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Research on Rural Wastewater Treatment Technology in Northwest China Based on Anaerobic Biofilm Coupled with Anaerobic Baffle Plate Reactor (ABR) Technology

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Abstract: The northwest of China has a shortage of water resources, and classic sewage treatment techniques have a high cost and produce waste nitrogen and phosphorus. In order to achieve inexpensive discharge standards, an anaerobic biofilm coupled with ABR technology was adopted as a treatment for normal rural wastewater in the arid and semi-arid vicinity of Northwest China to investigate its operational impact on the treatment of northwest China's rural domestic wastewater. The results illustrated that the best pollutant elimination effect was reached under the conditions of a set temperature of 35 °C, with a set hydraulic retention time of 3 d and the application of a suspended ball filler as a hanging biofilm carrier. Therefore, the aggregated process can boost the purification capacity and offer a reference to solving the difficulty of sewage discharge in non-agricultural irrigation areas.

Keywords: biofilm; anaerobic baffled reactor; septic tank; rural domestic sewage

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1. Introduction

The northwest, arid and semi-arid vicinity of China has a paucity of agricultural irrigation resources and a simple and unpredictable environmental ecological chain structure. It is also vulnerable to external disturbances [1]. The utilisation of agricultural fertilizers has led to increased surface-sourced pollution. At present, the primary goal of the region's wastewater treatment is to meet normal discharge standards, mostly through the utilisation of aerobic aggregation processes, which not only increase the expense of treatment but also wastes the nitrogen and phosphorus in sewage required for the development of crops [2]. Additionally, the "GB 5084-2005 [3] agricultural irrigation water quality standards" (the People's Republic of China national standard) released in 2005 aimed to remove Kjeldahl nitrogen and TP indicators. Therefore, in regions where agricultural irrigation is needed, a cheap process appears to be to recycle wastewater as irrigation water. At the same time, an inexpensive advanced treatment technique is used in non-agricultural irrigation to achieve normal discharge.

Based on the ongoing national conditions of China's water resources, numerous experts and researchers have suggested that the centralised sewage treatment model is not necessarily sustainable, and there are still bottlenecks in its applicability [4]. In addition, the high concentrations of nutrient elements (such as nitrogen, phosphorus, potassium and other organic fertilizer raw materials) contained in domestic sewage have not been reused, and a considerable amount of effort is essential for the extraction of valuable by-products. Centralised sewage treatment plants also yield a large amount of separated solid sludge that has concentrated the "outcomes " of pollution. The disposal of sludge is also the greatest challenge at present. If it is not resolved, the pollutants will return to the ecological environment through various means [5].

The northwest region is financially underdeveloped, and the selection of rural wastewater treatment technology should meet the requirements for low infrastructure costs, low operating costs and low management and maintenance costs but also guarantee that the non-agricultural irrigation effluent can meet discharge standards. At present, it is difficult for a single wastewater treatment process to meet the demands of non-agricultural irrigation-area effluent discharge standards; therefore, the choice of a mixture of methods to achieve enhanced purification capacity is a viable way. In view of the inexpensive natural wastewater treatment system, which has limited potential to bear the load, inexpensive anaerobic treatments, such as a pre-treatment technology, is an ideal choice [6].

Scholars at home and abroad have undertaken many studies concerning anaerobic baffle plate reactors (ABRs), their quick start-up and continuous operation coupled with other processes, but the refinement of ABRs is primarily aimed at the heterogeneous wave formulation of baffle plates, with simulations generally being used in the research [7]. Recent studies have revealed that ABRs are viable and have certain advantages when utilised in the treatment of low-concentration organic wastewater and low-temperature organic wastewater [8]. From this, it can be seen that there is room for the benefit of ABRs in rural domestic sewage engineering; however, further research is necessary to provide a foundation for the investigation results. A modified ABR as a pre-treatment process for rural wastewater can not only eliminate most of the suspended solids and organic matter in the wastewater but also effectively kill pathogenic bacteria, and the retained nitrogen and phosphorus can enhance crop yields while reducing the amount of fertilizer used [9]. In addition, the adjustability of anaerobic biofilm technology and decentralised sewage treatment technology is very consistent. Through the coupling of two technologies, such as the mixture of biofilm techniques and ABR septic tanks, significant milestones can be reached concerning decentralised sewage treatment technology [10]. Traditional septic tanks have two main functions. On the one hand, they enable anaerobic digestion, and on the other hand, they can intercept large particles of organic matter. Moreover, although the reactors have long start-up times due to their membrane coating, it will not influence the functional application of septic tanks. Compared to septic tanks, the membrane coating is an optimization procedure to further enhance water quality. In addition, in domestic sewage, ABR septic tanks are a push-flow type, and their impact load can assist with flushing the filler and resolving the clogging challenge imposed on anaerobic biofilm technology. Therefore, in order to take advantage of both technologies, the two are combined to enhance the nitrogen- and phosphorus-elimination capacity and impact load resistance and also offer a reference for solving the difficulty related to the discharge standards of regional non-agricultural wastewater irrigation.

