PERFORMANCE AND CARBON EMISSION ANALYSIS OF DECENTRALIZED INTEGRATED WASTEWATER TREATMENT SYSTEMS AROUND THE FAIRY LAKE, CHINA

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Abstract. As a prominent shortcoming of agricultural and rural pollution control, rural sewage treatment faces issues such as poor treatment effects and insufficient maintenance funds. In this study, an innovative household integrated ecological purification system (HIEPS) was developed. This technology integrated solar photovoltaic power generation technology and ecological treatment technology. HIEPS has been applied successfully in a rural decentralized wastewater treatment project near Fairy Lake, in Jiangxi Province, China for more than one year. The comprehensive analysis indicated that the HIEPS had excellent treatment and stability performance, with average removal efficiencies of 88.03%, 88.49%, 84.75%, 69.44%, and 82.85% for chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (NH_3N), total phosphorus (TP) and suspended solids (SS), respectively. There were no statistically significant differences in treatment efficiency and effluent concentration in different seasons, suggesting that the HIEPS could adapt to variations in ambient temperatures to maintain a stable treatment effect. In addition, the analysis of the operational benefits showed that the HIEPS remarkably reduced operational costs and contributed to carbon emission reduction.

Keywords: *rural area, decentralized treatment, domestic sewage, removal efficiency, carbon calculation*

Introduction

Due to rapid social economic development, the living standard in rural areas has been rising every year, and the lifestyle of the residents has changed dramatically. Concomitantly, per capita domestic water consumption and sewage discharge have increased each year (Fernandez et al., 2019). Untreated domestic sewage discharged into neighboring lakes and rivers or seeping into the subsoil, becoming a dominant pollution source of rural water bodies, which seriously threatens the rural ecological water environment and the health of the population (Li et al., 2024). Despite the positive progress that has been achieved in rural sewage treatment in recent years, there were still obvious problems such as low treatment rates and high operating costs (Zhang et al., 2024a). Therefore, to comprehensively promote the improvement of rural human settlements and the construction of beautiful villages, it is necessary to further advance the treatment of rural domestic sewage.

Rural wastewater is characterized by small water volume from a single household, dispersed discharge, and complex water quality. The centralized sewage treatment pattern requires the construction of costly sewage collection networks, and its long-term operation and maintenance also are a serious challenge (Hendy et al., 2023). However, the decentralized sewage treatment pattern is a low-energy treatment method that is suitable for the scattered distribution of emission sources (Zhao et al., 2024). Decentralized wastewater treatment equipment is independent of each other within a

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certain area and is collected and treated locally. It is suitable for rural areas with dispersed settlements, poor economic levels, low population densities, and complex topographical conditions (Hendy et al., 2023; Liu et al., 2024a). Based on the characteristics of domestic wastewater in rural areas and the status of wastewater management, a series of decentralized treatment technologies have emerged, such as constructed wetlands, oxidation ponds, and land-fast percolation ponds. Among, constructed wetlands as a sustainable, low-energy, and environmentally friendly treatment technology, it is favored for domestic wastewater treatment worldwide, but it has the problems of large floor areas and weak treatment efficiency (Sellami et al., 2009; Chen et al., 2022). In addition, integrated wastewater treatment facilities, such as johkasou, also have been widely used for decentralized rural wastewater treatment, especially in Japan, but their efficiency in treating nitrogen and phosphorus pollutants is poor (Nakagawa et al., 2007; Roosmini et al., 2018; Thakur and Medhi, 2019).

In recent years, with the global rise in awareness regarding carbon neutrality, wastewater treatment in rural areas is increasingly oriented towards energy conservation, emission reduction, low-carbon output, and resource utilization (Jiao et al., 2024). Solar photovoltaic technology emerges as an economical and low-carbon approach to energy supply. The adoption of solar photovoltaic power supply in rural wastewater treatment practice represents a sustainable and long-lasting development direction (Yang et al., 2024). There is a growing urgency to highlight the synergistic use of solar photovoltaic power generation with rural decentralized wastewater treatment systems.

Therefore, an attempt in this paper has been made to integrate constructed wetlands technology and solar power generation technology to form a household integrated ecological purification system (HIEPS) for treating rural domestic wastewater. This integrated wastewater treatment equipment possessed the advantages of ecological treatment technology and traditional biological treatment technology. Besides, solar photovoltaic technology is utilized to achieve low-carbon operation of wastewater treatment facilities. This coupling process of HIEPS has high treatment efficiency, a small footprint, low operating costs, and simple management. Moreover, to control domestic sewage surface pollution, the HIEPS technology was applied to the rural areas around Fairy Lake in Jiangxi province, China. HIEPS was also awarded the registration certificate of scientific and technological achievements of the Jiangxi Province (Registration No. Y20230331).

Currently, some of the existing rural wastewater treatment facilities are not operating satisfactorily due to problems such as substandard technology, poor supervision, and lack of operating budgets. The phenomenon of emphasizing construction and neglecting operation has occurred frequently. Furthermore, some studies exist that have focused on the impacts of rural domestic sewage discharge on ecosystems, as well as on sewage treatment technologies. The studies on the operation and maintenance of rural wastewater treatment facilities have been overlooked (Liu et al., 2024a). Therefore, it is necessary to investigate and evaluate the operational status of the HIEPS facilities at Fairy Lake to study on-site treatment performance and guarantee the sustainable operation of these facilities efficiently.

In this paper, the process mechanism and performance benefits of HIEPS were discussed. 14 sets of HIEPS facilities in the Fairy Lake wastewater treatment project were selected as research samples to study their operation status and treatment efficiency. The impact of environmental temperature and geographical characteristics on the operation and treatment effect of HIEPS was analyzed and studied comprehensively. In addition, the economic benefits and carbon emissions of HIEPS were analyzed and accounted. This paper systematically analyzed the scientific, feasible, and economical of the HIEPS in practical operation and application. This work can provide an engineering reference for other similar rural sewage treatment projects.

Materials and methods

Site description

Fairy Lake located in the southwest suburb of Jiangxi Province, China, is the earliest developed lake-type scenic spot in Jiangxi Province, with a water area of 50 square kilometers. There are 21 village committees and 233 village groups around Fairy Lake. A large amount of domestic sewage from residents is discharged directly or indirectly into the lake without reasonable treatment, which leads to the deterioration of water quality and affects human health and the ecological environment. In addition, chemical fertilizers and pesticides used in agricultural activities are one of the important sources of pollutants in lakes. These chemicals flow into lakes with rainwater or irrigation water, causing eutrophication of water bodies and disrupting the ecological balance of lakes (Ruan et al., 2024). The water quality of Fairy Lake showed a significant decline after 2016. Therefore, there is an urgent need to build comprehensive rural domestic sewage collection and treatment facilities to reduce surface source discharges of sewage. HIEPS was applied to projects of the decentralized rural sewage treatment at Fairy Lake. The project involves domestic sewage treatment terminal facilities for 6 village groups in 2 administrative villages near Fairy Lake, covering 154 households and serving a population of 476. These two villages were named Taqian Village and Huangtian Village, and were abbreviated as S1 and S2, respectively.

