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# Analysis on Mode and Benefit of Resource Utilization of Rural Sewage in a Typical Chinese City

**Zihan Gui, Jinhua Wen, Lei Fu, Shiwu Wang * and Baoxian Zheng**

Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China; guizh3@mail2.sysu.edu.cn (Z.G.); jinhuawen@outlook.com (J.W.); fulei200@uregina.ca (L.F.); zhbx_zj@163.com (B.Z.)
* Correspondence: shiwuwang01@outlook.com

**Abstract:** The treatment of rural domestic sewage is essential for the comprehensive improvement of the rural environment. At present, the rate of resource utilization of rural domestic sewage is generally low in China, which fits with the actual situation of rural areas, and low cost is becoming the requirement for the development of rural sewage treatment technologies. Adopting a tailored approach based on local conditions for utilising sewage resources is the best option for rural sewage management. Therefore, it is very important and urgent to explore and evaluate the mode of rural domestic sewage resource utilisation. This paper analyzes the current status of sewage resource utilization in rural China. It researches and explores sewage treatment technology and resource utilization models based on 10 study sites in Yongkang City, Zhejiang Province. At the same time, this article evaluates pollution control effectiveness and environmental emission reduction benefits. The results show that the effluent quality of the treated wastewater by the skid-mounted resource utilization equipment met the reuse requirements and maintained stable water quality. The project can save 251,900 tons of high-quality water resources annually, reducing COD by 78.51 tons, reducing $NH_3$-N and TP by 5.62 tons and 0.39 tons, respectively, and reducing carbon emissions by more than 134 tons. The project has achieved significant comprehensive benefits in water conservation, pollution reduction, and carbon reduction.

**Keywords:** rural sewage; resource utilization; rural sewage treatment equipment; benefit analysis; carbon reduction

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## 1. Introduction

Rural domestic sewage treatment is an important task in implementing the strategy of rural revitalization and an essential content of the comprehensive improvement of the rural environment [1]. According to the Water Resources Bulletin statistics, there are nearly 2.6 million natural villages in China, which produce 8.3–12.5 billion $m^3$ of rural domestic sewage every year [2]. In recent years, through the government's continuous measures to promote the comprehensive improvement of the rural environment, the rate of rural sewage treatment has been significantly improved [3,4]. Chinese rural areas are characterized by the uneven distribution of housing because of the differentiation of the terrain. Different living habits also lead to different water habits. At present, drainage systems in rural areas are incomplete [5]. To treat sewage, many resources and energy must be used manually in sewage treatment plants [6]. The more advanced the treatment process, the more resources and energy are consumed. Therefore, the most advanced sewage treatment technology is unsuitable for rural areas. Pursuing a higher sewage discharge standard does not align with the rural situation.

Based on comprehensive consideration of rural drainage conditions and water demand, tailored solutions and demand-based management are essential to achieve sustainable operation of rural domestic wastewater treatment equipment [7–9]. In recent years, on-site utilization and disposal have been increasingly emphasized in China as a means of resource recovery from rural domestic wastewater. Until now, most regions in China have issued or revised Discharge Standards for rural domestic sewage treatment, which explicitly encourage the use of tailwater [10]. In 2021, the Chinese government issued relevant guidelines emphasizing "steadily promoting the utilization of agricultural and rural sewage resources". At the same time, the guiding opinions also make it clear that by 2025, the reuse rate of reclaimed water in water-scarce cities at the prefecture level and above should reach over 25% nationwide [11]. Therefore, the utilization of sewage resources has become a priority option for rural domestic sewage treatment.

Water-saving in daily life and wastewater reuse are effective ways to solve southern China's water and ecological environmental problems. It can effectively alleviate the contradiction between the supply and demand of water resources, promote the high-quality development of water resources, and facilitate sustainable social development. Using sewage resources is an effective way to save pollution and reduce emissions. It can effectively address issues such as water scarcity, water pollution, and damage to water ecosystems while also improving the quality of rural ecological environments and contributing to the creation of beautiful countryside. The rural domestic sewage treatment work in Zhejiang Province is at the forefront of the country, and the construction of beautiful countryside has attracted nationwide attention [12]. Since 2003, Zhejiang Province has taken "demonstrating in a thousand villages and improving in ten thousand villages" as the main focus, implementing a series of rural domestic sewage treatment projects and accumulating rich practical experience in rural environmental governance [13]. This article takes Yongkang City in Zhejiang Province as a typical study case to explore the mode of rural sewage resource utilization and evaluate its comprehensive benefits of "water saving, emission reduction, and carbon reduction". In addition, it provides reference and decision-making support for the resource utilization of domestic sewage in typical rural areas in southern China.

## 2. Current Status of Resource Utilization of Rural Sewage in China

### 2.1. Problems Existing in the Utilization of Rural Sewage Resources

Rural domestic sewage mainly includes kitchen sewage, washing and toilet or bathing water in households. It is mainly rich in nitrogen and phosphorus and generally does not contain toxic and harmful substances [14]. According to statistics, the utilization of sewage resources was less than 2% of the national water supply in 2020 [11]. There are many reasons for the low utilization rate of rural domestic sewage resources. Firstly, China started research on rural domestic sewage treatment technology relatively late, and it has less experience than developed countries. While exploring sewage treatment modes, there was insufficient understanding of the actual situation, excessive pursuit of meeting discharge standards, and a lack of research and practical implementation of resource utilization modes. Secondly, rural sewage has irregular and intermittent discharge characteristics, difficulty in the collection, and complex structural composition. In most Chinese rural villages, the population is relatively dispersed, and the economic foundation in many rural areas is weak. The supporting facilities for resource utilization, such as storage and transportation of wastewater, cannot meet the demand. Therefore, it is challenging to implement resource utilization projects. Finally, farmers are concerned about the uncertainty of using reclaimed water for irrigation, which leads to a lack of enthusiasm for wastewater resource utilization. Especially in the southern regions with abundant water resources, there is a weak awareness of wastewater resource utilization, and a lack of recognition of its importance, resulting in low enthusiasm for reuse.

