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Study of the characteristics of pollutants in rural domestic sewage and the optimal sewage treatment process: a Chengdu Plain case study

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ABSTRACT

Domestic sewage is an important source of surface water pollution in the rural areas of developing countries, especially in the rural areas of China. In recent years, with the strategy of rural revitalization, China has paid increasing attention to the treatment of rural domestic sewage. Therefore, 16 villages in the Chengdu Plain were selected for the study, and seven indicators were analyzed and evaluated, including pH, five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total phosphorus (TP), suspended solids (SS) and total nitrogen (TN), in the water samples at the inlet and outlet of the wastewater treatment plant. The concentration of each pollutant in the rural scattered domestic sewage of the Chengdu Plain in Southwest China was obtained, and the concentration of each pollutant in domestic sewage was higher than that in summer. In addition, the preferred process for removing each pollutant was obtained by studying the effects of the treatment process, season and hydraulic retention time on the removal efficiency of each pollutant. The research results provide valuable references for the planning and process selection of rural domestic sewage treatment.

Key words: Chengdu Plain, process selection, rural domestic sewage, water quality analysis

HIGHLIGHTS

- Comparative analysis of the concentration of rural domestic sewage before entering and after leaving the wastewater treatment plant in the Chengdu Plain.
- The concept and calculation method of the 'α' was proposed.
- System removal efficiency (SRE) was used in the selection of optimal sewage treatment plants.
- The most suitable removal process for each pollutant is proposed.

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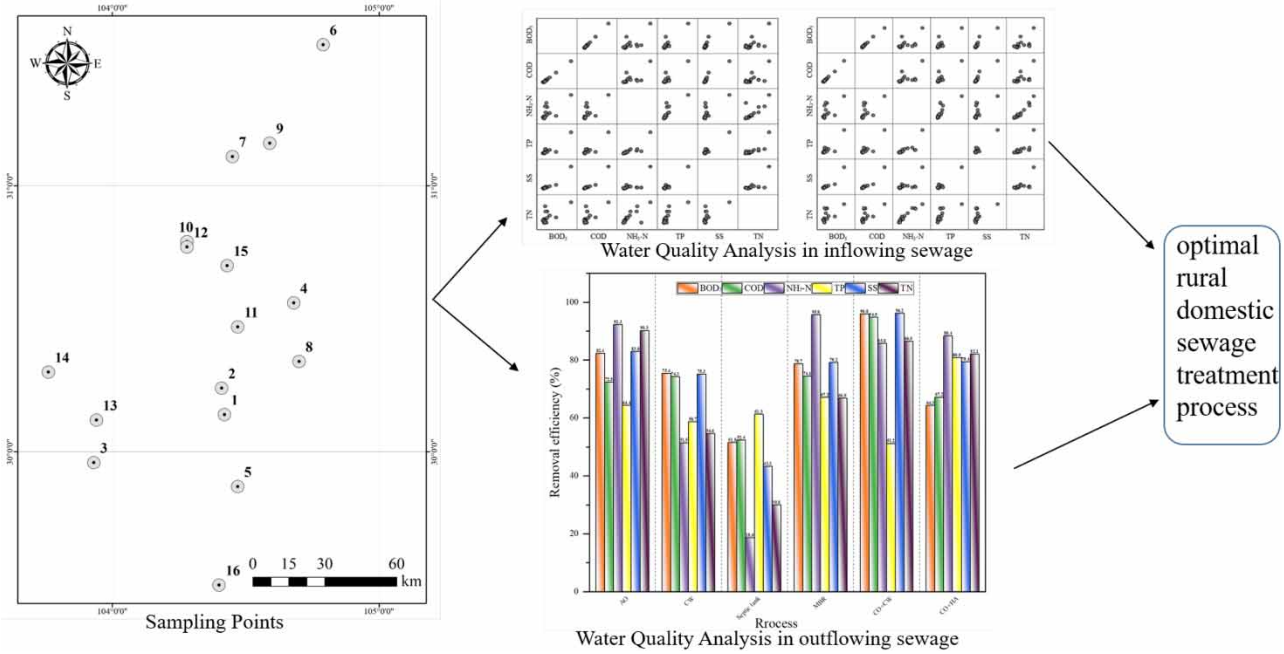
GRAPHICAL ABSTRACT



1. INTRODUCTION

In China, rural areas cover 94% of the national land area, and the rural population size is approximately 600 million (Wei *et al.* 2020; Zhang *et al.* 2021). However, the treatment of rural domestic sewage has not yet been solved, and most domestic sewage is discharged directly into nearby surface waters without treatment. With the development of the rural economy, the treatment of rural scattered domestic sewage has become an important issue affecting the sustainable development of rural areas. The annual discharge of rural domestic sewage in China exceeds 8×10^9 m^3, and the amount of sewage treatment is increasing each year (Chen *et al.* 2022). Although 34.87% of villages in China have sewage treatment plants, very few of them are used regularly, and only 4.5% of the overall sewage is treated each year (Ministry of Housing & Urban–Rural Development of the People's Republic of China 2020). The direct discharge of rural scattered domestic sewage containing considerable amounts of nitrogen, phosphorus, organic matter, and other pollutants into rivers can contribute to the eutrophication of water bodies (Wang *et al.* 2011, 2019; Yan *et al.* 2013; Song *et al.* 2018; Yu *et al.* 2019; Li *et al.* 2020; Mao *et al.* 2021). A study by Huang *et al.* (2019) showed that untreated rural domestic sewage can also interfere with the natural development and reproductive processes of aquatic animals, and thus, sewage can be harmful to the aquatic organisms and local residents in a watershed. For this reason, the Chinese government has proposed a strategic plan for 'new rural construction', which stipulates that rural domestic sewage must be treated before it is discharged into rivers or soil.