Process introduction

The wastewater treatment volume range of HIEPS is 0.5 m^3/d to 1.0 m^3/d, with a specification size of 2.0 m x 1.0 m x 0.75 m, and a floor space of about 2 m^2. The HIEPS is equipped with an anaerobic zone, an aerobic zone, an anoxic zone, a fine filtration zone, a nitrification solution reflux system, and a solar aeration system (*Figure 1*). The submerged spherical filler is made of polyvinyl chloride (PVC) with a diameter of 50 mm. The filtration system is compiled with new fiber materials, with a filter pore size of less than 10 um. The reflux unit consists of a quantitative peristaltic pump and a reflux tube. The solar supply unit consists of two 100 W solar panels and one 12V100A.h battery. The accompanying battery has a life of five days and provides power for the operation of the sewage lift pumps and aeration fans.

The sewage first passes through a basket grille to separate out the larger solid impurities and then enters the anaerobic zone, where the anaerobic microorganisms attached to the suspended spherical filler are used to initially degrade organic matter. The core microorganisms in the anaerobic zone of wastewater treatment are acidogenic bacteria and methanogens. Subsequently, the wastewater enters the bio-aerobic zone, which is divided into a plant uptake zone at the top and an aerobic zone at the bottom. The removal of pollutants is achieved by the interaction of aerobic microorganisms and plant root uptake. The aerobic zone primarily harbors heterotrophic and autotrophic bacteria, including autotrophic nitrifying bacteria, ammonium-oxidizing bacteria, and nitrite-oxidizing bacteria. Afterward, the effluent flows into the anoxic zone, in which the nitrification solution passes through the return system to the forward anaerobic zone. This measure strengthens the biological nitrogen removal. Finally, through the overflow port, the wastewater is discharged from the bottom outlet after entering the fine filtration zone. Among other things, the Fiber filter cloth in the fine filtration zone can filter out small suspended particles in the wastewater.

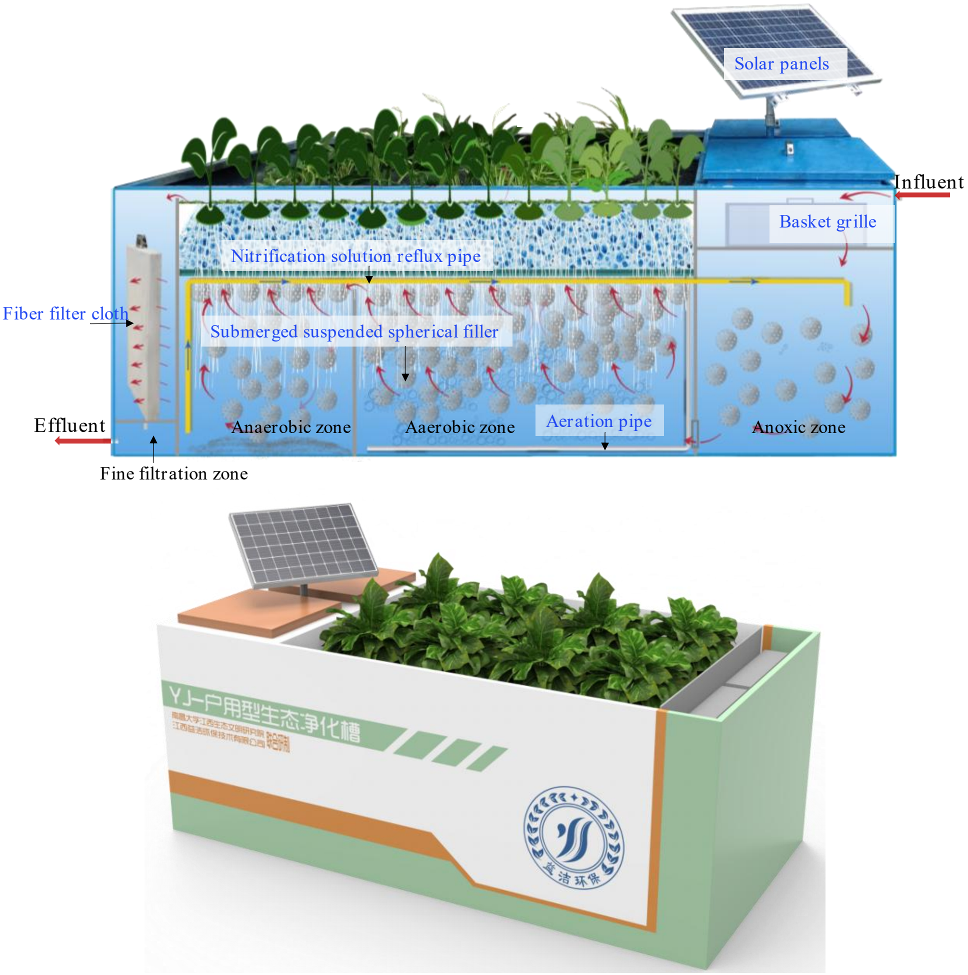

__Figure 1.__ The process principle diagram and physical model diagram of HIEPS

The HIEPS system employed in this study adopts a standardized design in both its treatment process and core components. Specifically, the plant absorption zone uniformly cultivates typical aquatic plants adapted to the local climate, including reeds and cattails. These plants not only directly absorb pollutants such as nitrogen and phosphorus from the water body, but their extensive root systems also provide a favorable interface for microbial growth. All HIEPS units studied exhibit high structural similarity in their core design. Each unit is internally filled with suspension spherical packing and fiber filter cloth of corresponding specifications, powered by solar photovoltaic systems during operation. Despite variations in external conditions such as geographical location, number of households served, and influent water quality, this standardized design philosophy aims to evaluate the adaptability and stability of HIEPS technology across diverse practical environments.

Monitoring methods and data analysis

In this study, 14 sets of HIEPS were selected as research samples to specifically analyze the treatment efficiency and operational performance, of which 9 and 5 were selected from village S1 and village S2, respectively. Since the commissioning of the HIEPS in July 2023, influent and effluent have been monitored quarterly to continuously track the effluent treatment effectiveness and stability. Thus, from June 2023 to October 2024, a total of six water quality monitoring sessions were conducted during the summer, autumn, and winter of 2023 and the spring, summer, and autumn of 2024. The monitoring items included six indicators: total phosphorus (TP), ammonia nitrogen (NH_3N), chemical oxygen demand (COD), total nitrogen (TN), suspended solids (SS), and pH.

According to the requirements of the local government, effluent discharge requirements for the implementation of Jiangxi Province's “discharge standards of pollutants for rural domestic sewage treatment Facilities” (DB36/ 1102-2019), and reaching first-degree wastewater discharge standards (*Table 1 and Table 2*). To ensure the reproducibility of the research process and the accuracy of the results, this thesis employed the following professional software for data processing, analysis, and visualization. Raw data entry, organization, and preliminary calculations were completed in Microsoft Excel 2021. All figures and charts in the thesis, including box plots of data distribution and bar charts of removal efficiency, were plotted and enhanced using OriginLab Origin 2023 software. The monitoring data were analyzed by one-way ANOVA using SPSS 22 to determine whether different geographic regions and climatic temperatures affect effluent water quality pollutant concentrations.