### 2.2. Research Status of Rural Sewage Resource Utilization

In recent years, as water supply and demand pressure has increased, the "exploitation" of unconventional water resources has attracted widespread attention. The research on the utilization methods and treatment processes of sewage resource recovery is gradually increasing [15,16]. Unlike the direction of utilizing urban sewage for resource recovery, reusing it in agricultural production is the optimal way to achieve resource recovery from rural domestic sewage. Li et al. proposed that the resource recovery of rural domestic sewage mainly focuses on developing irrigation [17]. Xu et al. proposed that by integrating the treatment of rural domestic sewage into agriculture, nitrogen and phosphorus in rural domestic sewage could be turned waste into treasure [18]. Studies have shown that direct irrigation of domestic sewage will adversely affect soil and crops [19–21]. However, it will help the growth of crops after moderate treatment [22–24]. Rural sewage treatment combined with agricultural production processes can make nitrogen and phosphorus nutrients become valuable fertilizers for agricultural planting. The abundant land resources in rural areas also can absorb nitrogen and phosphorus from domestic sewage [25]. From this perspective, rural domestic sewage treatment mode should shift from the traditional “end-of-pipe treatment” to “on-site treatment and nearby resources utilization”. In terms of treatment technology, rural sewage treatment usually adopts practical, reasonable, low-energy consumption and low-operating-cost technology. Generally, ecological, and biological treatment systems are used to treat sewage [26,27]. The ecological treatment technologies mainly include stabilization pond technology and constructed wetland technology. The biological treatment system mainly includes anaerobic digester treatment and biofilm technology.

There have been many successful cases of domestic sewage treatment technologies in rural areas of China. Based on this, they can be summarized into four resource utilization modes under different conditions [28,29]. The first mode is coupling the pollutant treatment process and economical crop cultivation. The characteristic of this model is to directly plant economic crops in the sewage treatment unit so that the income generated by the economic crops can compensate for the operation cost of the water treatment system while achieving sewage purification. This model has been applied in engineering projects in many places, such as Beijing, Jiangsu, and Anhui [28]. The second type is the wastewater irrigation model. Its characteristics are simple technology, low maintenance, low construction and operation costs, and the effluent quality only needs to meet the standard for farmland irrigation. Xiao et al. utilized this model to carry out a study on the utilization of rural domestic wastewater as a resource for agricultural irrigation in Zhejiang Province [30]. The research demonstrated that rural domestic wastewater could be feasibly utilized as a resource for agricultural irrigation after appropriate treatment.

The third approach is following the water quality requirements mode, which adjusts the process conditions of wastewater treatment equipment to achieve adjustable effluent quality based on the characteristics of agricultural water use [31]. This approach addresses the imbalance between wastewater discharge and agricultural water demand [32]. The fourth type is the black and grey water separation model based on source separation and quality-based treatment. It separates domestic sewage at the source and treats and utilizes it separately [33]. Zhang et al. believe that using centralized septic tanks, stabilization ponds, anaerobic fermentation technology, and other moderate treatments can be employed as water resources and nitrogen-phosphorus resources for agriculture in mountainous and semi-mountainous regions of Yunnan Province [34]. In the future, the key to rural domestic sewage treatment in China lies in whether it is based on green, low-carbon principles and tailored for local conditions, emphasizing the importance of recycling and reuse. Furthermore, for underdeveloped rural areas, emphasizing ecological sewage treatment methods, adopting the correct technological approach and governance policies, and persisting in pursuing the path of resource utilization.

## 3. Case of Rural Domestic Sewage Resource Utilization Mode

### 3.1. Overview of the Region

Yongkang City is in the low hilly area of central Zhejiang Province, with a total area of 1049 km$^2$, and the geographical location is shown in Figure 1. The city has a mild climate and belongs to the subtropical monsoon climate zone. The city’s annual average water resources are 845 million m$^3$, and the annual average per capita water resources are 1104 m$^3$. Yongkang City is the second batch of counties in China to complete the construction of a water-saving society. However, in the process of rapid economic development and urban-rural integration, Yongkang City not only urgently needs to increase the supply of water resources significantly but also produces a large amount of domestic sewage and other garbage, thus bringing ecological and environmental burdens. The multi-factor coupling of increased demand for water resources, increased total sewage discharge and intensified environmental water pollution further aggravates the "water crisis" threat.

**Figure 1.** Location map of Yongkang City.

The project selected 10 study sites nearby the Yangxi Reservoir and Taiping Reservoir, which are important water sources of Yongkang City: Houshantou (HST), Xiashao (XS), Yanhou (YH), Lingyanqianshi (LYQS), Ketouhu (KTH), Jingtou (JT), Dayuan (DY), Guzhufan (GZF), New Taiping (NTP), Taiping (TPG). The location is shown in Figure 2. In addition, the practice of recycling and efficient utilization of rural domestic sewage was explored in 10 sites.

Currently, three basic sewage treatment processes are involved in the 10 study sites (as shown in Table 1): Anaerobic-Anoxic-Oxic ($A^2/O$), Moving Bed Biofilm Reactor Process (MBBR), and constructed wetland. Eight research sites (HST, XS, etc.) use $A^2/O$-MBBR combined with constructed wetlands for wastewater treatment. The $A^2/O$-MBBR process is based on $A^2/O$ and MBBR. It can increase the implantation area of microorganisms by adding biological filler to the biochemical pond to improve the efficiency of sewage treatment. The sewage treatment process adopted by NTP combines $A^2/O$ and constructed wetlands. TPG uses PKA constructed wetland. PKA-constructed wetlands originated in the 1960s in Germany. It is a kind of vertical subsurface flow constructed wetland. The designed discharge standards of NTP meet the Second-level standards in the Discharge Standard of Zhejiang Province (DB33/973-2021). In addition to NTP, the design discharge standards of the other nine research sites meet the First-level standards in the Discharge Standard of Zhejiang Province (DB33/973-2021). The highly treated tailwater of HST, XS, YH, JT, DY and GZF discharges into nearby channels and eventually into Yangxi Reservoir. The highly treated tailwater of LYSQ and KTH drains into a natural pond next to Yangxi Reservoir. The highly treated tailwater of NTP also is discharged into nearby channels and eventually into Taiping Reservoir. The treated sewage from TPG is discharged directly into the nearby Taiping Reservoir.