Rural domestic sewage is the domestic wastewater produced by rural residents, including kitchen sewage, toilet sewage, and washing sewage, which is called 'the rural three waters'. It is characterized by wide dispersion, multiple sources, randomness, large daily and seasonal variations, low pollutant concentrations, and difficulty to regulate and control (Sun *et al.* 2013; Mao *et al.* 2021; Wang 2021; Yi *et al.* 2021). In response to increasing concerns about environmental pollution and human health, the Chinese government aims to develop and implement advanced wastewater treatment plants in rural areas to improve the rural environment, water quality, and lives of rural people (Ai *et al.* 2020; Bo & Wen 2022). Accelerating the research on rural domestic sewage treatment technologies and treating rural domestic sewage as scientifically and effectively as possible is a very important task, and it is of great significance for the overall improvement of the rural environment in China (Li *et al.* 2022); furthermore, it is an important step in the implementation of rural revitalization strategies (Chang *et al.* 2018; Zhang *et al.* 2020b). Selecting appropriate wastewater treatment methods to improve environmental conditions in rural areas has become a top priority for the State Council of China (Liu *et al.* 2013; Yu *et al.* 2019). The number of wastewater treatment plants in Chinese townships increased from 763 in 2007 to 3,437 in 2015 (Cheng *et al.* 2017). These

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wastewater treatment plants can be divided into centralized wastewater treatment systems and decentralized wastewater treatment systems; however, centralized wastewater treatment systems are more expensive to build and maintain (Libralato *et al.* 2012). Decentralized wastewater treatment methods are clearly more suitable for rural areas in China that have a low population density and scattered households (Chen *et al.* 2019a; Hong *et al.* 2019). There are various decentralized treatment methods for treating rural domestic wastewater. Examples include constructed wetlands (Chen & Yao 2014; Lam *et al.* 2015; Saumya *et al.* 2015; Lu *et al.* 2016; Chen *et al.* 2022), septic tanks (Chen & Yao 2014; Singh *et al.* 2019), contact oxidation (Li & Zhou 2011; Chen *et al.* 2022), membrane bioreactors (Chen *et al.* 2022), hydrolytic acidification (Cokgor *et al.* 2009; Feng *et al.* 2009; Cheng 2020), combined anaerobic and aerobic processes (Li *et al.* 2016; Zheng *et al.* 2019; Chen *et al.* 2022), land use systems (Wang *et al.* 2011; Sun 2017), aeration basins (Sun 2017; Xie *et al.* 2019), oxidation ditches (Wang *et al.* 2011), and high-efficiency algal ponds (Xie *et al.* 2019). Decentralized wastewater treatment technologies have been explored as cost-effective and promising viable options for reducing pollutant loads in rural areas (Chen & Yao 2014). Each option has advantages and disadvantages and a scope of application (Sun *et al.* 2013; Chen *et al.* 2022), and the removal efficiency is influenced by factors such as temperature, wetland plants, and pollutant concentration (Wang *et al.* 2019). According to the characteristics of rural domestic sewage in China, wastewater treatment systems require certain characteristics, including simple operation and maintenance, low investment and cost, and a high efficiency of organic matter and nutrient removal (Chen & Yao 2014). Therefore, exploring decentralized wastewater treatment methods applicable in rural areas in China is both an inevitable requirement for promoting sustainable social development and a necessary path for building beautiful and livable villages.

To explore the wastewater treatment methods applicable in rural areas in China, the characteristics of rural domestic sewage in the watershed must be studied. However, most of the current studies on rural environmental pollution in watersheds by Chinese scholars focus on the perspective of surface source pollution, and there are fewer studies that directly address the characteristics of pollutants in rural domestic sewage in watersheds. In addition, with the advancement of new rural construction and changes in farmers' lifestyles, the previous source census data do not reflect the rural areas situation in real time, and this shortcoming may limit guidance for the construction of rural wastewater treatment demonstration projects. Therefore, it is necessary to conduct research on rural domestic sewage (Wang *et al.* 2020). In this paper, the concentration of each characteristic pollutant in the influent and effluent of 16 typical rural domestic wastewater treatment facilities in the Chengdu Plain of Southwest China was studied. The results of this study initially reveal the discharge pattern and characteristics of rural domestic sewage in Southwest China, thus providing a reference for the control and treatment engineering of rural surface source pollution in Southwest China as well as for the control and treatment of surface source pollution in watersheds similar to the Chengdu Plain in Southwest China. In addition, this paper analyzed the effects of the treatment process, season, and hydraulic retention time on the removal efficiency of each characteristic pollutant and discussed the elements that should be considered when selecting wastewater treatment facilities. Through this study, we hope to obtain the water quality characteristics of rural domestic wastewater in Southwest China, and obtain the most suitable wastewater treatment technology for removing each pollutant, thus providing an important reference for the application of various treatment processes in domestic wastewater treatment in rural areas.

2. MATERIALS AND METHODS

2.1. Sampling sites

The Chengdu Plain includes all districts and counties in Chengdu and parts of Deyang, Mianyang, Ya'an, Leshan, and Meishan, and it is the largest plain in three provinces of Southwest China. The Chengdu Plain is home to the world-famous Dujiangyan Irrigation Project, which has developed agriculture, rich products, and a dense population, and it has been known as the 'Land of Heaven' since ancient times. There are many rivers in the Chengdu Plain, and the west side is composed of the surface water system inlet, giving birth to two major water systems, the Minjiang River and the Tuojiang River, which enter the plain and are fan-shaped diversions.

The main cause of river pollution in the Chengdu Plain is the discharge of a large amount of industrial sewage and domestic sewage. Therefore, this study aimed to grasp the characteristics of rural domestic sewage and consider the representativeness of the rural economic development level. Sixteen villages in the Chengdu Plain in Southwest China were selected for the study, mainly including some areas of Chengdu, Deyang, and Mianyang. The study area is located between 103.76°–104.79°E and 29.50°–31.53°N. The population size of each village ranges from 240 to 3,500 people, and the specific

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location of each village and sewage treatment methods are shown in Figure 1 and Table 1. The study area is in the warm and humid subtropical Pacific southeast monsoon climate zone, with an average temperature of 16.1 °C, an annual average sunshine duration of 986.1 h and abundant rainfall (Li 2020). The average temperature in the Chengdu Plain in summer is 24 °C and the average rainfall is 600 mm, while the average temperature in winter is 7 °C and the average rainfall is 30 mm (Zhang *et al.* 2020a).

2.2. Sampling collection methods

Samples were collected in strict accordance with the methods provided in the national standards (Ministry of Ecology and Environment of the People's Republic of China 2002b, 2009). Sampling points were established in each village before the point where domestic sewage entered the wastewater treatment plant and at a point after wastewater had been treated in the wastewater treatment plant. The domestic sewage before entering the sewage treatment plant was obtained at the outfall of each village as the inlet water quality, and the sewage treated by the sewage treatment plant was obtained at the sewage outfall as the outlet water quality. The domestic sewage at the inlet and outlet of each village sewage treatment plant was collected daily in summer and winter, and the average value was taken as the concentration of domestic sewage at the inlet and outlet of the sewage treatment plant in summer and winter, respectively.