Table 1. *Effluent quality discharge standard limits and water quality monitoring methods*

Wastewater Quality Indicator	Emission standards	Monitoring Methods
COD	60mg/L	Water quality determination of the chemical oxygen demand: dichromate
TN	20mg/L	Alkaline potassium persulfate digestion by ultraviolet spectrophotometry
NH_3N	8(15)*mg/L	Water quality determination of ammonia nitrogen: Nessler’s reagent spectrophotometry
TP	1mg/L	Water quality determination of the total phosphorus: ammonium
SS	20mg/L	Water quality determination of suspended solids: weight method
pH	6-9	Water quality determination of pH: electrode method

*The value outside parentheses is the control emission for water temperatures greater than 12°C, and the value in parentheses is the control emission for water temperatures less than 12°C

Carbon emission calculation

There are two types of carbon emissions from wastewater treatment systems: direct carbon emissions and indirect carbon emissions. Direct carbon emissions originate from greenhouse gases produced by biochemical reactions during the wastewater treatment process, mainly including methane (CH_4) and nitrous oxide (N_2O). The carbon dioxide (CO_2) from biochemical reactions in wastewater treatment processes is generally considered a biological source and is not included in the IPCC greenhouse gases emissions inventory (Wang et al., 2024). In carbon emissions accounting for wastewater treatment systems, although N_2O typically accounts for a relatively small absolute amount, its high global warming potential results in a disproportionately large contribution to the overall carbon emissions from wastewater treatment processes. Therefore, monitoring, accounting for, and controlling N_2O emissions must be given the highest priority when conducting carbon accounting and formulating carbon reduction strategies. Indirect carbon emissions come from the consumption of electricity and pharmaceuticals during the operation of the sewage treatment facilities.

Table 2. *The information about instruments types and manufacturers of water quality analysis*

Wastewater Quality Indicator	Standard Method	Primary Instrument Type	Manufacturer
COD	HJ 828-2017 (Dichromate Method)	COD Smart Digester, Spectrophotometer	Lanzhou Lianhua Environmental Technology Co., Ltd.
NH_3-N	HJ 535-2009 (Nessler's Reagent Spectrophotometry)	UV-Vis Spectrophotometer	Shanghai Yuanxi Instrument Co., Ltd.
TN	HJ 636-2012 (Alkaline Potassium Persulfate Digestion UV Spectrophotometry)	Smart Thermostatic Digester, UV-Vis Spectrophotometer	Beijing Bositech Technology Co., Ltd. (Digester) Shanghai Yuanxi Instrument Co., Ltd. (Spectrophotometer)
TP	HJ 670-2013 (Ammonium Molybdate Spectrophotometry)	Smart Thermostatic Digester, UV-Vis Spectrophotometer	Beijing Bositech Technology Co., Ltd. (Digester) Shanghai Yuanxi Instrument Co., Ltd. (Spectrophotometer)
SS	GB 11901-89 (Gravimetric Method)	Electric Drying Oven, Electronic Analytical Balance	Shanghai Jinghong Laboratory Instrument Co., Ltd. (Oven) Shanghai Sunny Hengping Scientific Instrument Co., Ltd. (Balance)
pH	Electrode Method	Laboratory pH Meter	Shanghai Yidian Scientific Instrument Co., Ltd. (Leici)

In this study, the operation process of the HIEPS is identified as the carbon accounting system boundary. HIEPS operates on green and clean energy generated by photovoltaic technology and does not consume any other electricity, which contributes to carbon reduction. Due to the small amount of sludge generated from the HIEPS and its direct reuse on agricultural land, the carbon accounting of the sludge treatment part is ignored. Besides, the HIEPS does not have a CH_4 recovery device, and without the addition of chemical agents due to the small volume of water to be treated. Therefore, the direct carbon emissions of the HIEPS include CH_4 and N_2O from the biochemical reactions, while indirect carbon emissions are non-existent. The carbon emission accounting method of wastewater treatment facilities in this paper refers to the Low Carbon Operation Evaluation technical Specification for Wastewater Treatment Plants (T/CAEPI-2022) (Zhou et al., 2024).

Direct carbon emissions

Direct carbon emissions of N_2O:

$$m_{N_2O,i} = \frac{Q_{rb,i} \times \left(TN_{rb,i} - TN_{eb,i}\right) \times EF_{N_2O}}{1000} \times C_{N_2O/N_2} \quad \text{(Eq.1)}$$

$$M_{N_2O} = \sum_{i=1}^{t} \left(f_{N_2O} \times m_{N_2O,i}\right) \quad \text{(Eq.2)}$$

$$E_{N_2O} = \frac{E_{CO_2}}{\sum_{i=1}^{t} Q_{rb,i}} \quad \text{(Eq.3)}$$

In the formula: $m_{N_2O,i}$: the direct emission of N_2O on day i, kgN_2O. $Q_{rb,i}$: Water inflow of sewage biological treatment unit on day i, m^3. $TN_{rb,i}$: an influent TN concentration on the day i of the sewage biological treatment unit, mg/L. $TN_{eb,i}$: An effluent TN concentration on the day i of the sewage biological treatment unit, mg/L. EF_{N_2O}: N_2O Emission factor, take the value of 0.016 kgN_2O-N/kgTN. C_{N_2O/N_2}: the ratio of N_2O/N_2 molecular weight, the value was 44/28. t: Number of days in the evaluation cycle, d. M_{N_2O}: direct carbon emission of N_2O, $kgCO_{2eq}$. f_{N_2O}: the greenhouse effect index of N_2O, take the value of 265 $kgCO_2/kgN_2O$. E_{N_2O} : direct carbon emission intensity of N_2O, $kgCO_{2eq}/m^3$.

Direct carbon emissions of CH_4:

$$m_{CH_4,i} = \left[\frac{Q_{ra,i} \times \left(COD_{ra,i} - COD_{ea,i}\right)}{1000}\right] \times B_0 \times MCF \quad \text{(Eq.4)}$$

$$M_{CH_4} = \sum_{i=1}^{t} \left(f_{CH_4} \times m_{CH_4,i}\right) \quad \text{(Eq.5)}$$

$$E_{CH_4} = \frac{M_{CH_4}}{\sum_{i=1}^{t} Q_{ra,i}} \quad \text{(Eq.6)}$$

In the formula: $m_{CH_4,i}$: the direct emission of CH_4 on day i, $kgCH_4$. $COD_{ra,i}$: an influent COD concentration on the day i of the sewage biological treatment unit, mg/L. $COD_{ea,i}$: An effluent TN concentration on the day i of the sewage biological treatment unit, mg/L.B_0: the yield coefficient of CH_4 when the unit of COD is degraded by anaerobic digestion, the value is 0.25 kg CH_4/kg COD. MCF: the CH_4 correction factor, the value is 0.03. M_{CH_4}: direct carbon emission of CH_4, $kgCO_{2eq}$.f_{CH_4}:the greenhouse effect index of CH_4, take the value of 28 $kgCO_2/kCH_4$. E_{CH_4} : direct carbon intensity of CH_4, $kgCO_2eq/m^3$.

Carbon reduction:

$$M_e = \sum_{i=1}^{t} \left(f_e \times w_i\right) \quad \text{(Eq.7)}$$

$$E_e = \frac{M_e}{\sum_{i=1}^{t} Q_{ra,i}} \quad \text{(Eq.8)}$$

In the formula: w_i : Electricity from electricity consumption for the operation of equipment supplied by photovoltaic power generation systems on day i, kW·h. f_e: Carbon emission factor for electricity consumption, using the emission factor for electricity consumption of the Southern Regional Power Grid, the value is 0.5752 $kgCO_2/(kW.h)$, the value from China's Ministry of Ecology and Environment's announcement of carbon dioxide emission factors for electricity in 2022. M_e: carbon reduction, $kgCO_{2eq}$. E_e: carbon intensity of carbon reduction, $kgCO_2eq/m^3$.