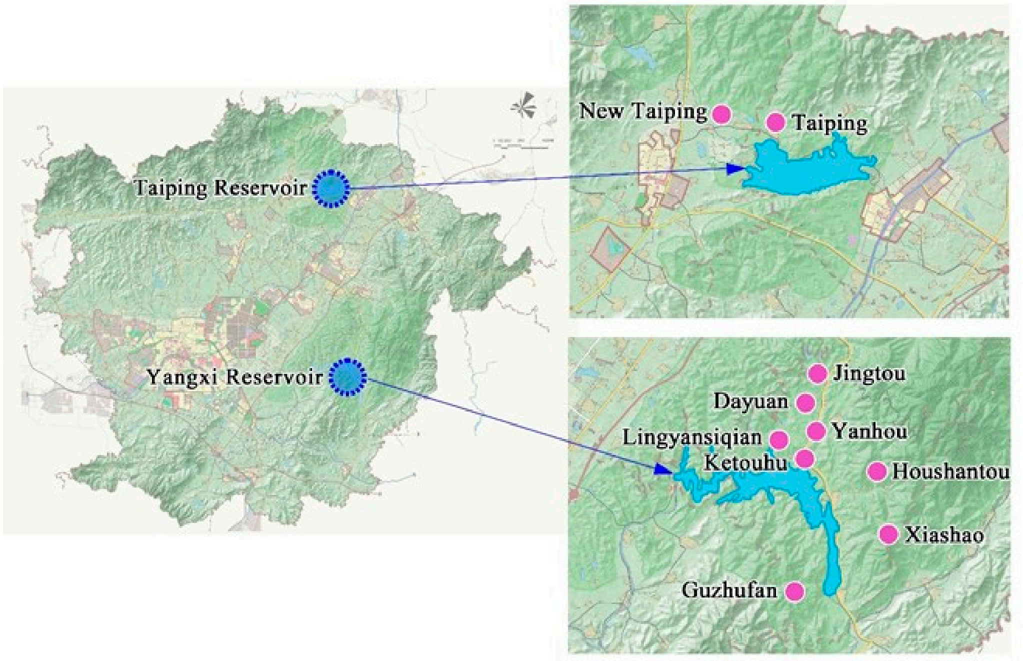


**Figure 2.** Spatial distribution of rural domestic sewage resource utilization stations.

**Table 1.** Design standards for sewage treatment in 10 study sites.

| Name | Type of Treatment Process | Design Discharge Standard * |
|---|---|---|
| HST | $A^2$/O-MBBR+ constructed wetland | First-level |
| XS | | |
| YH | | |
| LYSQ | | |
| KTH | | |
| JT | | |
| DY | | |
| GZF | | |
| NTP | $A^2$/O+ constructed wetland | Second-level |
| TPG | PKA constructed wetland | First-level |

Notes: * Discharge Standard of Zhejiang Province (DB33/973-2021): First-level (COD $\leq$ 60 mg/L, SS $\leq$ 20 mg/L, $NH_3$-N $\leq$ 15 mg/L, TN $\leq$ 15 mg/L, TP $\leq$ 2 mg/L, Coliform group $\leq$ 10,000 MPN/L); Second-level (COD $\leq$ 100 mg/L, SS $\leq$ 30 mg/L, $NH_3$-N $\leq$ 25 mg/L, TN $\leq$ 15 mg/L, TP $\leq$ 3 mg/L, Coliform group $\leq$ 10,000 MPN/L).

### *3.2. Current Situation of Domestic Sewage Quality*

The sewage type in the project area is mainly domestic sewage. According to the field investigation, some sewage treatment facilities near Yangxi Reservoir have overflow intakes and odors at outtakes, such as YH, HST and JT. Many biofilms grew in the ditches at the equipment outlet in DY. It indicates that the pollutant concentration is high at the equipment outlet. There was vinasse in the inlet well of XS. The constructed wetland of NTP is blocked, and the sewage treatment result is not good.

Since no water was taken from KTH, LYQS and GZF, water samples from the sewage treatment facilities of seven villages were collected and analysis. The test indexes include Chemical Oxygen Demand (COD), ammonia nitrogen ($NH_3$-N), total nitrogen (TN) and total phosphorus (TP), and the test results are shown in Table 2. According to the analysis of the test results, it was found that the treatment effect of HST is better. The water quality of the other study sites did not meet the design discharge standards. Removing nitrogen and phosphorus in the equipment is ineffective, especially the TP. Among them, the treatment equipment in DY has the lowest efficiency of pollutant removal and is ineffective. In addition, the concentration of pollutants in some treatment equipment is low at the water inlet. The test results showed that no sewage entered the treatment equipment in YH.

**Table 2.** Quality of incoming and outgoing water from sewage treatment facilities.

| | | COD (mg/L) | $NH_3$-N (mg/L) | TN (mg/L) | TP (mg/L) |
|---|---|---|---|---|---|
| JT | Inlet | 78.0 | 10.8 | 21.0 | 2.92 |
| | Outlet | 79.0 | 8.0 | 16.0 | 1.84 |
| DY | Inlet | 86.0 | 19.6 | 23.6 | 4.50 |
| | Outlet | 82.0 | 19.3 | 21.5 | 3.40 |
| YH | Inlet | 64.0 | 2.4 | 3.0 | 0.45 |
| | Outlet | 49.0 | 0.0 | 0.0 | 0.21 |
| HST | Inlet | 63.0 | 12.5 | 13.0 | 3.47 |
| | Outlet | 59.0 | 0.1 | 7.9 | 0.61 |
| XS | Inlet | 162.0 | 43.9 | 46.0 | 12.10 |
| | Outlet | 86.0 | 19.2 | 26.0 | 3.32 |
| NTP | Inlet | 79.0 | 11.4 | 12.8 | 3.58 |
| | Outlet | 73.0 | 7.2 | 7.4 | 1.15 |
| TP | Inlet | 134.0 | 15.2 | 22.9 | 4.99 |
| | Outlet | 59.0 | 0.0 | 6.0 | 2.73 |

## *3.3. Analysis of Main Treatment Technology and Treatment Effect*

### 3.3.1. Treatment Technology

The location of the sites belongs to the first-level protection area of the water source. The effluent quality of equipment must meet the discharge standard of First-level [35]. Therefore, in sites where the effluent quality does not meet the discharge standard or the effluent quality is unstable, the original treatment process is reformed. The reconstruction method is to replace the initially constructed wetland unit filling and install the skid-mounted equipment at all study sites. Skid-mounted equipment is a kind of equipment which can treat rural domestic sewage and use it safely. The purpose of installing skid-mounted equipment is to further remove phosphorus and nitrogen from tailing water. Therefore, it can improve the effluent quality of the facility and ensure the recycling and utilization of domestic sewage.

Rural domestic sewage is an essential resource of water and fertilizer. In the research on the resource utilization of rural domestic sewage combined with agriculture, the imbalance between sewage discharge and agricultural irrigation water demand should be fully considered. Farmland irrigation has obvious seasonal and non-continuous. The discharge of sewage is continuous. There is also a limit to how much tailwater a field can accept. Sewage that exceeds the self-purification capacity of farmland is discharged directly. It will cause secondary pollution of the surrounding environment. Therefore, the destination of sewage in both agricultural irrigation and non-irrigation periods should be considered. The treatment process is the realization unit of resource utilization in the irrigation period. In the non-irrigation period, sewage must be treated in depth, which can be used as an environmental risk control unit.