2.3. Sample analysis methods

The water quality at the inlet and the outlet of each sampling point was analyzed with reference to the Analytical Methods for Water and Wastewater Monitoring (Fourth Edition) (Ministry of Ecology and Environment of the People's Republic of China 2002a). The analytical indicators included pH, BOD_5, COD, NH_3-N, TP, TN, and SS. pH was determined by the glass

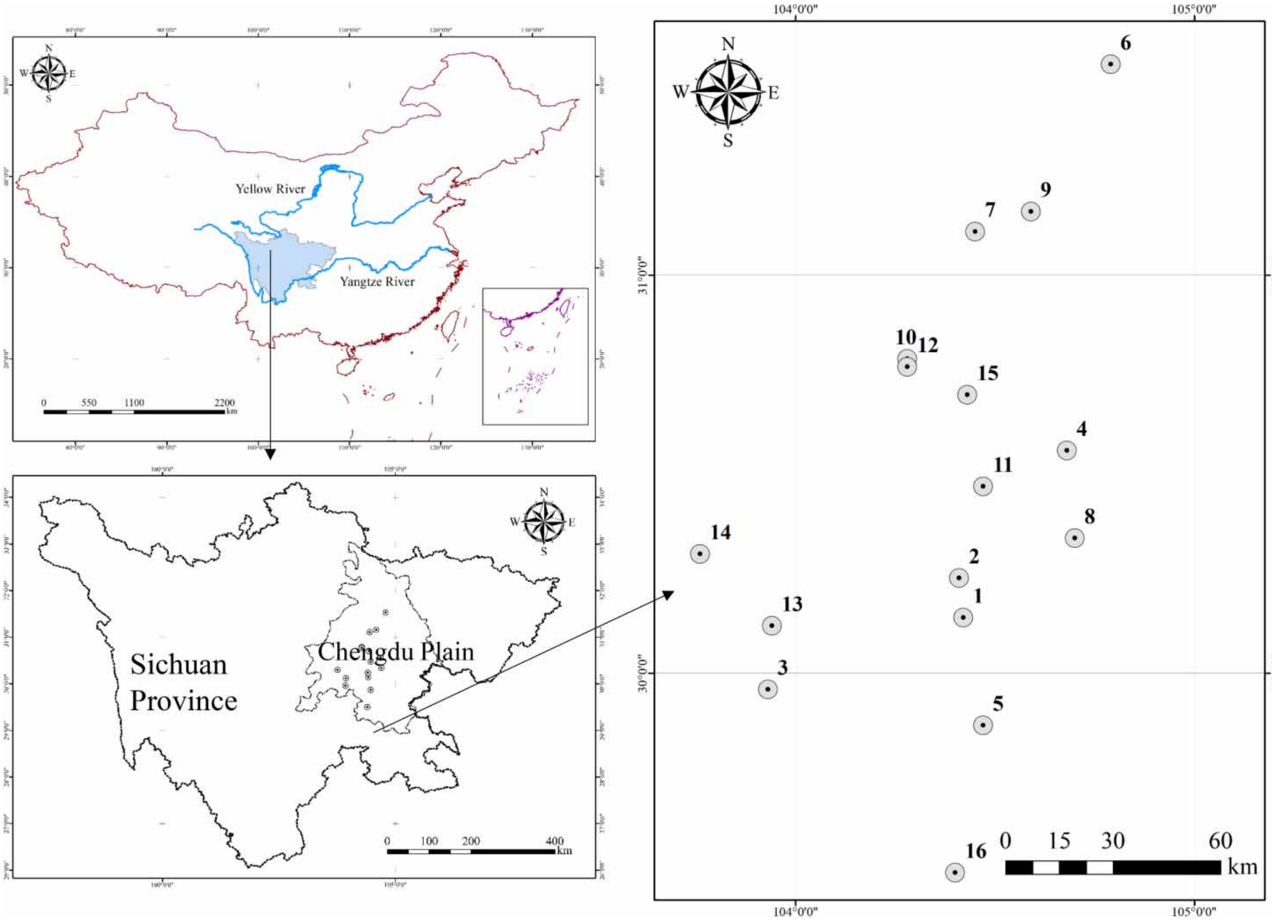

Figure 1 | Map of the study area and village distribution.

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Table 1 | Statistics of specific information of each village

Number	Village	Population (person)	Design treatment scale (t/d)	Sewage treatment process
1	Laolong	3,500	250	Septic tank
2	Qingfeng	2,000	250	Contact oxidation + Vertical flow constructed wetland (CO + CW)
3	Jinhua	1,600	100	MBR-integrated equipment (MBR)
4	Shipao	240	30	Anoxic/Oxic (A/O)
5	Shuangbao	500	40	CW
6	Wensheng	1,200	80	CW
7	Diaoqiao	1,000	70	CO + CW
8	Wuxing	780	50	MBR
9	Shunhe	550	40	CW
10	Xinshan	300	30	CW
11	Zhanlong	300	20	CW
12	Hongshu	1,500	150	MBR
13	Tudi	800	100	MBR
14	Baosheng	1,200	130	MBR
15	Renhe	1,200	90	Contact oxidation + Hydrolytic acidification (CO + HA)
16	Mashi	1,500	150	CO + CW

electrode method; BOD_5 was determined by the dilution and inoculation method with a minimum detection limit of 2 mg/L; COD was determined by the dichromate method with a minimum detection limit of 10 mg/L; NH_3-N was determined by the nano-reagent spectrophotometric method with a minimum detection limit of 0.05 mg/L; TP was determined by the ammonium molybdate spectrophotometric method with a minimum detection limit of 0.01 mg/L; TN was determined by the ultraviolet spectrophotometric method with alkaline potassium persulfate elimination with a minimum detection limit of 0.05 mg/L; and SS was determined by the weight method. The indicators were labeled and tracked in the sample at the same time, and parallel double sample measurement was guaranteed during the measurement process to ensure accurate monitoring results.

2.4. Data analysis and calculation methods

All statistical analyses, such as the mean value and Pearson correlation coefficient, were performed by SPSS 26.0, and scatter matrix plots were drawn by SPSS 26.0. The distribution characteristics of each characteristic pollutant were tested by the Shapiro–Wilk test. If the value of the Shapiro–Wilk test *p*-value was greater than 0.05, it indicated that the distribution of each pollutant obeyed a normal distribution. The correlation between each characteristic pollutant was determined by Pearson correlation analysis.

The calculation of the exceedance multiplier is:

$$E_x = \frac{C_d}{C_s}$$

where E_x is the exceedance multiplier of each pollutant, C_d is the actual detected concentration of each pollutant (mg/L), and C_s is the concentration of the national standard (mg/L). Most of China's township sewage treatment plants implement the Class I B standard in the Emission Standards for Pollutants from Urban Sewage Treatment Plants (GB18918-2002). The emission concentration limits of each pollutant indicator are as follows: BOD_5: 20 mg/L; COD: 60 mg/L; NH_3-N: 8 mg/L; TP: 1 mg/L; TN: 20 mg/L; and SS: 20 mg/L.