Results and discussions

Treatment effectiveness of wastewater

The boxplots of influent and effluent concentrations of contaminants directly reflect the distribution of data. As shown in *Figure 2*, the mean values of the influent concentrations were recorded as follows: COD at 240.48 mg/L, TN at 48.83 mg/L, NH_3N at 30.98 mg/L, TP at 3.91 mg/L, SS at 142.94 mg/L. After treatment by the facilities, the mean values of effluent concentration were COD at 27.92 mg/L, TN at 14.54 mg/L, NH_3N at 4.64 mg/L, TP at 0.67 mg/L, SS at15.39 mg/L. The effluent concentration ranges of COD, TN, NH_3N, TP and SS were 13 to 47 mg/L, 5 to 19.6 mg/L, 2.26 to 7.5 mg/L, 0.19 to 0.99 mg/L, and 9.34 to 18.94 mg/L, respectively. The results indicated that the effluent quality of the HIEPS was superior to the emission standard requirements.

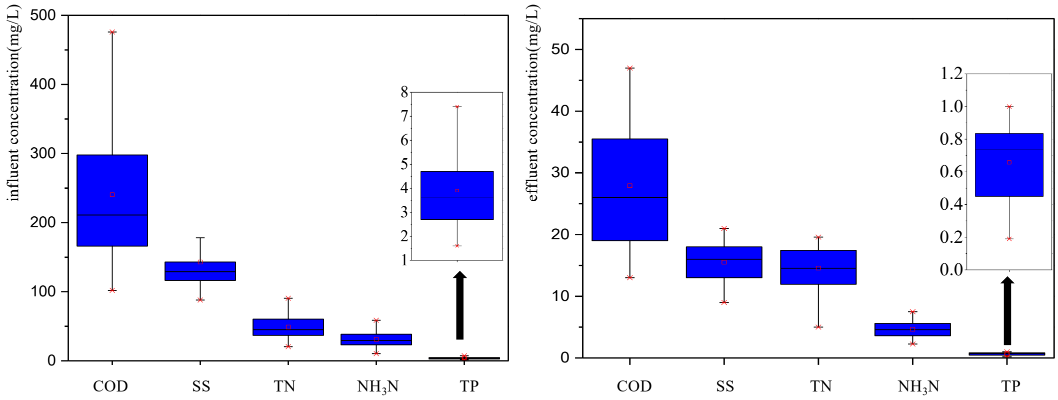

Figure 2. *Average concentration of pollutants in influent and effluent*

As shown in *Figure 3*, the contaminant's average removal efficiencies of COD, TN, NH_3N, TP, and SS were 88.03%, 88.49%, 84.75%, 69.44%, and 82.85%, respectively. This reflects the superior pollutant removal efficiency of the HIEPS and guarantees excellent effluent quality. The monitoring analysis found high removal efficiencies for COD, TN, NH_3N, and SS, with values above 80%. This can be attributed to the fact that the HIEPS utilized the ecological substrate of aquatic plants to provide growth areas for algae and bacteria, which rapidly multiply to form a mushroom-algae composite ecological treatment system. The composite system strengthened the biological treatment effectiveness and further guaranteed the effluent water quality (Chen et al., 2022). Nevertheless, the removal efficiency of TP was relatively low. This may be attributed to the fact that plant harvesting in the project's actual management process was carried out by local villagers. Consequently, certain management delays occur in practice, leading to untimely harvesting of plants. This hinders the absorption of phosphorus-containing substances by the root systems of aquatic plants. Furthermore, operational parameters such as the content of dissolved oxygen in wastewater and the nitrate reflux ratio also influence the removal of phosphorus-containing substances (Sánchez et al., 2023). The specific reasons for this need to be further analyzed and researched.

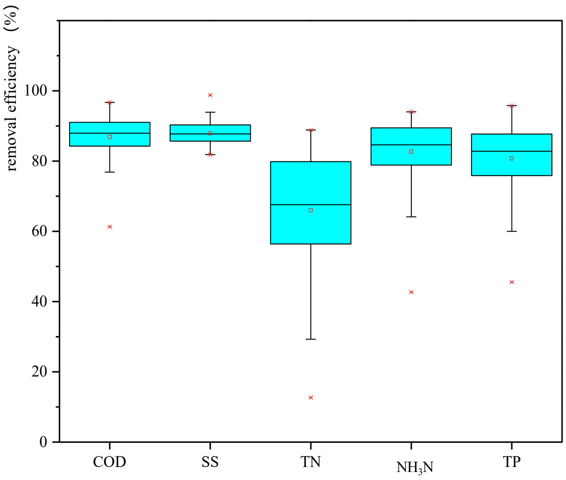

Figure 3. *Average pollutant removal efficiency*

The influence of ambient temperature and geographical characteristics

Temperature is an important factor affecting the activity of microorganisms during wastewater treatment. A suitable temperature range for the production and metabolism of microorganisms exists. Several studies have shown that the operational conditions and treatment effectiveness of wastewater treatment facilities are affected by the ambient temperature (Ong et al., 2016). This is because temperature affects microbial activity, aquatic plant growth and metabolism, and dissolved oxygen concentration in wastewater (Yang et al., 2024). Therefore, to overcome the adverse effects of temperature on wastewater treatment facilities, it is necessary to analyze the effect of ambient temperature on the treatment effectiveness of the HIEPS.

The Fairy Lake is located in southeastern China and has a subtropical monsoon climate with distinct seasons. The climate temperature varies greatly for different seasons, with average temperatures of 14°C, 35°C, 20°C, and 7.0°C in spring, summer, autumn, and winter respectively. Ambient temperature data were collected using onsite data loggers installed near each HIEPS unit, and the daily average temperature for each monitoring period was calculated. In addition, considering that the impact of ambient temperatures on wastewater treatment facilities may have a delay, the tasks of water quality samples are taken at times when climatic temperatures remain relatively stable.

The monitoring data of influent water quality can reflect raw water characteristics of direct rural domestic wastewater discharges. As shown in *Figure 4*, the influent concentration of pollutants in different seasons showed a certain degree of volatility. Relative to other seasons, pollutant concentrations in influent showed maximum values in the summer. This indicated that the water quality of rural domestic sewage has seasonal variation characteristics. As shown in *Figure 5*, water quality monitoring in different seasons in 2023 and 2024 found that the removal efficiency of pollutants of HIEPS was also characterized by seasonal variations, showing that the treatment efficiency in summer and autumn was slightly higher than that in winter and spring. Specifically, the average removal efficiencies of COD, HN_3N, TN, TP, and SS in summer were 89.95%, 86.63%, 76.54%, 83.17%, and 89.21%, respectively. In winter, the value decreased to different degrees, but the removal rates of HN_3N and COD were basically maintained at more than 70% and 75%, respectively. HN_3N and COD are important indicators to evaluate the microbial activeness of aerobic biochemical systems (Zhang et al., 2024b). The above results showed that the HIEPS wastewater treatment facility has high treatment performance and stable running status in all seasons of the year.