In this study, the effluent water quality index of the equipment should meet the Quality Standard for Farmland Irrigation Water (GB5084-2005) during the irrigation water period. The limits of main indexes are pH 5.5–8.5, COD $\leq$ 60 mg/L, SS $\leq$ 15 mg/L, Coliform group $\leq$ 20,000 MPN/L. In the non-irrigation period, reclaimed water is mainly used for landscape and ecological water supplements. Therefore, the quality index meets the Quality Standard of Landscape Water for Municipal Sewage Recycling (GB/T18921-2019). The limits of main indexes were pH 6.0–9.0, Turbidity $\leq$ 10 NTU, TP $\leq$ 0.5 mg/L, TN $\leq$ 15 mg/L, $NH_3$-N $\leq$ 5 mg/L, Coliform group $\leq$ 1000 MPN/L.

To make the domestic sewage after treatment can meet the water quality index requirements of rural domestic sewage utilization. This project uses a skid-mounted chemical device consisting of a biochemical reactor, a low-cost ceramic filter element, and an electrochemical UV disinfection. In addition, the equipment combines the characteristics of rural irrigation to achieve automation as much as possible and reduce management requirements. The technological process of skid-mounted equipment for the use of rural domestic sewage is shown in Figure 3. The skid-mounted equipment uses a self-priming pump to lift the treated irrigation water into the biochemical reactor unit. In the first unit of the equipment, raw water passes through a biofilm cultured with a fluidized bed packing and undergoes a biochemical reaction to remove contaminants. After removing SS and other pollutants through sand core filtration by a self-priming pump, the raw water is transferred to the second unit. The second unit, electrochemical and ultraviolet equipment, disinfected the water, and the supernatant was put into the storage tank. The stored water enters the front end of the irrigation system, and the effluent is pumped out through the pipe.

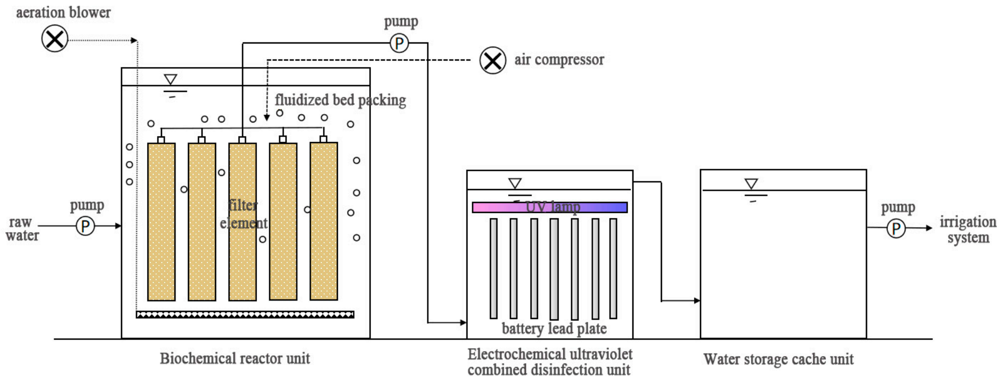


**Figure 3.** Rural domestic sewage treatment skid-mounted equipment.

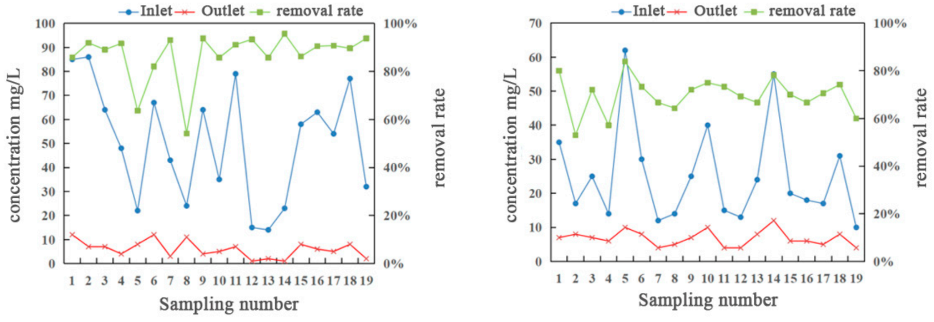
### 3.3.2. Analysis of Pollutant Treatment Effect

Water quality was sampled at ten sites after the installation of equipment. PH, SS, COD, and fecal coliform were detected during the irrigation period. The removal of pollutants by the equipment is shown in Figure 4 and Table 3. The water intake of the equipment comes from the tailwater of rural domestic sewage treatment facilities. The concentration of pollutants is not high. The pollutant concentration of the inlet water of the equipment fluctuates greatly. However, the concentration of the outlet water is not affected by the fluctuation of the inlet water concentration and always remains below the limit value. The equipment has a good performance in shock resistance. In the effluent treated by the equipment, all four indexes can meet the Quality Standards of Agricultural water (COD $\leq$ 60 mg/L, SS $\leq$ 15 mg/L, Coliform group $\leq$ 20,000 MPN/L lg20,000 = 4.3).

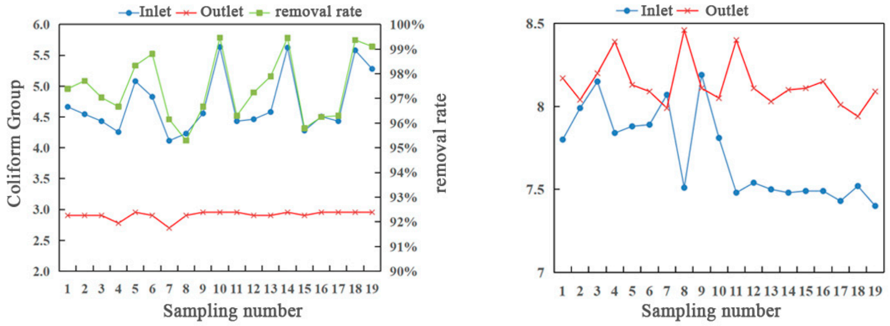
**Table 3.** Inlet and outlet water concentration and removal rate during the irrigation period.

| Index | Influent Concentration | Water Quality Regular Rate | Effluent Concentration | Removal Rate |
|---|---|---|---|---|
| COD (mg/L) | 50.2 | 57.9% | 5.9 | 86.7% |
| SS (mg/L) | 25.1 | 31.6% | 6.8 | 69.8% |
| Coliform group (MPN/L) | 103,736.8<br>lgN = 4.7 | 21.1% | 821.1<br>lgN = 2.9 | 97.7% |

The main indexes of water quality in the non-irrigation period were pH, Turbidity, TP, TN, $NH_3$-N and fecal coliform. Among them, pH and fecal coliform have been analyzed previously, and the results show that they can meet the standard in a non-irrigation period. The removal of pollutants by the equipment is shown in Figure 5 and Table 4. The pollutant concentration of the inlet water of the equipment also fluctuates greatly. However, the effluent concentration of the equipment is still unaffected by the intake pollutant concentration fluctuation, and the indexes always meet the standards. It also reflects that the equipment has the stability of effluent quality. All indexes of effluent treated by the equipment can meet the landscape standard (Turbidity ≤ 10 NTU, TP ≤ 0.5 mg/L, TN ≤ 15 mg/L, $NH_3$-N ≤ 5 mg/L).