The calculation of pollutant removal efficiency is:

$$E_f = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} \times 100\%$$

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where E_f is the pollutant removal efficiency, C_{in} is the concentration of a pollutant at the inlet (mg/L), and C_{out} is the concentration of a pollutant at the outlet (mg/L).

The calculation of the estimated actual wastewater treatment volume is:

$$Q_a = \frac{p \times q \times k}{1{,}000}$$

where Q_a is the estimated actual wastewater treatment volume (t/d); p is the population of each village (person); q is the daily sewage discharge per capita (L/person-day), determined according to the Chinese national standards (Ministry of Health of the People's Republic of China 1989), which was taken as 80 L/person-day; and k is the domestic sewage discharge coefficient, which was taken as 0.8 according to a similar study (Yuan *et al.* 2010).

To analyze the pollutant removal efficiency with different hydraulic retention times, the concept of α was introduced, and it represents the length of the hydraulic retention time. A smaller α value indicates a longer hydraulic retention time. The formula for calculating α is as follows:

$$\alpha = \frac{Q_a}{Q_d}$$

where Q_a is the same as described above and Q_d is the design treatment scale (t/d).

3. RESULTS AND DISCUSSION

3.1. Characteristics of sewage water quality in inflowing sewage

3.1.1. Pollutant concentrations in inflowing sewage

The water samples of domestic sewage collected from 16 villages were statistically analyzed to obtain the overall characteristics of rural domestic sewage in the study area, and the Shapiro–Wilk test was used to test whether pH, BOD_5, COD, NH_3-N, TP, SS, and TN satisfied a normal distribution. The results are shown in Table 2.

As seen in Table 2, the *p*-value of the S–W test of each characteristic pollutant was less than 0.05, except for that of pH, where the *p*-value was greater than 0.05. The results indicated that the distribution of pH satisfied a normal distribution among villages, while the distribution of the remaining characteristic pollutants did not satisfy a normal distribution among villages. Therefore, the BOD_5, COD, NH_3-N, TP, SS, and TN were log-transformed, and the Shapiro–Wilk test was still used to test the significance of each characteristic pollutant after log-transformation. The results showed that the significance of BOD_5, COD, NH_3-N, TP, SS, and TN after logarithmic transformation was greater than 0.05, so BOD_5, COD, NH_3-N, TP, SS, and TN satisfied the log-normal distribution. When the normal distribution is satisfied, the mean can be described by the arithmetic mean; however, when the log-normal distribution is satisfied, the mean can be described by the geometric mean. The average values of pH, BOD_5, COD, NH_3-N, TP, SS, and TN in the whole study area were 7.15, 23.5 mg/L, 82.4 mg/L, 9.5 mg/L, 1.6 mg/L, 42.6 mg/L, and 18.3 mg/L in summer and 7.15, 31.5 mg/L, 91.7 mg/L, 14.6 mg/L, 2.3 mg/L, 54.5 mg/L, and 26.82 mg/L in winter, respectively. The results were similar to those of Zhang *et al.* (2008), who studied the drainage of some rural domestic sewage in the Minjiang Basin within Sichuan Province. The pH values were stable near the neutral level in both summer and winter, indicating that domestic sewage did not cause acid-base pollution of water bodies, and this result was consistent with the results of Xie *et al.* (2018), who analyzed the water quality of rural domestic sewage in Southwest China.

Figure 2 shows the difference in BOD_5, COD, NH_3-N, TP, SS, and TN concentrations between winter and summer (concentration difference = winter concentration − summer concentration). Figure 2 shows that the concentrations of each pollutant in the study area were higher in winter than in summer, except for the concentration of COD in Shunhe village and the concentrations of COD and SS in Xinshan village, which were higher in summer. The results of this study were consistent with the findings of other scholars (Hou *et al.* 2012; Li *et al.* 2014; Liu 2015).

3.1.2. Correlation analysis of pollutant concentrations in inflowing sewage

As shown in Section 3.1.1, the pH value conformed to a normal distribution, and the BOD_5, COD, NH_3-N, TP, SS, and TN concentrations conformed to a log-normal distribution, so Pearson correlation analysis was performed on each characteristic

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Table 2 | Summary of monitoring results of rural domestic sewage quality in the study area

	Concentration (mg/L)													
	pH		**BOD_5**		**COD**		**NH_3-N**		**TP**		**SS**		**TN**	
Indicators	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Maximum value	7.79	7.80	300.0	320.0	632.0	630.0	77.1	90.0	17.6	19.2	450.0	430.0	72.0	82.0
Minimum value	6.67	6.72	1.0	2.1	31.0	32.0	0.4	1.3	0.3	1.0	13.0	19.0	5.0	8.2
Arithmetic mean	7.15	7.15	49.5	59.5	123.5	131.6	18.9	25.7	2.8	3.4	67.4	76.6	24.4	33.8
Geometric mean	7.14	7.15	23.5	31.5	82.4	91.7	9.5	14.6	1.6	2.3	42.6	54.5	18.3	26.8
Significance *p*-value (S–W test)	0.785	0.557	0.000	0.000	0.000	0.000	0.002	0.003	0.000	0.000	0.000	0.000	0.010	0.025
Significance after log-transformation *p*-value (S–W test)	0.498	0.247	0.758	0.783	0.074	0.158	0.682	0.745	0.702	0.056	0.062	0.052	0.844	0.422

Note: Shapiro–Wilk test with *p*-value > 0.05 indicates that the data in this group obeyed a normal distribution.