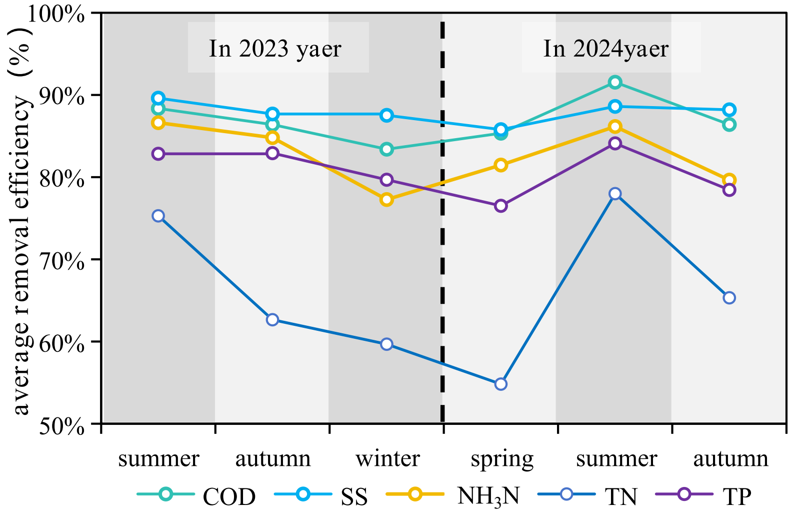

Figure 4. *Pollutant concentrations in influent water in different seasons*

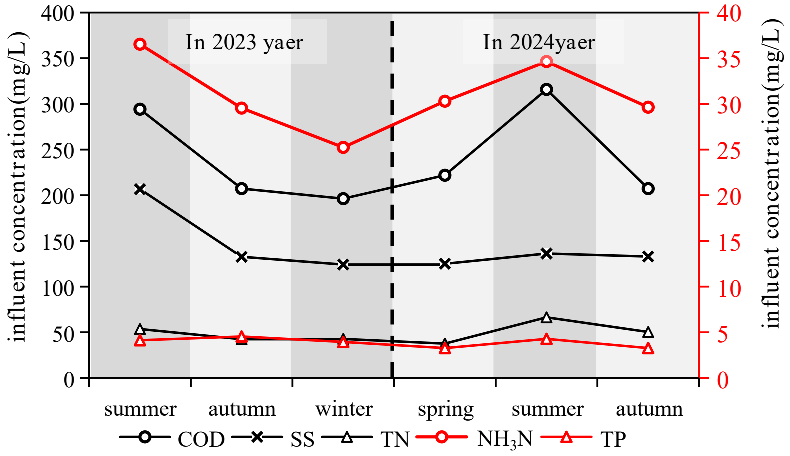

Figure 5. *Treatment efficiency of pollutants in different seasons*

The phenomenon of seasonal characteristics of treatment efficiency may be related to the growth and metabolic state of aquatic plants and microorganisms. With high temperatures and abundant rainfall in summer, aquatic plants are at a rapid growth stage, thus absorbing large quantities of pollutants from sewage and converting them into nutrients. In contrast, with low temperatures and a dry climate in winter, plant growth and metabolism slow down, and the absorption and transformation of pollutants in wastewater become weaker. Furthermore, the growth of nitrification and denitrification microorganisms was adversely affected by the low-temperature environment, leading to decreased NH_3N removal.

Although the pollutant removal efficiency of HIEPS is seasonal, presenting better treatment performance in summer than in other seasons. However, the results of one-way ANOVA showed that the probability of significance P-value of the mean effluent concentrations of the pollutants in different seasons was more than 0.05. This indicated that there was no statistically significant difference in climatic temperatures on pollutant removal efficiency at the 95% confidence intervals. Overall, the HIEPS can overcome climatic differences and maintain superior and stable pollutant removal benefits.

The geology of an area is less important than the environmental temperature. Due to variations in population density and types of human activities, geographical space also influences the quality and quantity of domestic wastewater to a certain extent, thereby affecting the operational performance of wastewater treatment facilities. This project covered the domestic wastewater treatment in Village S1 and Village S2 near Fairy Lake. There are differences between the two villages in terms of geography and habitat. Village S1 is close to the township and the Fairy Lake scenic spot, the terrain is relatively flat and the population density is high. While village S2 is located in a gully between hilly mountain ranges, with a small population and dispersed settlements. Additionally, actual population density data for the two villages was obtained from firsthand design materials and field survey records of the actual engineering project. The population density of village S1 and S2 was 311 persons/km^2 and 203 persons/km^2, respectively. Therefore, it is necessary to analyze whether have an effect of geographical differences on the operational effectiveness of HIEPS. As shown in Figure 6a, the influent concentrations of COD, HN_3N, TN, and SS of village S1 were slightly higher than those of village S2. To some extent, it was confirmed that domestic sewage from densely populated areas contains higher concentrations of pollutants. Despite geographic spatial variation in influent pollutant concentrations, there was less geographic variability in pollutant effluent concentrations and treatment efficiencies (*Figures 6b and 6c*). In addition, as shown in *Figure 7*, there is less variability in pollutant effluent concentrations from the 14 HIEPS, and the equipment operates with stability in different areas. The results of one-way ANOVA showed that the probability of significance P-value of the mean effluent concentrations of the pollutants in different geographic was more than 0.05. This indicated that there was no statistically significant difference in geographic pollutant removal efficiency at the 95% confidence interval. HIEPS can successfully overcome the variability between geographic environment, human environment, and influent quality, and maintain the stability and effectiveness of removing various pollutants.

Effectiveness evaluation

Rural domestic sewage treatment should be based on ecology and advance green development. Economic and ecological benefits can be promoted in a synergistic approach (Liu et al., 2024b). The ecological treatment advantages of constructed wetlands are integrated into HIEPS, forming a biological-ecological combination of wastewater treatment technology. The operation of HIEPS can overcome obstacles such as poor treatment of pollutants and large facility footprints, thereby guaranteeing effluent effectiveness and reducing operating costs (Jácome et al., 2016; Moreira and Dias, 2020). Furthermore, HIEPS is a successful illustration of the synergistic effect between solar photovoltaic power generation technology and rural decentralized wastewater treatment systems. The power consumption of the equipment during the operation of HIEPS is derived from solar energy. When solar radiation is sufficient, the photovoltaic system can generate electricity directly to meet the power demand and store the remaining power in the battery. When solar radiation is insufficient, power can be supplied by the storage battery, thus realizing the low-carbon operation of the system (Singh, 2013).