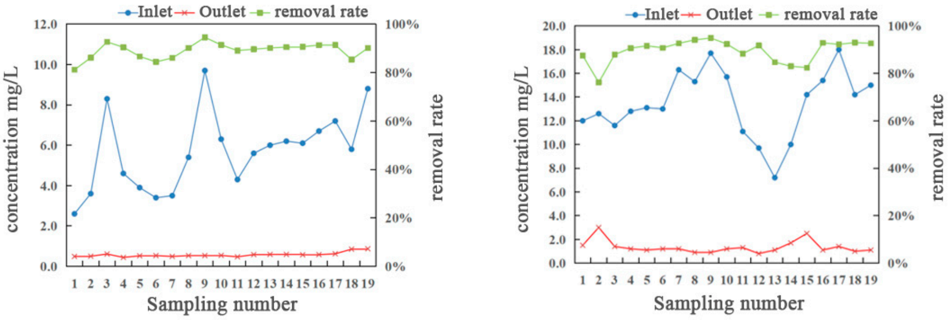


(a) COD (b) SS

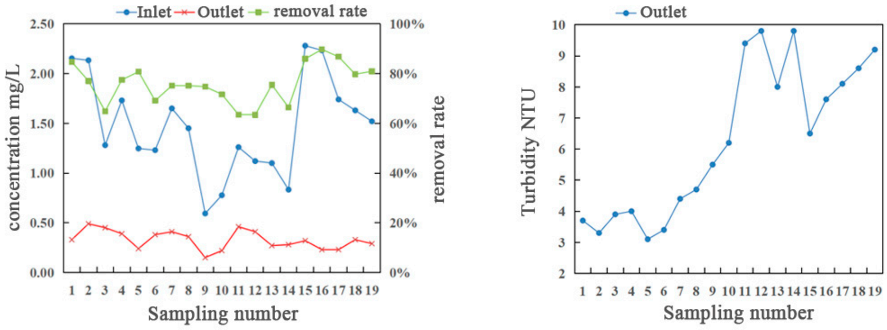


(c) Coliform Group (d) pH

**Figure 4.** Water inlet and outlet of skid-mounted equipment during irrigation period.



(a) TP (b) TN



(c) $NH_3$-H (d) Turbidity

**Figure 5.** Water inlet and outlet of skid-mounted equipment during the non-irrigation period.

**Table 4.** Inlet and outlet water concentration and removal rate during the non-irrigation period.

| Index | Influent Concentration | Water Quality Regular Rate | Effluent Concentration | Removal Rate |
|---|---|---|---|---|
| TP | 1.47 | 0% | 0.33 | 75.9% |
| TN | 13.4 | 78.9% | 1.3 | 89.4% |
| $NH_3$-N | 5.68 | 31.6% | 0.57 | 89.0% |

## 4. Benefit Assessment of Case

### *4.1. Environmental Benefits*

The total annual sewage output of 10 study sites in the project area is 251,900 t after monitoring and analysis. Suppose the generated sewage is discharged directly into the surrounding environment without treatment. In that case, it will pose a major threat to the two drinking water sources and seriously impact the water environment. After three years of operation, the collected domestic sewage is treated and reused in situ, which has a significant emission reduction effect and improves the rural living environment (as shown in Table 5). The project evaluation lasted for three years, and the average annual reduction of COD was 78.51 t, BOD 47.85 t, $NH_3$-N 5.62 t and TP 0.39 t. In addition, the use of reclaimed water has also played a water-saving effect, saving 251,900 tons of water annually. With the continuous improvement of the living environment, the overall water environment improvement effect of the 10 study sites will be further demonstrated.

**Table 5.** Reduction of pollutants after treatment of rural domestic sewage.

| Name | Volume ($m^3$/d) | Reduction of Pollutants (t) | | | |
|---|---|---|---|---|---|
| | | COD | BOD | $NH_3$-N | TP |
| HST | 120 | 12.70 | 8.32 | 0.66 | 0.044 |
| XS | 30 | 3.18 | 2.08 | 0.16 | 0.011 |
| YH | 60 | 6.35 | 4.16 | 0.33 | 0.022 |
| LYQS | 20 | 2.12 | 1.39 | 0.11 | 0.007 |
| KTH | 40 | 4.23 | 2.77 | 0.22 | 0.015 |
| JT | 20 | 2.12 | 1.39 | 0.11 | 0.007 |
| DY | 90 | 9.53 | 6.24 | 0.49 | 0.033 |
| GZF | 60 | 6.35 | 4.16 | 0.33 | 0.022 |
| NTP | 100 | 12.78 | 6.94 | 0.91 | 0.037 |
| TPG | 150 | 19.16 | 10.40 | 2.30 | 0.192 |
| Total (Annual) | 251,900 | 78.51 | 47.85 | 5.62 | 0.389 |

### *4.2. Carbon Reduction Benefits*

The links involving carbon emission in the social water cycle can be summarized as the water intake process, water supply process, water use process, drainage process and reclaimed water utilization process. The carbon emission reduction benefit of the project is mainly using the reclaimed water for agricultural irrigation, thereby reducing the freshwater consumption and associated carbon emissions in the study area. In this paper, two scenario models, namely conventional and renewable water resources utilization, are set for carbon emission calculation and comparison to evaluate rural sewage resource utilisation's carbon emission reduction benefits.

(1) Conventional water resources utilization

The water sources of the sites are Yangxi Reservoir and Taiping Reservoir. Carbon emissions during the water intake process include reservoir and water lifting. The formula for calculating carbon emissions generated by water supply in surface water storage projects is as follows [36]:

$$C_I = Q \cdot (W_S + W_L) \cdot EF_{CO_2} \quad (1)$$

where, $C_I$ is the carbon emission of water supply in the reservoir, kg; $Q$ is water quantity, m$^3$; $W_S$, $W_L$ are the energy consumption intensities during the reservoir impoundment and water lifting processes, respectively, kWh/m$^3$; $EF_{CO_2}$ is the carbon emission coefficient of electric power. Yongkang City is located in the East China region of China. According to the data from State Grid, the value is 0.7921 kg/kWh.

