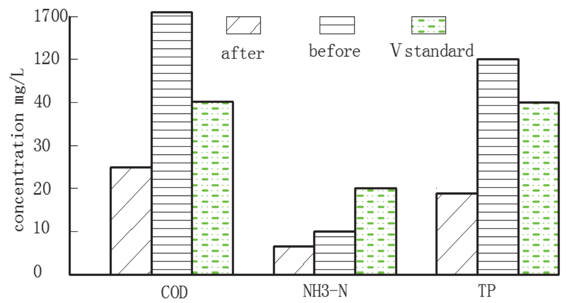

Fig. 8. Comparison of river water quality at sampling site 7

4.3. Control effects on the environmental costs of livestock manure pollution

This paper analyzes the emission reduction effects of the biogas heat storage greenhouse ecosystem model in controlling water pollution, soil pollution and microbial pollution from the perspective of economics.

The reduction in the environmental cost of water pollution control is evaluated by the Eq. 1 using the analogy method and the market value method (Zhang et al., 2005):

$$EC_{water,\,D} = (\theta - \theta_D) \cdot \sum R \cdot K \quad (1)$$

where: $EC_{water,\,D}$ is the reduction in the environmental cost of livestock pollutant control in water; R is the pollution loss rate of pollutants to the Yitng River; θ is the proportion of the amount of one livestock pollutant in the total amount of such pollutant in the

Yitng River under natural treatment conditions; θ_D is the proportion of the amount of one livestock pollutant in the total amount of such pollutant in the Yitng River under biogas engineering conditions; and K is the value of a certain function of the Yitng River water body.

The nitrogen removal rate from the biogas project is 68%, 28% for θ and 8% for θ_D (Wu et al., 2012). The loss rate (R) of the value of drinking water source caused by nitrogen pollutant is 0.999, and the function value of drinking water source in Yitng River is 101.5 million yuan. By using the formula, it can be concluded that the reduction of water pollution in Yitng River livestock and poultry project can reduce the environmental cost by 20.3 million RMB.

The reduction in the environmental cost of soil pollution control is evaluated as show in Eq. (2):

$$E_{Csoil,D} = \sum S \bullet Tr \bullet Pr \qquad (2)$$

where: $E_{Csoil,D}$ is the reduction in the environmental cost of livestock pollutant control in soil; S is the area of farmland where livestock manure pollutants are reduced; Tr is the grain yield of the polluted area; Pr is the average price of grain in that year.

Soil pollution mainly includes nitrogen pollution and heavy metal residue pollution to crop products. The environmental benefits of controlling nitrogen pollution in farmland were assessed. After treated with biogas, the nitrogen in the excrement of livestock and poultry is lower than the pollution standard of 150 $kg \cdot hm^{-2}$, which will not cause farmland pollution. The annual output of corn in Soonln village is $1200t^{-1}$. The average selling price of corn is 2,400 RMB t^{-1}, and the village can reduce environmental costs by 6.9 million RMB. The reduction in environmental cost of microbial pollution control is evaluated as show in Eq. 3:

$$EC_{health,\ D} = Wp \bullet P + \sum \varphi \bullet TA \qquad (3)$$

where: $EC_{health,\ D}$ is the reduction in the cost of livestock microbial pollution control; Wp is the reduction in the medical cost of human diseases due to the reduction of microbial pollution; P is the number of poultry farmer households; φ is the decline of livestock and poultry diseases in percentage under biogas engineering conditions; and TA is the breeding loss caused by livestock microbial pollution. After fermentation by biogas, the excrement of livestock and poultry can effectively settle down and kill the bacterial pathogens, viral pathogens, parasitic pathogens and fly and fly eggs. The incidence of poultry infectious diseases decreased by 68%, and the loss of cultivation could be reduced by 31.8 million RMB through the biogas project. Therefore, after the implementation of the ecological model, the village could reduce the environmental loss by 23 million RMB. After calculation, the environmental cost controlled by the village is 50.2 million RMB. This study does not estimate the environmental cost of ammonia and heavy metal pollution control of livestock and poultry manure.

The construction cost of the ecological model is about 45 thousand RMB per farmer. The ecological greenhouses, through planting economic crops such as vegetables and strawberries, can make a profit of about 100 thousand RMB per year. The construction cost can be recovered within half a year after the implementation of the model. This village can increase income above 3 million RMB a year, economic benefit is considerable. In summary, this model can bring good economic, environmental and social benefits.

5. Conclusions

Taking Soonlng Village as an example, this paper investigates the environmental pollution caused by the livestock husbandry in this village and builds a targeted model of biogas heat storage greenhouse ecosystem, which composites livestock manure and corn straw and utilizes biogas fermentation. Use this ecological model, it can indirectly reduce the pollutants through the comprehensive utilization of livestock manure. This system can realize the soil rotation and tillage, and provide the temperature needed for the plant growth for the thermal greenhouse, so that farmers can realize multi-season planting and increase their income.

The ecological model can be applied in practical use to breed specialized households, form a benign circular system of ecological agriculture, and effectively control the environmental harm of non-point pollutants of livestock and poultry manure. The environmental cost controlled by the village is 50.2 million RMB. This village can increase income above 3 million RMB a year. It can be seen that this model can bring good environmental, economic and social benefits.

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