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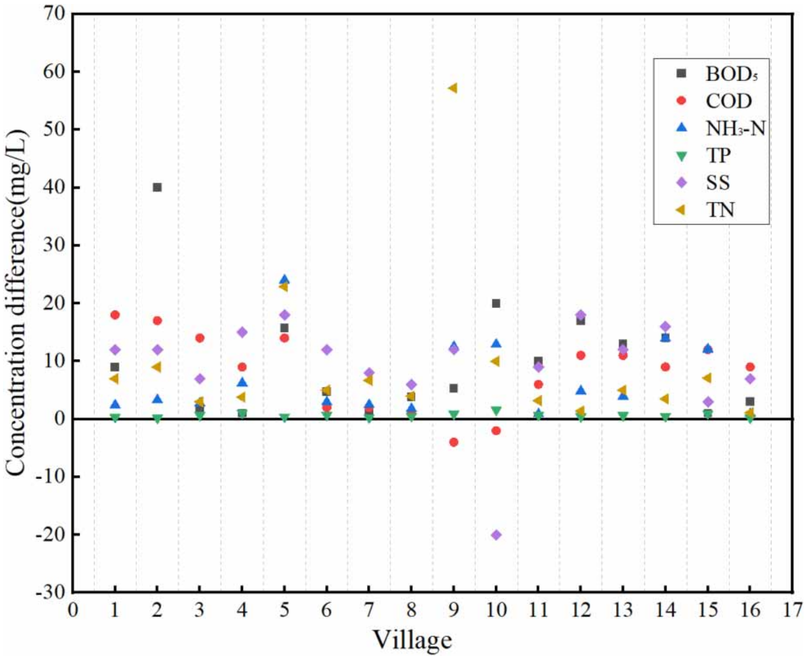

Figure 2 | Differences between the winter and summer concentrations of each characteristic pollutant.

pollutant concentration. The study of the correlation of each index of imported water quality is necessary to grasp the relationship between the pollutants, and it has certain guiding significance for the selection of wastewater treatment technology. Pearson correlation analysis was performed on each characteristic pollutant concentration using SPSS software, and the statistical table of correlation coefficients of each index was obtained as shown in Table 3. The scatter plot matrix of each characteristic pollutant concentration is shown in Figure 3.

As shown in Table 3 and Figure 3, there were significant or highly significant correlations between the concentrations of all characteristic pollutants except pH. In summer, there were highly significant correlations between the concentrations of BOD_5, COD, NH_3-N, TP, SS, and TN. In winter, there were significant or highly significant correlations between the concentrations of BOD_5, COD, NH_3-N, TP, SS, and TN.

According to the results of other scholars, the strong correlation between each characteristic pollutant is due to the adsorption of other pollutants during the flow of SS (Hu 2013) or the presence of each characteristic pollutant in the form of SS (Cao & Chen 2003). Based on the strong correlation between the SS and the remaining pollutants, in the process of wastewater removal, the concentration of each of the remaining pollutants was reduced when the SS pollutants were removed. Therefore, the concentration of each pollutant can be reduced to a greater extent if precipitation and filtration are carried out first in the wastewater treatment process, and this research result can provide a reference for establishing the removal procedure of the wastewater treatment process. In addition, NH_3-N, TP, and TN were highly significantly positively correlated, which was probably caused by most of the nitrogen and phosphorus coming from detergents, laundry detergents, and other cleaning products in rural domestic sewage and resulted in a certain homogeneity of nitrogen and phosphorus pollution.

3.1.3. Analysis of excess indexes of pollutant concentrations in inflowing sewage

With the continuous improvement of the living standards of rural residents, the load generated by rural domestic sewage will increase significantly in the future and pose great challenges to local sewage treatment. It is necessary to study the main exceedance indexes in current domestic sewage, which provides some reference for the future treatment of rural domestic sewage. In this study, the excess indexes of domestic sewage water quality in each village were analyzed, and the analysis results are shown in Table 4.

To draw conclusions that were unaffected by the extreme values in the data, the median was used to reflect the general level of exceedance of domestic sewage quality standards within the study area. As seen from Table 4, the relationship between the

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Table 3 | Statistics of the correlation coefficient of each characteristic pollutant concentration

Indicators	**pH**	**BOD_5**	**COD**	**NH_3-N**	**TP**	**SS**	**TN**
pH	1.000(1.000)						
BOD_5	0.071(0.044)	1.000(1.000)					
COD	0.046(0.053)	0.998**(0.996**)	1.000(1.000)				
NH_3-N	0.471(0.466)	0.696**(0.603*)	0.688**(0.616*)	1.000(1.000)			
TP	0.249(0.287)	0.894**(0.842**)	0.895**(0.873**)	0.822**(0.772**)	1.000(1.000)		
SS	0.173(0.190)	0.953**(0.932**)	0.952**(0.950**)	0.729**(0.665**)	0.968**(0.960**)	1.000(1.000)	
TN	0.002(0.396)	0.655**(0.576*)	0.665**(0.587*)	0.747**(0.974**)	0.799**(0.711**)	0.686**(0.597*)	1.000(1.000)

Note: Correlation coefficients outside the parentheses are for winter and those inside the parentheses are for summer.

** p-value < 0.01, * p-value < 0.05.

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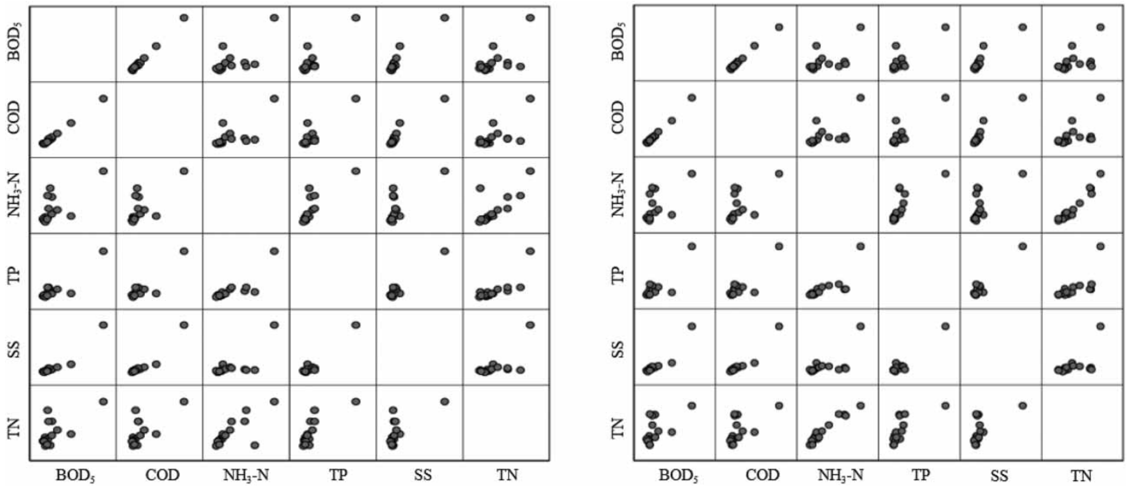

Figure 3 | Scatter matrix of the concentration of each characteristic pollutant (summer on the left, winter on the right).