The water supply process can include the water treatment process at the water plant (i.e., turning raw water into tap water) and the distribution process. Therefore, $C_S$ of carbon emissions produced in the water supply process can be calculated as follows:

$$C_S = Q \cdot (W_p + W_d) \cdot EF_{CO_2} \tag{2}$$

where, $W_p$, $W_d$ are the energy consumption intensities during the water treatment and the distribution processes, respectively, kWh/m$^3$.

The main process generating carbon emissions during drainage is the collection, treatment, and discharge of wastewater. Similarly, the carbon emissions generated during the water supply process $C_T$ calculated as follows:

$$C_T = Q \cdot W_T \cdot EF_{CO_2} \tag{3}$$

where, $W_T$ is the energy consumption intensities during the drainage process, kWh/m$^3$.

Based on the water usage data and energy intensity information associated with the activities involved (as shown in Table 6), we can calculate the carbon emissions from the conventional water utilization process.

**Table 6.** Energy used for the water social cycle in China.

| **Sub-Industry** | **Activity** | **Energy Intensity (kWh/m$^3$)** | **Source** |
|---|---|---|---|
| raw freshwater collection & extraction | raw freshwater collection | 0.14 | Sun et al., 2015 [37]; Huang et al., 2015 [38] |
| | raw freshwater extraction | 0.2 | Hu et al., 2013 [39] |
| tap water treatment & supply | tap water treatment | 0.31 | China Urban Water Association, 2015 |
| | Tap water supply | 0.2 | China Urban Water Association, 2015 |
| wastewater treatment & supply | wastewater collection, treatment & discharge | 0.6 | Hu et al., 2013 [39] |

(2) Renewable water resources utilization

The carbon emissions of the reclaimed water utilization process of the project mainly include the energy consumed in the treatment process of sewage resource utilization equipment and the transportation process of the reclaimed water pipe network. Considering that the reclaimed water in the project is generally used in nearby fields, the carbon emissions generated by the pipeline network transportation are negligible. Therefore, the carbon emissions in the process of reclaimed water use are calculated as follows:

$$C_R = Q \cdot W_R \cdot EF_{CO_2} \tag{4}$$

In the formula, the $W_R$ the energy intensity of the sewage resource treatment process is the energy intensity of the rural domestic sewage resource utilization equipment. According to the analysis of energy consumption and design water quantity, the value is 0.778 kWh/m$^3$.

According to the carbon emission accounting analysis process and calculation formula, the carbon emissions under different scenarios are calculated. As seen above, the annual output of sewage is 251,900 tons. The carbon emission results of utilizing 251,900 tons of raw freshwater for irrigation under conventional water resources utilization scenarios and utilizing 251,900 tons of reclaimed water for farmland irrigation under unconventional water resources utilization scenarios are compared in Table 7. It can be seen from the table that the carbon emission reduction benefits brought by the utilization of sewage resources in the case are apparent. The study area reduces $CO_2$ emissions by about 134 tons a year. For the conventional water utilization scenarios, the carbon emission reduction benefit of unconventional water resources can reach 46.34%.

**Table 7.** Comparison of carbon emission results.

| Scenarios | Sub-Industry | Water Volume (t) | Carbon Emission Coefficient (kg/kWh) | Carbon Emission (kg) |
|---|---|---|---|---|
| Conventional water resources utilization | water intake | 251,900 | 0.7921 | 67,840.2 |
| | water supply | | | 101,760.3 |
| | drainage | | | 119,718.0 |
| | Total | | | 289,318.5 |
| Renewable water resources utilization | reclaimed water | 251,900 | 0.7921 | 155,234.3 |
| | Total | | | 155,234.3 |

### 4.3. Socio-Economic Benefit

The construction and maintenance costs of rural wastewater resource utilization equipment are not high. The cost comparison for the four resource utilization models discussed in Section 2.2 is presented in Table 8. The coupling of pollutant treatment and economical crop mode and the following water quality requirements mode can utilize treated wastewater for irrigation while meeting the standard discharge requirements. On the other hand, the wastewater irrigation mode or the black and grey water separation mode is limited to reuse in agricultural fields. Regarding construction costs, the water quality requirements mode is the highest, while the black and grey water separation mode has the lowest price.

**Table 8.** Cost comparison of different rural sewage resource utilization modes [28].

| Mode | Construction (10,000 yuan/t) | Maintenance (yuan/t) | |
|---|---|---|---|
| coupling of pollutant treatment and economical crop | 1 | 0.18 | |
| wastewater irrigation | 1.2 | 0.1 | |
| following the water quality requirements | 1.6 | 0.3 | |
| black and grey water separation | 0.55 | black water (transportation): | 65 yuan/time |
| | | grey water: | 0.1 |

Note: Taking a 10 t/d sewage treatment equipment as an example.

Regarding maintenance costs, the water quality requirements mode has the highest cost, while the wastewater irrigation mode has the lowest cost. In the eastern region of China, the average construction cost for a centralized Sewage Treatment Plant meeting first-level standards is 1.53 yuan/ton, and the operating and maintenance cost is 1.5 yuan/ton [40]. Compared with centralized Sewage Treatment plants, decentralized resource utilization equipment costs are even more affordable. This project belongs to the following water quality requirements mode. Although it has the highest construction and maintenance costs among all modes, it occupies the smallest land area. Therefore, it incurs almost no additional costs (such as land use fees or compensation fees). In addition, this mode is convenient for transportation, flexible in installation, and suitable for use in rural areas. In summary, the most suitable and cost-effective investment mode in the study sites is the following the water quality requirements mode.

Beyond the low treatment cost, what's more important is that rural domestic sewage supply is mainly unaffected by climatic factors and exhibits minimal variations in water quality. Through intensive treatment, management, and maintenance, it can be considered an unconventional water source with a large quantity and stable quality. On the one hand, utilizing recycled wastewater can reduce the extraction and use of fresh water, alleviate regional water supply-demand conflicts, and lower water treatment costs. On the other hand, organic nutrients such as nitrogen and phosphorus in treated wastewater can provide plants and crops with nutrient supplementation, promote crop yield, and result in highly efficient adjustments in agricultural industry structure.