2. Materials and Methods

2.1. Test Device

An ABR device diagram is exemplified in Figure 1. The instrument adopted for the test primarily includes a raw-water intake bucket, a peristaltic pump (with flow meter) and an ABR device. For domestic sewage, the intake bucket is pumped by the peristaltic pump into the ABR device. According to the requirements of the test, the ABR device is equipped with different fillers. The effective volume of the ABR device is 163 L, of which the length, width and height are 1.63 m, 0.20 m and 0.50 m, respectively. The overall material used is an acrylic plate, which is divided into five compartments and two parts. Among them, the front compartment is designed as the precipitation area, and the rear part is the ABR reaction area. Each compartment of the reaction area is split into the upper and lower flow chambers according to the hydraulic flow pattern; the horizontal width proportion is 4:1, and the folding plate is a 45 folding plate. According to the comprehensive analysis of the hydraulic flow simulation in the reactor, the results demonstrated that the 45 deflector plates were set at the bottom of this test setup in order to eradicate the probable dead zone in the reaction process.

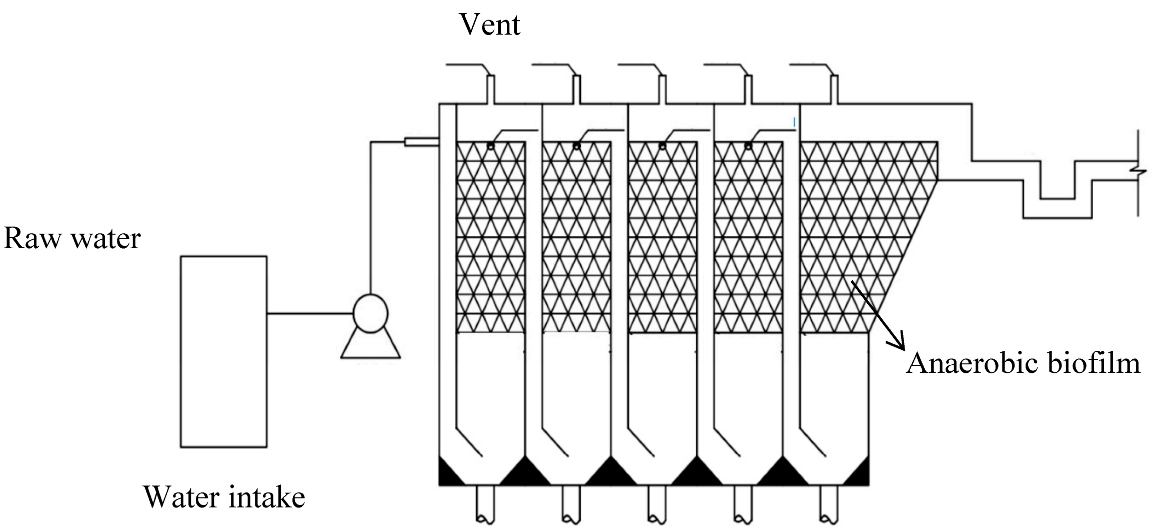


Figure 1. Diagram of the ABR setup.

2.2. Influent Water Quality

The water quality in the area of the typical locations of the rural domestic sewage treatment was examined and tested after reviewing the pertinent literature and information concerning the situation of rural domestic sewage discharge at home and abroad. Table 1 [1–4] displays, in summary analysis, the typical range of rural home wastewater.