Table 4 | Statistics on the number of exceedances of each characteristic pollutant

Indicators	**Season**	**BOD$_5$**	**COD**	**NH$_3$-N**	**TP**	**TN**	**SS**
Maximum value	Summer	15.00	10.53	9.64	17.60	3.60	27.50
	Winter	16.00	10.50	11.25	19.20	4.10	26.50
Minimum value	Summer	1.20	1.15	1.01	1.10	1.05	1.15
	Winter	1.05	1.00	1.28	1.25	1.12	1.07
Median	Summer	2.25	1.78	2.57	2.40	2.10	2.35
	Winter	2.15	1.93	3.56	2.99	2.28	2.60

magnitude of exceedance of each pollutant was as follows: NH_3-N > TP > SS > BOD_5 > TN > COD (summer) and NH_3-N > TP > SS > TN > BOD_5 > COD (winter).

Table 4 shows that the most serious exceedances of pollutants in the study area were found for NH_3-N, TP, and SS in both summer and winter. The median exceedances of NH_3-N were 2.57 and 3.56 in summer and winter, respectively; the median exceedances of TP were 2.40 and 2.99 in summer and winter, respectively; and the median exceedances of SS were 2.35 and 2.60 in summer and winter, respectively. Some scholars (e.g., Huang *et al.* 2016; Chen *et al.* 2019b) have shown that the reason for the high concentrations of NH_3-N and TP may be due to the large number of poultry, such as chickens and ducks, and livestock, such as pigs and cattle, in rural areas, as these animals produce a large amount of manure containing a large amount of NH_3-N. In addition, more phosphorus-containing detergents and laundry detergents are used in the washing processes of residents and lead to a high concentration of TP in the washing effluent. The wastewater treatment process should focus on NH_3-N and TP to avoid eutrophication in the surrounding water bodies. The reason for the high SS concentration may be because the study area is in the warm and humid subtropical Pacific southeast monsoon climate zone with abundant rainfall, and the abundant rainfall brings large-particle pollutants into the outfall area due to the combined flow of rain and sewage.

3.2. Analysis of pollutant removal efficiency

3.2.1. Comparison of pollutant removal efficiency by different processes

For rural areas with specific conditions, the characteristics of domestic sewage discharge should be comprehensively investigated to select a targeted wastewater treatment process. For existing rural domestic wastewater treatment processes, it is important to evaluate the process applicability (Zhang 2020), and the removal efficiency is particularly important in the evaluation of process applicability.

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In this study, the water samples collected from the inlet and outlet of each village wastewater treatment plant were analyzed, and the removal efficiency of each process for each characteristic pollutant (taking summer as an example) was calculated, as shown in Figure 4. The figure shows that for BOD_5 and COD, the CO + CW treatment effect was the best, with removal efficiencies of 96 and 94.86%, respectively, followed by the A/O treatment, MBR-integrated equipment, and CW treatment; furthermore, the CO + HA treatment and septic tank had the worst organic matter removal. For NH_3-N, the best removal process was from the MBR with 95.75% removal efficiency, followed by the A/O process, CO + HA treatment process, and CO + CW treatment process, and finally, the CW process and septic tank. For TP, the best removal process was from the CO + HA treatment process with 80.90% removal efficiency, while there was no significant difference in the removal efficiency of the remaining processes, with a removal rate of approximately 60%. For SS, the highest removal efficiency was observed in the CO + CW treatment process, with a removal efficiency of 96.23%, the lowest removal efficiency was observed in the septic tank, with a removal efficiency of 43.33%, and the remaining processes had a removal efficiency of approximately 80%. For TN, the highest removal efficiency was observed for the A/O process, with a removal efficiency of 90.26%, followed by the CO + CW treatment process, CO + HA treatment process, and MBR-integrated equipment, and the lowest removal efficiency was observed for the CW process and septic tank.

Currently, most rural areas in China have not yet or are planning to build wastewater treatment plants. The removal efficiency of each pollutant by different processes was obtained in this study, and this information can provide an important reference basis for the selection of wastewater treatment processes in different types of areas.