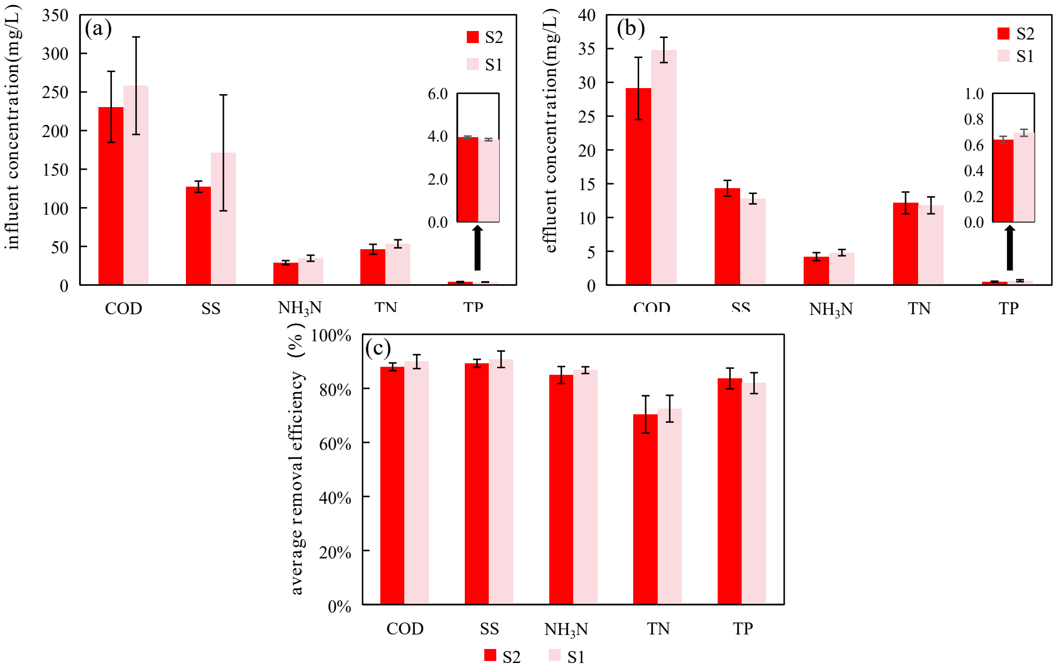

Figure 6. *The influent concentration, effluent concentration and average treatment efficiency of Village S1 and Village S2*

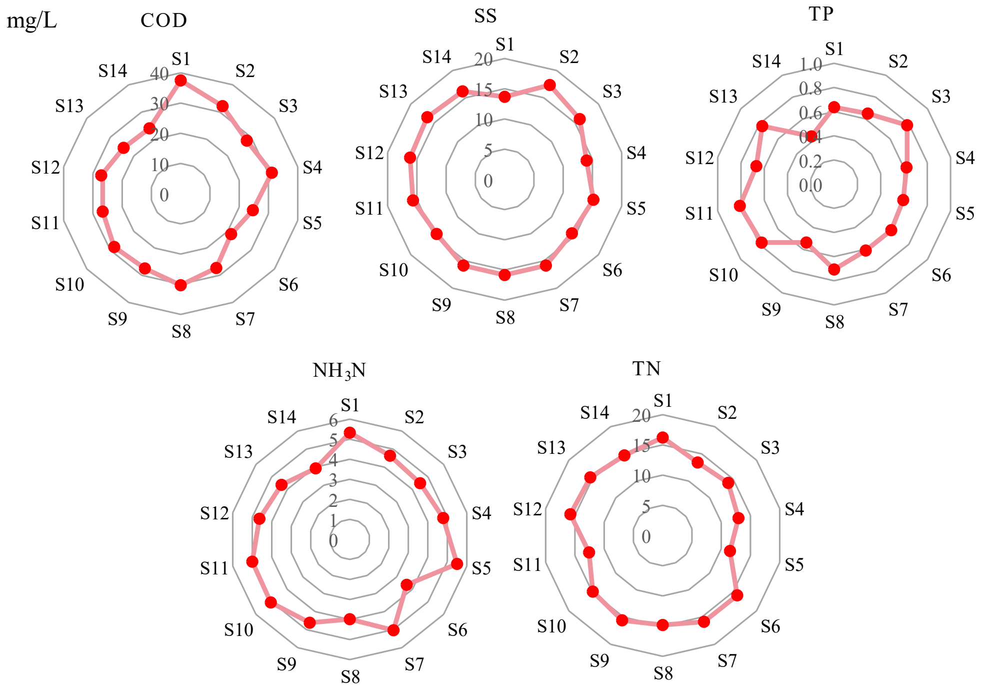

Figure 7. *Pollutant effluent concentrations from 14 sewage treatment facilities*

Rural wastewater treatment facilities should be constructed and operated with systematic consideration of project construction investment costs and facility operation and management costs. During the construction phase, HIEPS adopts a decentralized wastewater treatment model. Household pollution sources are directly connected to the treatment facility locally, thus avoiding the expense of costly pipeline network infrastructure investment. During the operation phase, equipment maintenance costs of general sewerage facilities mainly include electricity, labor, and repairs, and the electricity costs are a major part. The main power consumption of the HIEPS is one 15W DC electromagnetic aeration fan and one 400W DC elevator pump, and power supply from two 100 W solar panels and one 100 Ah battery. Photovoltaic complementary technology can achieve a stable power supply and green low-carbon operation of the equipment. Besides, the HIEPS requires no personal supervision or maintenance. Only regular rinsing of grates and harvesting of aquatic plants is required. This significantly reduced maintenance costs.

Table 3 has compared and analyzed the treatment efficiencies of HIEPS with other rural wastewater treatment technologies. Compared to the ecological treatment technologies of constructed wetlands, oxidation ponds, and soil percolation ponds, the HIEPS is more advantageous in terms of pollutant removal efficiency, floor space, and investment cost (Zhai et al., 2011; Vergeles et al., 2015). Although both membrane bio-reactor (MBR) and HIEPS have high organic pollutant removal efficiency, MBR is unfavorable for nitrogen and phosphorus pollutant removal. In addition, the operation and maintenance costs of HIEPS are significantly lower than those of MBR. Because the membrane is vulnerable to blockage and contamination during MBR operation, frequent membrane washing and replacement work is required (Ren et al., 2010). Overall, relative to other rural decentralized wastewater treatment equipment, HIEPS not only has a high and stable treatment efficiency for all types of pollutants but also has simple maintenance and high economic benefits. Therefore, in terms of technical, economic, and ecological assessments, the HIEPS is a promising option for wastewater treatment in rural areas.

Table 3. *Comparison of average removal efficiency of wastewater treatment technologies*

Process	**Removal efficiency (%)**					**Reference**
	COD	**NH_3N**	**TN**	**TP**	**SS**	
Constructed wetlands	77.3	51.5	50.1	46.7	72.1	(Vergeles et al., 2015)
Oxidation ponds	36.56	/	/	/	30.40	(Ali et al., 2017)
MBR	87.4	/	35.2	25.6	94.0	(Ren et al., 2010)
A^2O-MBR	72.8	89.4	75.5	64.1	/	(Yang et al., 2021)
Soil purification tank	65.6	72.3	70.6	62.5	/	
HIEPS	88.03	84.75	88.49	69.44	82.85	In the study

Analysis of carbon accounting

The wastewater treatment industries are one of the largest sources of greenhouse gas emissions globally (Li et al., 2023). Carrying out carbon emission accounting and tapping the carbon reduction potential of the sewerage system play an important role in achieving the dual-carbon target and the task of reducing pollution and carbon synergies (Chen et al., 2023; Zhou et al., 2024). The HIEPS operational process includes direct carbon emissions and carbon reduction from photovoltaic power generation.