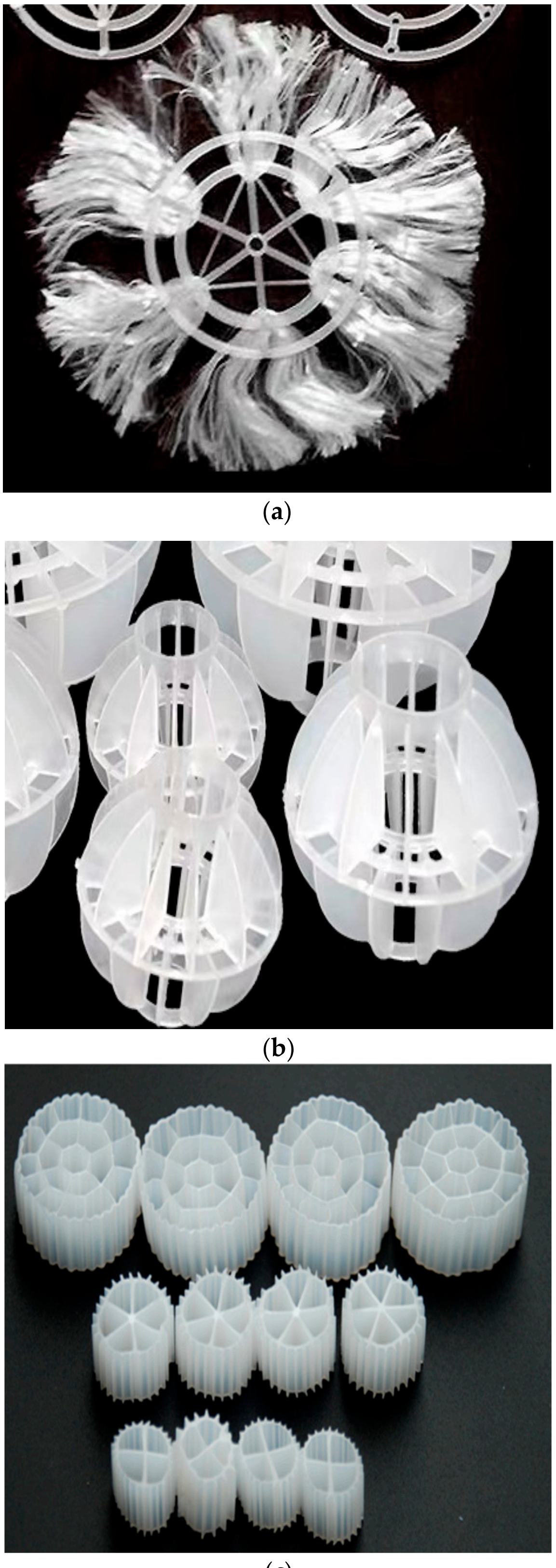
Table 1. Rural domestic sewage water quality parameters range.

Indicators	COD (mg/L)	SS (mg/L)	TP (mg/L)	TN (mg/L)	NH_4^+-N (mg/L)
Scope	121.55~408.45	31.15~165.28	2.15~6.35	24.25~77.34	22.01~39.74

Artificially synthesized wastewater from rural domestic sewage uses substances such as NH_4Cl and KH_2PO_4 in tap water. In addition, because the growth of methanogens may be influenced by trace elements, nutrients are added to the preparation water in accordance with Table 2 and trace elements are added according to Table 3. In order to keep the pH level in the ABR septic tank at about 7.0, it is also required to add the right amount of NaHCO3 to the feed water. This is because the proliferation of filamentous bacteria is likely to occur in an acidic environment.

The elastic packing is a filler made from an elastic section connected to another strip. It has the advantages of a uniform distribution, it is difficult to obstruct, and it is an effective treatment. The floating ball has an inner and an outer layer and is constructed of polypropylene formed through injection molding. The interior portion is a rotating cylinder, and the outer portion is a hollow fishnet sphere. It has the characteristics of strong biological adhesion, a large specific surface area, high porosity and strong hydrophilicity. Fluidised bed filler is a new type of bioactive carrier, which is made of high-quality copolymer materials; thus, it will not be degraded, and it is not harmful to microorganisms after being soaked in wastewater for a long time. Additionally, it has a highly effective decarbonization capability as well as a superior ammonia nitrogen removal impact.