With the promotion of rural domestic sewage resource utilization projects, the integration of rural domestic sewage resource utilization and the construction of beautiful countryside will significantly improve rural production and living conditions, guarantee farmers' physical and mental health, and promote the transformation of their ways of life. Furthermore, by raising farmers' awareness of water conservation and environmental protection, the construction of ecological civilization will be transformed from passive behavior to the conscious actions of farmers.

## 5. Conclusions and Recommendations

Tailored solutions that consider the rural ecological environment are needed to treat rural domestic sewage. This will achieve a virtuous cycle of pollution control and resource utilization while addressing local conditions. After proper treatment, the resource utilization of rural domestic sewage can reduce the investment in sewage treatment and recover agricultural water resources and nitrogen and phosphorus substances. By fully using rural land resources and the purification capacity of the water environment, the win-win situation of pollution control and nutrient utilization can be achieved under the premise of an acceptable rural ecological environment. Amid the urgent need to improve the rural living environment, the resource utilization of rural domestic sewage will be a powerful measure for the sustainable use of water resources.

This article takes 10 study sites in Yongkang City, Zhejiang Province, as an example, which collect domestic sewage and carry out deep treatment for agricultural irrigation and road greening, thus substituting more natural high-quality water resources to ensure residents' lives. Based on the current low utilization rate of rural domestic sewage resources in China, analysis and evaluation were conducted on the resource utilization mode, related treatment equipment, treatment effectiveness, and generated benefits of rural domestic sewage resource utilization. The results indicate that by simply retrofitting existing sewage facilities with compact, low-cost, and highly automated modular equipment for advanced treatment, the treated effluent quality can meet reuse requirements and maintain stable water quality. The project has cumulatively saved 251,900 tons of high-quality water resources, reduced COD by 78.51 tons, and achieved reductions of 5.62 tons and 0.39 tons for $NH_3$-N and TP, respectively. In addition, the carbon emission reduction equivalent exceeds 134 tons, achieving significant comprehensive benefits in terms of "water conservation, emission reduction, and carbon reduction".

Against the backdrop of the national promotion of sewage resource utilization, Zhejiang Province should take the opportunity of pilot construction and, based on the existing layout of sewage facilities, introduce new technologies to replace traditional processes and improve the effectiveness of rural domestic sewage treatment. Zhejiang Province also should, based on local conditions, adopt different models for each natural village according to their unique characteristics and water quality standards. Furthermore, priority should be given to selecting treatment technologies that offer high cost-effectiveness and can effectively resolve the simple transformation mode. To promote comprehensive coverage, Zhejiang Province aims to increase the utilization rate of domestic sewage resources and actively explore the establishment of demonstration points for agricultural pollution control to effectively transform the inherent impression of 'dirty, disorderly, and poor' associated with agricultural pollution, showcasing a new and unique rural landscape.

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## References

1. Zheng, T.; Xiong, R.; Li, W.; Wu, W.; Ma, Y.; Li, P.; Guo, X. An enhanced rural anoxic/oxic biological contact oxidation process with air-lift reflux technique to strengthen total nitrogen removal and reduce sludge generation. *J. Clean. Prod.* **2022**, *348*, 131371. [CrossRef]
2. Jia, X.M.; Yu, Q.; Wang, W.Y.; Zhao, F.; Dong, X.H. Considerations for rural domestic sewage treatment during the 14th Five-Year Plan. *J. Agric. Resour. Environ.* **2020**, *37*, 623–626.
3. Bo, Y.; Wen, W. Treatment and technology of domestic sewage for improvement of rural environment in China. *J. King Saud Univ.-Sci.* **2022**, *34*, 102181. [CrossRef]
4. Zhang, R.; Lu, C.C.; Lee, J.H.; Feng, Y.; Chiu, Y.H. Dynamic environmental efficiency assessment of industrial water pollution. *Sustainability* **2019**, *11*, 3053. [CrossRef]
5. Li, X.; Huang, S.; Shi, W.; Lin, Q. Efficiency Calculation and Evaluation of Environmental Governance Using the Theory of Production, Life, and Ecology Based on Panel Data from 27 Provinces in China from 2003 to 2020. *Systems* **2023**, *11*, 174. [CrossRef]
6. Capodaglio, A.G.; Olsson, G. Energy issues in sustainable urban wastewater management: Use, demand reduction and recovery in the urban water cycle. *Sustainability* **2019**, *12*, 266. [CrossRef]
7. Li, Q.; Wang, F.; Wang, Y.; Zhou, C.; Chen, J.; Forson, K.; Miao, R.; Su, Y.; Zhang, J. Effect of reservoir characteristics and chemicals on filtration property of water-based drilling fluid in unconventional reservoir and mechanism disclosure. *Environ. Sci. Pollut. Res.* **2023**, *30*, 55034–55043. [CrossRef]
8. Li, Q.; Wu, J. Factors affecting the lower limit of the safe mud weight window for drilling operation in hydrate-bearing sediments in the Northern South China Sea. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2022**, *8*, 82. [CrossRef]
9. Li, Q.; Wang, F.; Wang, Y.; Bai, B.; Zhang, J.; Lili, C.; Sun, Q.; Wang, Y.; Forson, K. Adsorption behavior and mechanism analysis of siloxane thickener for $CO_2$ fracturing fluid on shallow shale soil. *J. Mol. Liq.* **2023**, *376*, 121394. [CrossRef]
10. Chen, P.; Zhao, W.; Chen, D.; Huang, Z.; Zhang, C.; Zheng, X. Research Progress on Integrated Treatment Technologies of Rural Domestic Sewage: A Review. *Water* **2022**, *14*, 2439. [CrossRef]
11. Li, L.; Liu, X.; Zhang, X. Public attention and sentiment of recycled water: Evidence from social media text mining in China. *J. Clean. Prod.* **2021**, *303*, 126814. [CrossRef]
12. Liu, D.; Zou, C.; Xu, M. Environmental, ecological, and economic benefits of biofuel production using a constructed wetland: A case study in China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 827. [CrossRef] [PubMed]
13. Xu, W.; Liu, Z. Evaluation on the Current Situation of Integrated Treatment of Rural Sewage in China: A Case Study of Anhui Province. *Water* **2023**, *15*, 415. [CrossRef]
14. Xiao, M.; Li, Y. Distribution Characteristics and Ecological Risk Assessment of Heavy Metals under Reclaimed Water Irrigation and Water Level Regulations in Paddy Field. *Pol. J. Environ. Stud.* **2022**, *31*, 2355–2365. [CrossRef]
15. Wei, Y.; Zhang, A.; Ma, Y. A Bibliometric Review of Rural Living Environment Improvement Research in China Based on CNKI Database: 1992–2022. *Sustainability* **2023**, *15*, 6561. [CrossRef]
16. Huang, J.; Wen, X.; Tang, Q.; Liu, D.; Chen, S. An Innovative Waterwheel-Rotating Biological Contactor (WRBC) System for Rural Sewage Treatment. *Water* **2023**, *15*, 1323. [CrossRef]
17. Li, S.; Li, H.; Liang, X.; Chen, Y.; Cao, Z.; Xu, Z. Rural wastewater irrigation and nitrogen removal by the paddy wetland system in the Tai Lake region of China. *J. Soils Sediments* **2009**, *9*, 433–442. [CrossRef]
18. Xu, M.; Bai, X.; Pei, L.; Pan, H. A research on application of water treatment technology for reclaimed water irrigation. *Int. J. Hydrog. Energy* **2016**, *41*, 15930–15937. [CrossRef]
19. Hussain, A.; Alamzeb, S.; Begum, S. Accumulation of heavy metals in edible parts of vegetables irrigated with water and their daily intake to adults and children, District Mardan, Pakistan. *Food Chem.* **2013**, *136*, 1515–1523.
20. Travis, M.J.; Wiel-Shafran, A.; Weisbrod, N.; Adar, E.; Gross, A. Greywater reuse for irrigation: Effect on soil properties. *Sci. Total Environ.* **2010**, *408*, 2501–2508. [CrossRef]
21. Mojid, M.A.; Wyseure, G. Implications of municipal wastewater irrigation on soil health from a study in Bangladesh. *Soil Use Manag.* **2013**, *29*, 384–396. [CrossRef]
22. Parsons, L.R.; Sheikh, B.; Holden, R.; York, D.W. Reclaimed water as an alternative water source for crop irrigation. *HortScience* **2010**, *45*, 1626–1629. [CrossRef]