The annual water treatment volume of 14 sets of HIEPS was about 3832.50 m^3/y. Through analysis and calculation, Carbon emissions and carbon intensity was obtained. As shown in *Table 4*, the annual direct carbon emission from the 14 sets of HIEPS is about 1046.69 $kgCO_2eq/y$, and N_2O emission is 5.12 times higher than direct CH_4 emissions. The annual carbon reduction from photovoltaic power generation is 517.31 $kgCO_2eq/y$. This can be found in carbon reductions that were two times greater than carbon emissions. From the perspective of carbon emissions intensity, the direct carbon emissions intensity of the HIEPS is 0.27 $kgCO_2eq/m^3$, and carbon reduction intensity from photovoltaic power generation is 0.13 $kgCO_2eq/m^3$. Li et al. (2023) investigated the carbon emissions during the operation of the A_2O wastewater treatment process and found that the direct and indirect carbon emission intensities were 0.35 $kgCO_2eq/m^3$ and 0.65 $kgCO_2eq/m^3$ respectively. It can be noted that the carbon emission intensity of the HIEPS in this study is significantly lower than in the above study. This situation is mainly due to the fact that HIEPS does not require the addition of chemicals and uses solar photovoltaic technology to provide green energy. In general, the carbon emission intensity of HIEPS is at a low level during the operation process and contributes to carbon reduction. Therefore, the clean and low-carbon operation of wastewater treatment facilities can be promoted by researching low pharmaceutical consumption technologies and exploring the transformation and upgrading of power supply methods (Li et al., 2023).

Table 4. *Carbon emissions and carbon reduction of 14 sets of HIEPS*

Carbon accounting	**Type of Carbon emissions**	**Carbon emissions ($kgCO_2eq/y$)**	**Carbon intensity ($kgCO_2eq/m^3$)**
direct carbon emissions	N_2O	875.62	0.23
	CH_4	171.07	0.04
carbon reduction	Electricity from solar	517.31	0.13

HIEPS combined complementary photovoltaic and constructed wetland ecological technologies to optimize energy supply and improve pollutant treatment efficiency. However, to better respond to the complex and multiple demands for rural wastewater treatment, further research is needed on HIEPS systems. Aiming at the problem of poor phosphorus removal, studies have shown that the combination of other advanced treatment processes can have a beneficial effect in exploring and solving this problem. For example, the study reported that applied iron electrolysis technology to sewage treatment facilities. Long-term studies have found that the release of phosphorus into the bulk phase is prevented by the accumulated iron provided by iron electrolysis, resulting in stable and efficient phosphorus removal (Mishima et al., 2018). In addition, in order to advance the goal of carbon neutrality, it is necessary to explore cleaner power supply and lower carbon treatment technologies. This requires advancing pollution and carbon reduction from the full life cycle process of wastewater treatment (Lutterbeck et al., 2017). Generally speaking, a lack of budget makes continuous operation and regular monitoring impossible in most rural areas, which poses a big challenge for the stable operation of decentralized wastewater treatment facilities. The construction of remote monitoring platforms is a feasible way to improve efficiency and reduce the costs of operating and supervising these facilities (Song et al., 2020).

Conclusions

Currently, China is in the process of promoting rural revitalization and achieving the dual-carbon goal comprehensively. Against this background, the HIEPS has emerged as a kind of integrated equipment specifically suited to treating decentralized rural domestic sewage. The equipment incorporates the advantages of constructed wetlands. The pollutant removal in sewage is enhanced by microbial degradation and absorption by aquatic plants. In addition, the integration of solar photovoltaic power generation technology into rural wastewater treatment systems can resolve problems of difficult access to electricity and insufficient operating costs. Based on the decentralized rural wastewater treatment project in Fairy Lake, this paper comprehensively analyzed and evaluated the HIEPS which has high pollutant removal efficiency and stable operation status. The HIEPS can also overcome environmental temperature differences and maintain excellent treatment performance. In terms of economic and ecological benefits, HIEPS not only has lower construction and operation costs but also has great potential for reducing pollution and low-carbon output. Therefore, HIEPS has a widespread application prospect in remote rural areas with complex terrain and dispersed settlements. In further, to develop more efficient, economical, low-carbon, and sustainable rural wastewater treatment technologies, it is necessary to continuously optimize the pollutant treatment technologies of HIEPS, explore greener and lower-carbon energy supply methods, and construct more effective operation and management models.

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REFERENCES

[1] Ali, H. Q., Farooq, A., Ahmed, M. (2017): Monitoring the Wastewater Treatment Efficiency of Oxidation Ponds at Chokera, Faisalabad. – Mehran University Research, Journal of Engineering and Technology 36(4): 987-994.

[2] Chen, P., Zhao, W., Chen, D., Huang, Z., Zhang, C., Zheng, X. (2022): Research Progress on Integrated Treatment Technologies of Rural Domestic Sewage: A Review. – Water 14(15): 2439. https://doi.org/10.3390/w14152439.

[3] Chen, H., Zheng, Y., Zhou, K., Cheng, R., Zheng, X., Ma, Z., Shi, L. (2023): Carbon emission efficiency evaluation of wastewater treatment plants: evidence from China. – Environmental Science and Pollution Research 30: 76606-76616. https://doi.org/10.1007/s11356-023-27685-9.

[4] Fernandez, D. C., Camargo, J. A. E., Fernandez, M. P., Antizar-Ladislao, B. (2019): *Carex paniculata* constructed wetland efficacy for stormwater, sewage and livestock wastewater treatment in rural settlements of mountain areas. – Water Science & Technology 79(7): 1338-1347. https://doi.org/10.2166/wst.2019.130.

[5] Hendy, I., Zelenakova, M., Pietrucha-Urbanik, K., Salama, Y., Abu-hashim, M. (2023): Decentralized Constructed Wetlands for Wastewater Treatment in Rural and Remote Areas of Semi-arid Regions. – Water 15(12): 2281. https://doi.org/10.3390/w15122281.

[6] Jácome, J. A., Molina, J., Suárez, J., Mosqueira, G., Torres, D. (2016): Performance of constructed wetland applied for domestic wastewater treatment: Case study at Boimorto (Galicia, Spain). – Ecological Engineering 95: 324-329. https://doi.org/10.1016/j.ecoleng.2016.06.049.

[7] Jiao, F. F., Zhang, X. Z., Zhang, T., Hu, Y., Lu, R., Ma, G. Y., Chen, T., Guo, H. B., Li, D. P., Pan, Y., Li, Y. Y., Kong, Z. (2024): Insights into carbon-neutral treatment of rural

wastewater by constructed wetlands: A review of current development and future direction. – Environmental Research 262: 119796. https://doi.org/10.1016/j.envres.2024.119796.

[8] Li, Y., Gu, H., Zhao, G., Li, H., Zhang, M., Yang, X.-L., Song, H.-L. (2023): Carbon accounting of A2O process based on carbon footprint in a full-scale municipal wastewater treatment plant. – Journal of Water Process Engineering 55: 104162. https://doi.org/10.1016/j.jwpe.2023.104162.

[9] Li, Y., Ge, S., Luan, J., Wang, Y., Zhuang, L.-L., Zhang, J. (2024): Optimization and mechanism of strengthened biological contact oxidation for rural domestic wastewater treatment. – Journal of Water Process Engineering 65: 105788. https://doi.org/10.1016/j.jwpe.2024.105788.

[10] Liu, M., Lin, Z., Li, J., Zhu, M., Tang, Z., Li, K. (2024a): Performance Assessment of Rural Decentralized Domestic Wastewater Treatment Facilities in Foshan, China. – Water 16(13): 1901. https://doi.org/10.3390/w16131901.

[11] Liu, Y. Y., Feng, B., Yao, Y. (2024b): Research Trends and Future Prospects of Constructed Wetland Treatment Technology in China. – Water 16(5): 738. https://doi.org/10.3390/w16050738.