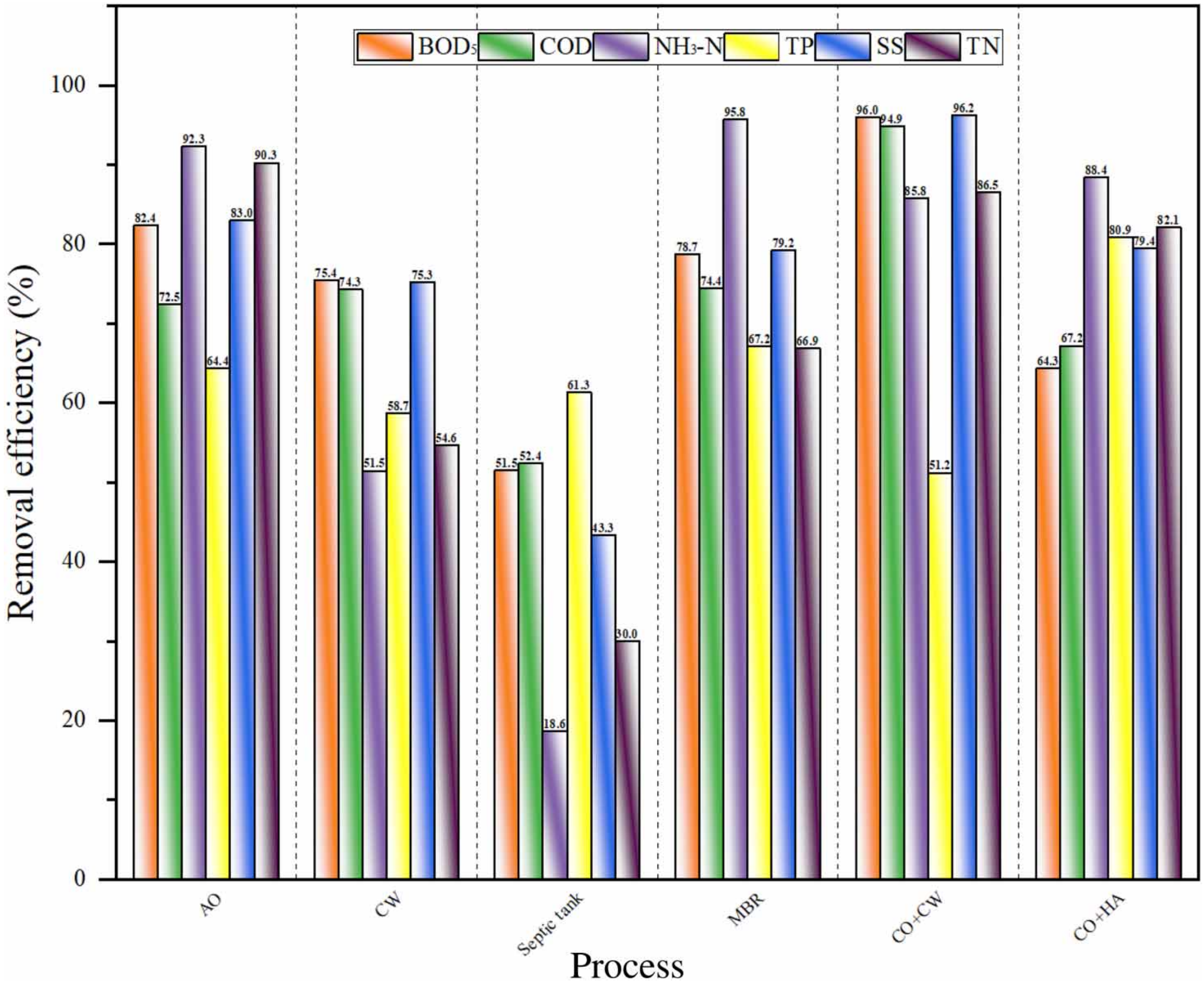

Figure 4 | Removal efficiency of each characteristic pollutant by the process (in summer).

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3.2.2. Comparison of pollutant removal efficiency in different seasons

The collected water samples were analyzed, and the removal efficiency of each process for each characteristic pollutant in winter and the reduction rate relative to the removal efficiency in summer are shown in Table 5. The table shows that for organic BOD_5 and COD, the smallest decrease in removal efficiency in winter compared with summer was from the CO + CW treatment process. For NH_3-N, the smallest decrease in removal efficiency in winter was observed with the MBR-integrated treatment equipment. For TP, the smallest decrease in removal efficiency in winter was observed in the CO + CW treatment process and CO + HA treatment process; however, for SS and TN, the smallest decrease in removal efficiency in winter was observed in the CO + HA treatment process. The removal efficiency of various processes for each characteristic pollutant was generally reduced in winter compared with summer, but the reduction rate was different. The appropriate wastewater treatment technology should be selected based on the actual level of local pollutants to minimize the influence of temperature on wastewater treatment.

The results of this study showed that the climatic temperature is an important factor affecting the wastewater treatment process, and temperature affects the activity of microorganisms, which is consistent with the results of other scholars in related fields (Zhang *et al.* 2009; Jóźwiakowski *et al.* 2020; Li *et al.* 2022). Therefore, the study of pollutant removal efficiency in different seasons can serve as a guide for the selection of wastewater treatment processes, and the process that is used should ensure a high pollution elimination effect in different seasons and ideally be less affected by season.

3.2.3. Comparison of pollutant removal efficiency with different hydraulic retention times

Each wastewater treatment facility has a certain design treatment scale. When the actual amount of domestic sewage generated is larger than the design treatment scale, it will lead to an insufficient hydraulic retention time of the wastewater, which in turn will affect the wastewater treatment effect. This section discusses and analyzes the removal efficiency of each characteristic pollutant, starting from the relationship between the actual estimated sewage generated and the design treatment scale. According to the calculation method of the actual sewage treatment estimated volume and α in Section 2.4, the actual sewage treatment estimated volume and α value of each village were calculated as shown in Table 6. The influence of α on the removal efficiency of each characteristic pollutant was analyzed (taking summer as an example), and Figure 5 shows the correlation between α and the removal efficiency of BOD_5. The correlation coefficient between α and the BOD_5 removal efficiency was obtained by Pearson correlation analysis as -0.861 ($p < 0.05$). Combined with Figure 5, it can be seen that there is a significant negative correlation between α and the BOD_5 removal efficiency. This result indicates that a smaller α results in a higher removal efficiency and a better removal effect of each pollutant.

In this study, the concept of α was proposed, and a significant negative correlation between α and removal efficiency was obtained. The research results can provide new ideas for the design of wastewater treatment plants, e.g., estimate the amount of domestic sewage generated according to the local population and domestic sewage discharge coefficient or try to increase the design treatment scale of wastewater treatment plants within the controllable cost so that the hydraulic retention time can be increased, which could effectively improve the pollutant removal efficiency.

Table 5 | Winter removal efficiency of each characteristic pollutant by each process and the reduction rate relative to the summer removal efficiency

	Removal efficiency (%)					
Process	**BOD_5**	**COD**	**NH_3-N**	**TP**	**SS**	**TN**
A/O	74.69(9.31)	65.59(9.49)	82.38(10.77)	52.15(18.97)	76.37(7.96)	84.28(6.62)
CW	66.06(12.41)	64.10(13.73)	44.85(12.83)	52.91(9.91)	66.73(11.34)	45.66(16.43)
Septic tank	45.95(10.77)	45.58(12.98)	15.61(16.03)	49.60(19.15)	39.00(10.00)	21.40(28.67)
MBR	73.39(6.74)	69.79(6.22)	95.18(0.60)	56.19(16.32)	73.97(6.59)	57.06(14.75)
CO + CW	89.64(6.63)	91.25(3.80)	78.80(8.20)	47.31(7.60)	91.82(4.58)	80.47(7.00)
CO + HA	56.20(12.64)	59.52(11.40)	85.20(3.59)	74.14(8.36)	76.19(4.09)	77.16(6.02)

Note: Removal efficiency in winter is shown outside of parentheses, and the decrease in removal efficiency in winter relative to summer is shown in parentheses.

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Table 6 | Statistics of actual sewage volume estimation and α calculation results for each village

Number	Design treatment scale (t/d)	Actual sewage volume estimation (t/d)	α
1	250	224.0	0.90
2	250	128.0	0.51
3	100	102.4	1.02
4	30	15.4	0.51
5	40	32.0	0.80
6	80	76.8	0.96
7	70	64.0	0.91
8	50	49.9	1.00
9	40	35.2	0.88
10	30	19.2	0.64
11	20	19.2	0.96
12	150	96.0	0.64
13	100	51.2	0.51
14	130	76.8	0.59
15	90	76.8	0.85
16	150	96.0	0.64

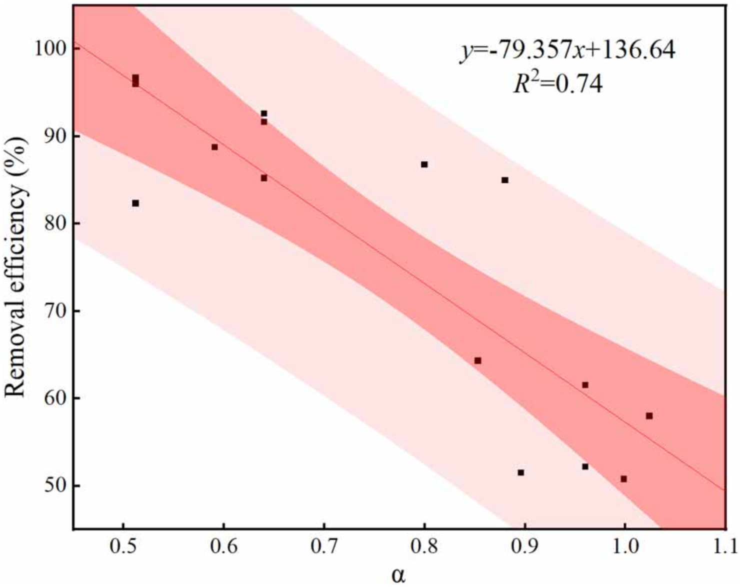

Figure 5 | Plot of the correlation between α and BOD_5 removal efficiency (taking summer as an example).