The effect of biofilm carrier materials on the effluent treatment effect of the reactor was investigated in the experiment, and the selected materials and their properties and physical objects are shown in Table 4 and Figure 2a–c, respectively.



(**a**) (**b**) (**c**)

Figure 2. (**a**) Elastic packing, (**b**) floating ball, (**c**) fluidised bed filler.

Table 2. Composition and concentration of synthetic wastewater dispensed from rural domestic sewage.

Indicators	Corresponding Components	Content (mg/L)
COD	$C_{12}H_{24}O_{11}$, $C_6H_{12}O_6$	100~150
Total Nitrogen	NH_4Cl	25~50 (Subsequent adjustment according to COD concentration)
Total phosphorus	KH_2PO_4	2~8 (Subsequent adjustment according to COD concentration)
Alkalinity	$NaHCO_3$	Adjustment according to the actual situation

Table 3. The dosage of trace elements.

Name	Dosing Amount (g/L)
$MnCl_2 \cdot 4H_2O$	0.5
$CuCl_2 \cdot 2H_2O$	0.03
$ZnCl_2$	0.05
$CaCl_2 \cdot 2H_2O$	8
$FeCl_3 \cdot 4H_2O$	2
$MgSO_4 \cdot 4H_2O$	0.1

Table 4. Hanging film filler and its properties.

Packing Type	Specification	Specific Surface Area (m^2/m^3)
Elastic packing	$\Phi 180 \times 100$ mm	348
Floating ball	$\Phi 25$ mm	460
Fluidised bed filler	$\Phi 25 \times 12$ mm	300

2.3. Inoculated Strain

The cultivation of membrane-bound microorganisms is an important part of the rapid start-up success and efficient and stable operation of the ABR [11]. In the experiments, the ABR units were inoculated with a mixture of strains of bacteria isolated from swine farm methane sludge samples and anaerobic sludge samples, which were continuously fed into the raw water after one day of resting.

2.4. Experimental Analysis Methods

A start-up phase and an operational phase make up this experiment, which treats home wastewater outdoors using a biofilm-coupled ABR septic tank. The film-mounted microorganisms need time to adapt during the start-up phase; therefore, the influent water is simulated artificial sewage containing few impurities. Because the simulated sewage cannot accurately represent the actual application of the ABR unit in practice, the actual domestic black water produced by the power station workers is used in this phase of the experiment. There are some differences between actual domestic black water and actual rural sewage, but it is feasible to use actual domestic black water in this phase of the experiment. The single-factor method was used in this phase of the experiment to select three indicators: HRT (hydraulic retention time), hanging film carrier and temperature, and three values were set to derive the optimum reaction conditions for the biofilm-coupled ABR septic tank unit.

According to "Water and wastewater monitoring and analysis techniques" (4th edition), the main index detection methods were as follows: COD was diagnosed using the rapid closed catalytic digestion method; for SS, we used the GB 11901-1989 [12]"Weight method"; for ammonia nitrogen, we used HJ 535-2009 [13] "Nessler reagent spectrophotometry"; TN was oxidized by potassium persulfate–UV spectrophotometry; TP was determined through the use of molybdenum antimony antispectrophotometry.

3. Results and Discussion

3.1. Effect of Different HRT on the Operation of Anaerobic Biofilm-Coupled ABR Septic Tanks

The main parameters affecting the operation of an ABR are temperature, HRT, OLR (organic loading rate), pH and ammonia nitrogen concentration, among others.

After the start-up of the biofilm-coupled ABR septic tank was complete, the domestic wastewater from the power station was used as the influent, and the influent bucket was insulated to a certain extent through the addition of a heating rod. The hydraulic retention time was changed by adjusting the mode of the peristaltic pump flow rate, and the HRT was set to 5 d, 3 d and 1 d, respectively. Each working condition was run for 14 d. The effluent indexes of the ABR unit were monitored to study the changes in the indexes of the biofilm-coupled ABR septic tank operating under different HRT working conditions, and the parameters of the influent water are shown in Table 5.