[12] Lutterbeck, C. A., Kist, L. T., Lopez, D. R., Zerwes, F. V., Machado, Ê. L. (2017): Life cycle assessment of integrated wastewater treatment systems with constructed wetlands in rural areas. – Journal of Cleaner Production 148: 527-536. https://doi.org/10.1016/j.jclepro.2017.02.024.

[13] Mishima, I., Hama, M., Tabata, Y., Nakajima, J. (2018): Long-term investigation of phosphorus removal by iron electrocoagulation in small-scale wastewater treatment plants. – Water Science & Technology 78(6): 1304-1311. https://doi.org/10.2166/wst.2018.402.

[14] Moreira, F. D., Dias, E. H. O. (2020): Constructed wetlands applied in rural sanitation: A review. – Environ Res 190: 110016. https://doi.org/10.1016/j.envres.2020.110016.

[15] Nakagawa, G., Ebie, Y., Tsuneda, S., Matsumura, M., Inamori, Y. (2007): Use of real-time PCR to examine the relationship between ammonia oxidizing bacterial populations and nitrogen removal efficiency in a small decentralized treatment system 'Johkasou'. – Water Science and Technology: A Journal of the International Association on Water Pollution Research 55(7): 203-210. doi: 10.2166/wst.2007.146.

[16] Ong, Y. H., Chua, A. S. M., Huang, Y. T., Ngoh, G. C., You, S. J. (2016): The microbial community in a high-temperature enhanced biological phosphorus removal (EBPR) process. – Sustainable Environment Research 26(1): 14-19. https://doi.org/10.1016/j.serj.2016.04.001.

[17] Ren, X., Shon, H. K., Jang, N., Lee, Y. G., Bae, M., Lee, J., Cho, K., Kim, I. S. (2010): Novel membrane bioreactor (MBR) coupled with a nonwoven fabric filter for household wastewater treatment. – Water Research 44(3): 751-760. https://doi.org/10.1016/j.watres.2009.10.013.

[18] Roosmini, D., Aldilla Fajri, J., Fujisawa, T., Trianda, Y., Ishiguro, Y., Cui, G., Li, F., Yamada, T., Pribadi, K., Sugeng, B., Hadihardaja, I. K. (2018): Effect of Aeration Rates on Removals of Organic Carbon and Nitrogen in Small Onsite Wastewater Treatment System (Johkasou). – MATEC Web of Conferences 147: 04008. https//doi.org/10.1051/matecconf/201814704008.

[19] Ruan, W., Peng, Y., Liao, R., Man, Y., Tai, Y., Tam, N. F., Zhang, L., Dai, Y., Yang, Y. (2024): Removal, transformation and ecological risk assessment of pesticide in rural wastewater by field-scale horizontal flow constructed wetlands of treated effluent. – Water Research 256: 121568. https://doi.org/10.1016/j.watres.2024.121568.

[20] Sánchez, M., Ruiz, I., Soto, M. (2023): Sustainable wastewater treatment using a new combined hybrid digester – Constructed wetland system. – Journal of Environmental Chemical Engineering 11(5): 110861. DOI:10.1016/j.jece.2023.110861.

[21] Sellami, H., Benabdallah, S., Charef, A. (2009): Performance of a vertical flow constructed wetland treating domestic wastewater for a small community in rural Tunisia. – Desalination and Water Treatment 12(1-3): 262-269. https://doi.org/10.5004/dwt.2009.951.

[22] Singh, G. K. (2013): Solar power generation by PV (photovoltaic) technology: A review. – Energy 53: 1-13. https://doi.org/10.1016/j.energy.2013.02.057.

[23] Song, X., Liu, R., Yu, Q., Sheng, X., Chen, L. (2020): Management mode construction for operation and supervision of rural sewage treatment facilities: Towards the information-to-intelligence strategy. – Bioresource Technology Reports 11: 100481. https://doi.org/10.1016/j.biteb.2020.100481.

[24] Thakur, I. S., Medhi, K. (2019): Nitrification and denitrification processes for mitigation of nitrous oxide from waste water treatment plants for biovalorization: Challenges and opportunities. – Bioresource Technology 282: 502-513. https://doi.org/10.1016/j.biortech.2019.03.069.

[25] Vergeles, Y., Vystavna, Y., Ishchenko, A., Rybalka, I., Marchand, L., Stolberg, F. (2015): Assessment of treatment efficiency of constructed wetlands in East Ukraine. – Ecological Engineering 83: 159-168. https://doi.org/10.1016/j.ecoleng.2015.06.020.

[26] Wang, T., Wang, Z., Wang, T., Shumin, M., Hu, S., Gao, S., Ye, L., Runfa, C., Arhonditsis, G. (2024): Evaluation of the role of urban domestic wastewater treatment systems for greenhouse gases emissions in China. – Ecological Informatics 81: 102571. https://doi.org/10.1016/j.ecoinf.2024.102571.

[27] Yang, F., Zhang, H., Zhang, X., Zhang, Y., Li, J., Jin, F., Zhou, B. (2021): Performance analysis and evaluation of the 146 rural decentralized wastewater treatment facilities surrounding the Erhai Lake. – Journal of Cleaner Production 315: 128159. https://doi.org/10.1016/j.jclepro.2021.128159.

[28] Yang, Y., Li, C.-K., Han, L., Yang, Z.-P., Xiao, N.-N., Zhang, N., Dong, Y.-Y., Chen, Z.-W., Xi, H., Wang, W.-D. (2024): Performance assessment of solar photovoltaic-based constructed wetland for sustainable rural wastewater treatment. – Journal of Water Process Engineering 59: 105068. https://doi.org/10.1016/j.jwpe.2024.105068.

[29] Zhai, J., Qin, C., Xiao, H. W., He, Q., Liu, J. (2011): Constructed Wetlands for Wastewater Treatment in Mainland China: Two Decades of Experience. – Applied Mechanics and Materials 90-93: 2977-2986. https://doi.org/10.4028/www.scientific.net/AMM.90-93.2977.

[30] Zhang, J., Jiang, Y., Zhang, H., Feng, D., Bu, H., Li, L., Lu, S. (2024a): A critical review of characteristics of domestic wastewater and key treatment techniques in Chinese villages. – The Science of the Total Environment 927: 172155. https://doi.org/10.1016/j.scitotenv.2024.172155.

[31] Zhang, X., Ma, G., Chen, T., Yan, C., Chen, Y., Wang, Q., Peng, X., Xu, W., Hao, T., Zhang, T., Lu, R., Li, D., Pan, Y., Li, Y.-Y., Kong, Z. (2024b): Towards carbon-neutral biotechnologies for rural wastewater: A review of current treatment processes and future perspectives. – Journal of Water Process Engineering 58: 104773. https://doi.org/10.1016/j.jwpe.2024.104773.

[32] Zhao, S. Y., Li, G., Shui, P. P., Nie, W. B., Qu, H., Yan, J., Li, H., Wang, R. L. (2024): Novel overlapping constructed wetlands with water drops reoxygenation and lightweight fillers for decentralized wastewater treatment. – Bioresource Technology 408: 131170. https://doi.org/10.1016/j.biortech.2024.131170.

[33] Zhou, G., Xiong, Z., Lian, X., Ding, Y. (2024): Carbon emission calculation of three biological nitrogen removal processes: A case of rare earth element tailings wastewater in Southern Jiangxi, China. – Journal of Water Process Engineering 60: 105130. https://doi.org/10.1016/j.jwpe.2024.105130.