3.3. Comprehensive evaluation of rural domestic sewage treatment technology

Rural domestic sewage treatment in the context of rural revitalization strategies is an important issue related to a country's livelihood (Deng & Wheatley 2016; Wang & Zhang 2019). At present, the common evaluation systems of rural domestic sewage treatment technology include the hierarchical analysis method (Xia *et al.* 2012), fuzzy integral model method (Shen *et al.* 2014), entropy value method (Shen *et al.* 2014), and relaxed DEA model method (Cheng *et al.* 2020). Rural domestic sewage treatment methods should be integrated with local geographic conditions, economic conditions, environmental conditions and management levels in rural areas, and feasible rural domestic sewage treatment technologies must have a

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simple design, high treatment efficiency, low sludge production, simple maintenance, and low operating costs (Liu *et al.* 2013; Li *et al.* 2022); therefore, it is of great significance to explore processes that have low energy consumption, high efficiency, high utilization, and simple operation and maintenance (Ladu & Lu 2014).

According to the results of the study reported in Section 3.2, the removal efficiency of rural domestic sewage was related to the treatment process, season, and hydraulic retention time. To obtain the most suitable wastewater treatment process for removing each pollutant, the influence of factors such as season and hydraulic retention time on the wastewater removal efficiency must be excluded, and the system removal efficiency (SRE) of each pollutant by each process was obtained.

The hydraulic retention time and wastewater treatment plant water quality at the outlet were calculated as follows:

$$t = \frac{V}{Q}$$

$$C_t = C_o \exp(-kt)$$

where t is the hydraulic retention time (s); V is the effective volume of the reaction tank (m^3); Q is the influent flow (m^3/s); C_t is the effluent water quality of the wastewater treatment plant (mg/L); C_o is the influent water quality of the wastewater treatment plant (mg/L); and k is the primary kinetic reaction rate constant.

According to the above formula, we can obtain the following formula for calculating the SRE:

$$\text{SRE} = \left[1 - \left(\frac{C_t}{C_o}\right)\alpha\right] \times 100\%$$

The SRE of each pollutant for each process in summer and winter was obtained according to the formula, and the results are shown in Table 7. Considering the basic principle of sustainable development, the primary criterion for selecting the technology for rural wastewater treatment plants should be the ecological criterion, i.e., the removal efficiency of pollutants from sewage. Based on this, combined with the calculation results of the SRE and the results of the SRE in summer and winter, we can conclude that for areas with more serious BOD_5 pollution, the preferred wastewater treatment process is the CO + CW treatment process, and the removal efficiency in summer exceeds 80%. For areas with more serious COD pollution, the preferred wastewater treatment process is the CW treatment process, and the removal efficiency in summer reaches 69.57%. For areas with serious NH_3-N pollution, the preferred wastewater treatment process is the MBR-integrated equipment, and the removal efficiency exceeds 90% in both summer and winter. For areas with serious TP, SS, and TN pollution, the preferred wastewater treatment process is the CO + HA treatment process, and the removal efficiency of TP, SS, and TN in summer is 75.52, 73.93, and 76.83%, respectively. Previous studies have focused mostly on the removal efficiency of various pollutants by one treatment process; they did not propose the most suitable treatment process for each pollutant. The present study filled this gap and obtained the most suitable wastewater treatment process for each pollutant, and this information can provide an important reference basis for the selection of domestic sewage treatment technology in rural areas, especially in the Chengdu Plain.

Table 7 | Systematic removal efficiency of each pollutant by each process

	Removal efficiency (%)					
Process	**BOD_5**	**COD**	**NH_3-N**	**TP**	**SS**	**TN**
A/O	58.72(50.38)	48.20(41.96)	72.98(58.74)	40.91(31.33)	59.47(52.09)	69.50(61.08)
CW	70.34(60.15)	69.57(58.32)	46.98(40.38)	55.20(47.66)	72.11(61.77)	49.69(40.72)
Septic tank	47.86(42.52)	48.71(42.17)	16.90(14.17)	57.49(46.03)	40.02(35.91)	27.46(19.48)
MBR	69.37(62.46)	64.52(58.85)	90.14(91.71)	57.03(45.64)	69.00(63.15)	55.09(46.21)
CO + CW	80.63(68.53)	58.28(51.00)	64.43(55.37)	19.96(17.67)	58.00(46.11)	64.21(51.08)
CO + HA	58.37(50.43)	61.21(53.64)	83.95(80.29)	75.52(68.33)	73.93(70.47)	76.83(71.49)

Note: Outside the brackets are the SRE in summer, and inside the brackets are the SRE in winter.

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4. CONCLUSIONS

In this study, the concentrations of the characteristic pollutants in the rural scattered domestic sewage of the Chengdu Plain in the southwestern region of China were obtained by monitoring and analyzing the rural domestic sewage. The concentrations of the pollutants in the domestic sewage in winter were higher than those in summer. Pearson correlation analysis showed that significant correlations existed between the concentrations of the characteristic pollutants except for pH. The results of this study initially reveal the discharge pattern and characteristics of rural domestic sewage in Southwest China and provide a basic reference for the control and treatment engineering of rural surface source pollution in Southwest China. In addition, this study found that the removal efficiency of rural domestic sewage was related to the treatment process, season, and hydraulic retention time. There was a significant negative correlation between α and the removal efficiency. Combined with the calculation results of the SRE and the research results of the SRE comparison in summer and winter, we can conclude that the preferred process for the removal of BOD_5 is the CO + CW treatment process; the preferred process for the removal of COD is the CW process; the preferred process for the removal of NH_3-N is the MBR-integrated equipment; and the preferred process for the removal of TP, SS, and TN is the CO + HA treatment process. The research results provide new ideas for the construction of rural domestic sewage treatment technology in China and valuable references for rural domestic sewage treatment planning and process selection.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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