Table 5. Test feed water quality parameters.

Indicator	COD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	Temperature (°C)
Range	164.76~469.95	61.18~167.80	42.99~85.61	2.77~7.45	19.2~25.8

3.1.1. Analysis of the Variation of COD at Different HRT during the Operation Phase

The influent COD concentration of the ABR unit ranged from 215.54 to 299.78 mg/L under the set HRT of 5 d (Figure 3). The effluent COD concentration of the ABR coupled with biofilm ranged from 106.24 to 166.43 mg/L, with a removal rate of 40.23% to 60.92%, with an average removal rate of 54.74%. After the start-up phase, the removal rate of the ABR unit was maintained at a good level. After adjusting the HRT of the ABR unit for 3 d, the COD concentration of the influent water was 248.05~469.95 mg/L, and the COD concentration of the effluent water was 149.68~306.32 mg/L, the removal rate was 53.88~70.94%, the average removal rate was 62.82%, and it can be seen that after shortening the HRT, the removal rate of COD by the ABR unit appeared to increase, and the effect was good. The removal rate of COD from the ABR unit increased after shortening the HRT, and the effect was good. When the HRT was reduced again to 1 d, the influent COD concentration of the ABR plant ranged from 164.76 to 279.14 mg/L, and the effluent COD concentration ranged from 74.52 to 161.34 mg/L. The removal rates ranged from 42.03% to 60.64%, with an average removal rate of 49.01%. The removal rate of the ABR unit showed a decreasing trend after further shortening the HRT, but the removal rate was still stable at over 42.00%.

When decreasing HRT from 5 d to 1 d step by step, the COD removal rate of the biofilm-coupled ABR device showed an increasing trend before decreasing, which is mainly due to the fact that the longer HRT can make the microorganisms fully contact the organic matter in the feed water. The environment is suitable for the growth, metabolism and reproduction of anaerobic microorganisms, and the main hydrolytic acidification reaction occurs in the system, which promotes the microbial decomposition of large particles of organic matter. When the HRT was reduced to 3 d, the COD removal rate of the ABR unit increased, mainly because after the HRT was further shortened, the folding plate in the unit prevented the re-mixing effect, making the mixing of each compartment more adequate, and the COD concentration of the influent water increased by 27.16% compared to the HRT = 5 d. The increase in the organic load of the influent water promoted the increase in the COD removal rate of the ABR unit. The increase in feed water organic load contributed to the increase in COD removal rate of the ABR unit. When the HRT was reduced again to 1 d, the hydraulic retention time was very short and the organic matter contained in the influent water flowed directly into the rear compartment before it was completely degraded in the front compartment, resulting in a significant decrease in the COD removal rate as the microorganisms could not fully contact the organic matter [14].