23. Mounzer, O.; Pedrero-Salcedo, F.; Nortes, P.A.; Bayona, J.M.; Nicolas-Nicolas, E.; Alarcón, J.J. Transient soil salinity under the combined effect of reclaimed water and regulated deficit drip irrigation of Mandarin trees. *Agric. Water Manag.* **2013**, *120*, 23–29. [CrossRef]
24. Wang, S.; Teng, Y.; Cheng, F.; Lu, X. Application Potential of Constructed Wetlands on Different Operation Mode for Biologically Pre-Treatment of Rural Domestic Wastewater. *Sustainability* **2023**, *15*, 1799. [CrossRef]
25. Wang, Z.; Li, J.; Li, Y. Using reclaimed water for agricultural and landscape irrigation in China: A review. *Irrig. Drain.* **2017**, *66*, 672–686. [CrossRef]
26. Yi, L.; Jiao, W.; Chen, X.; Chen, W. An overview of reclaimed water reuse in China. *J. Environ. Sci.* **2011**, *23*, 1585–1593. [CrossRef]
27. Kanaujiya, D.K.; Paul, T.; Sinharoy, A.; Pakshirajan, K. Biological treatment processes for the removal of organic micropollutants from wastewater: A review. *Curr. Pollut. Rep.* **2019**, *5*, 112–128. [CrossRef]
28. Dong, L.; Zhang, W.; Bai, L.; Xu, C.; Wang, G. Analysis on current situation and model of resource utilization of rural sewage in China. *J. Environ. Eng. Technol.* **2022**, *12*, 2089–2094. (In Chinese)
29. Zhu, Z.; Dou, J. Current status of reclaimed water in China: An overview. *J. Water Reuse Desalination* **2018**, *8*, 293–307. [CrossRef]
30. Xiao, M.; Li, Y.; Zheng, S.; Wang, L.; Cai, J.; Wang, W. Effect of rural domestic sewage regeneration irrigation on paddy soil properties and water and nitrogen utilization in southern China. *Irrig. Drain.* **2023**, *72*, 515–529. [CrossRef]
31. Zheng, F.; Wang, J.; Xiao, R.; Chai, W.; Xing, D.; Lu, H. Dissolved organic nitrogen in wastewater treatment processes: Transformation, biosynthesis and ecological impacts. *Environ. Pollut.* **2021**, *273*, 116436. [CrossRef] [PubMed]
32. Lin, Q.; Luo, A.; Zhang, Y.; Wang, Y.; Liang, Z.; Yuan, P. Employing Artificial Neural Networks to Predict the Performance of Domestic Sewage Treatment Terminals in the Rural Region. *Math. Probl. Eng.* **2021**, *2021*, 5264531. [CrossRef]
33. Liu, Y.; Zhu, J.; Huo, R.; Tian, Z.; Yang, G.; Jin, Y. Current situation and problems of rural domestic sewage discharge in Hebei Province. *Rural Econ. Sci. Technol.* **2020**, *31*, 32–36. (In Chinese)
34. Zhang, C.; Jin, Z.; Zhao, X.; Gu, W. Suggestions on Resource Utilization of Rural Domestic Sewage in Mountainous and Semi-mountainous Area of Yunnan Province. *J. Environ. Sci.* **2002**, *41*, 32–36. (In Chinese)
35. *GB18918-2002*; Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant. NSPRC. National Standards of the People's Republic of China: Beijing, China, 2002. Available online: https://www.ecolex.org/details/legislation/discharge-standard-of-pollutants-for-municipal-wastewater-treatment-plant-national-standard-gb-18918-2002-lex-faoc136765/ (accessed on 1 July 2003).
36. Xiang, X.; Jia, S. China's water-energy nexus: Assessment of water-related energy use. *Resour. Conserv. Recycl.* **2019**, *144*, 32–38. [CrossRef]
37. Sun, P.; Lin, N.; Mao, Z. Energy saving assessment of Huangzangsi Water Control Project. *Henan Water Conserv. South-North Water Transf* **2015**, *20*, 61–62. (In Chinese)
38. Huang, H.; Wang, N.; Dong, H. Study on environmental impact from substituting plain reservoirs with Hangzangsi Water Control Project. *Water Resour. Hydropower Eng* **2015**, *46*, 77–80. (In Chinese)
39. Hu, G.; Ou, X.; Zhang, Q.; Karplus, V.J. Analysis on energy–water nexus by Sankey diagram: The case of Beijing. *Desalination Water Treat.* **2013**, *51*, 4183–4193. [CrossRef]
40. Tan, X.; Shi, L.; Ma, Z.; Zhang, X.; Lu, G. Institutional analysis of sewage treatment charge based on operating cost of sewage treatment plant—An empirical research of 227 samples in China. *China Environ. Sci.* **2015**, *35*, 3833–3840. (In Chinese)