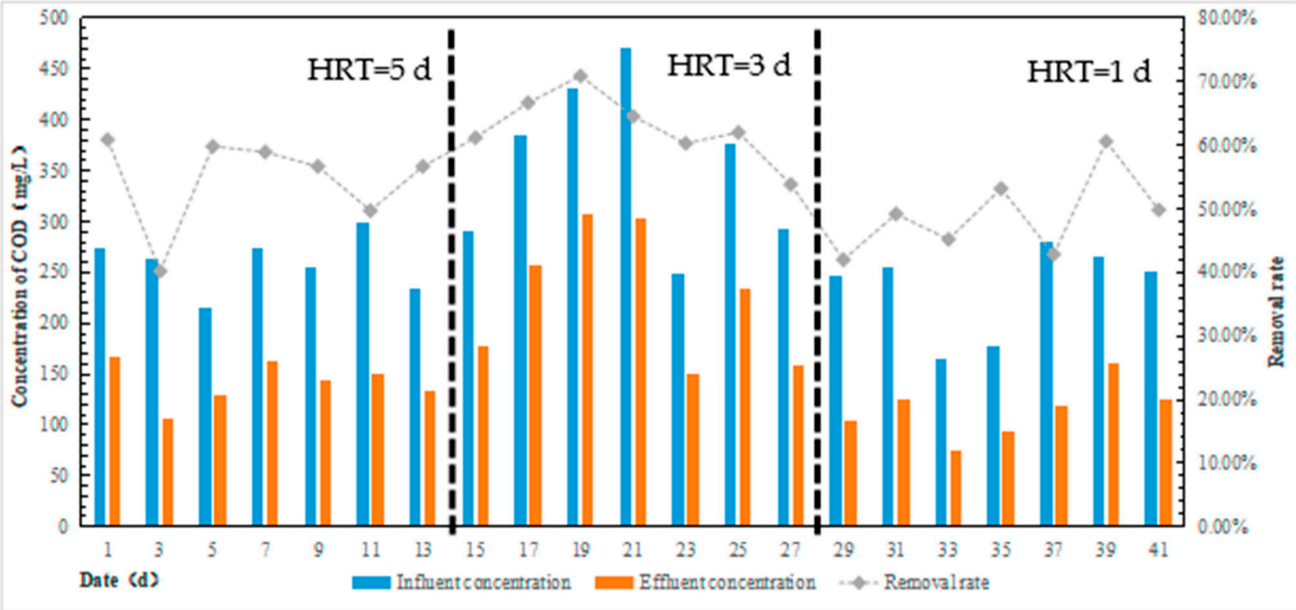


Figure 3. Effect of different HRT biofilms coupled with ABR septic tanks on COD removal.

The main reason is that, on the one hand, the hanging film filler in each compartment helps to intercept part of the organic matter in the incoming water and, on the other hand, after the start-up phase, the surface of the filler has been fully hung with a layer of biofilm, which also enhances the removal rate of COD in the ABR septic tank. On the other hand, after the start-up phase, the surface of the filler has been sufficiently coated with a biofilm, which also enhances the COD removal rate of the ABR plant and, at the same time, under the condition of HRT = 3 d, the treatment efficiency of the effluent is improved, and the organic matter in the effluent is fully contacted with the biofilm, indicating that HRT = 3 d is the best hydraulic retention time for COD removal at the present experimental stage.

3.1.2. Analysis of SS Variation at Different HRTs during the Operational Phase

Figure 4 shows that when the HRT of the biofilm-coupled ABR unit = 5 d, the SS concentration of the influent was 74.58~167.80 mg/L, and the SS concentration of the effluent from the ABR unit was 16.31~25.05 mg/L, with corresponding removal rates of 75.00%~86.18% and an average removal rate of 82.47%. When the HRT of the ABR unit = 3 d, the SS concentration of the influent water ranged from 61.18 to 113.61 mg/L, and the SS concentration of the effluent water ranged from 11.07 to 27.97 mg/L, with the corresponding removal rates ranging from 75.31% to 83.33%, with an average removal rate of 76.33%. When the HRT of the ABR unit = 1 d, the SS concentration of the influent water ranged from 61.18 to 126.43 mg/L, and the SS concentration of the effluent water ranged from 12.82 to 28.55 mg/L, with the corresponding removal rates ranging from 70.00% to 83.58%, and the average removal rate was 77.44%.

It can be seen that with the shortening of the HRT, the ABR device, as a whole, showed a decreasing trend, which is mainly due to the fact that the removal of SS by the ABR device mainly relies on the retention and adsorption of the biofilm and the sedimentation effect of the device; therefore, a longer HRT will make the hydraulic flow rate lower, which helps the settling of impurities, and with the further shortening of the HRT time, the hydraulic load further increases. As the HRT time was further reduced, the hydraulic load was further increased, and the higher hydraulic load directly led to the weakening of the settling effect and a decrease in SS removal by the ABR unit. Overall, the biofilm-coupled ABR plant performed well in terms of SS removal under different HRT conditions, with an average removal rate of 78.75% for the whole stage, and 77.44% even when the HRT was shortened to 1 d. This indicates that the biofilm has a positive effect on optimizing the SS removal performance of the ABR plant and can enhance the ability of the ABR system to resist hydraulic factors. The average removal rate was 77.44%, even at a reduced HRT of 1 d. This indicates that the biofilm has a positive effect in terms of optimizing the SS removal performance of the ABR plant and enhances the ability of the ABR system to cope with hydraulic shock loads.

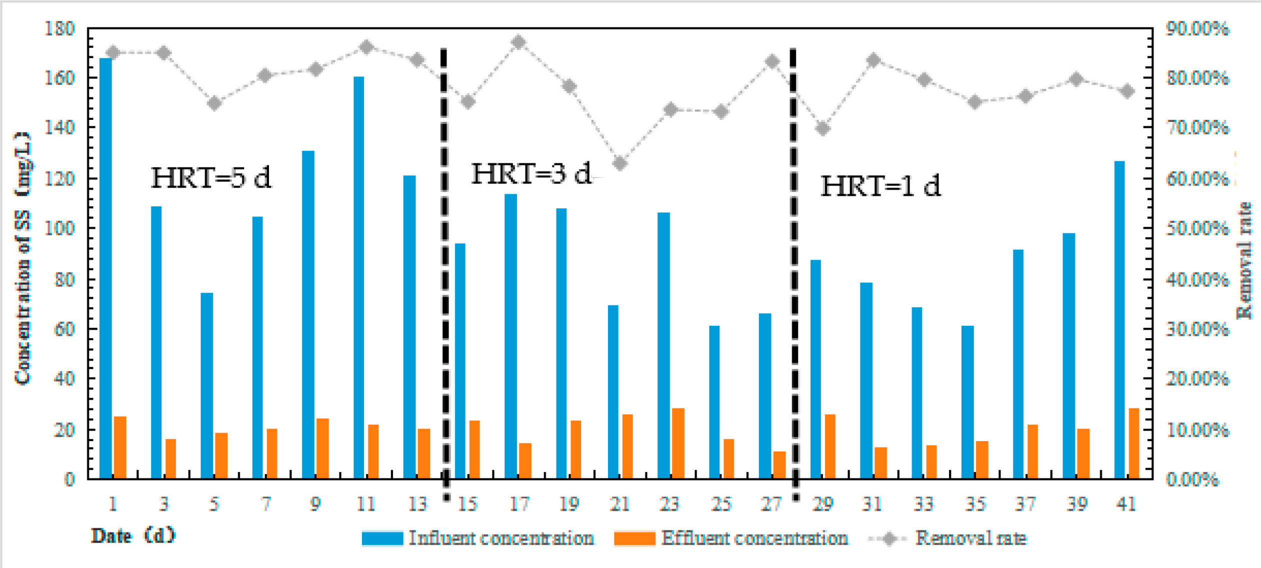


Figure 4. Effect of different HRT biofilms coupled with ABR septic tanks on SS removal.

3.1.3. Analysis of the Variation of TN (Total Nitrogen) at Different HRT during the Operation Phase

Figure 5 shows that at HRT = 5 d, the influent TN concentration of the biofilm-coupled ABR unit was 42.99~61.69 mg/L, the effluent TN concentration was 40.83~57.19 mg/L, the corresponding removal rate was −3.25~11.37% and the average removal rate of TN was 3.89%. When the HRT = 3 d was adjusted, the TN concentration in the influent water was 48.38~85.61 mg/L, and the TN concentration in the effluent water was 48.56~78.06 mg/L. The corresponding removal rates were −1.40~17.30%, with an average removal rate of 5.42%. When the HRT = 1 d was lowered again, the TN concentration in the influent water was 46.76~75.54 mg/L, and the TN concentration in the effluent water was 44.96~73.92 mg/L. The corresponding removal rates were −4.31~9.09%, with an average removal rate of 3.99%.

It can be seen that the TN removal rates of the biofilm-coupled ABR device are all lower under different HRT settings. The main reason is that in the denitrification reaction of microorganisms, the denitrifying microorganisms usually select oxygen as the electron acceptor and do not prefer nitrite, and in an anaerobic environment, where the oxygen concentration is very low, organic nitrogen compounds are usually converted into ammonia instead of nitrate; therefore, the denitrification reaction is limited and will only occur when the influent water contains nitrate or nitrite [15]. The anaerobic environment inhibits the conversion of ammonia to NO_2^--N and NO_3^--N, resulting in denitrification processes, such as nitrification–denitrification or anaerobic ammonia oxidation not reacting smoothly and, therefore, the biofilm-coupled ABR plant has limited the removal of the total nitrogen.

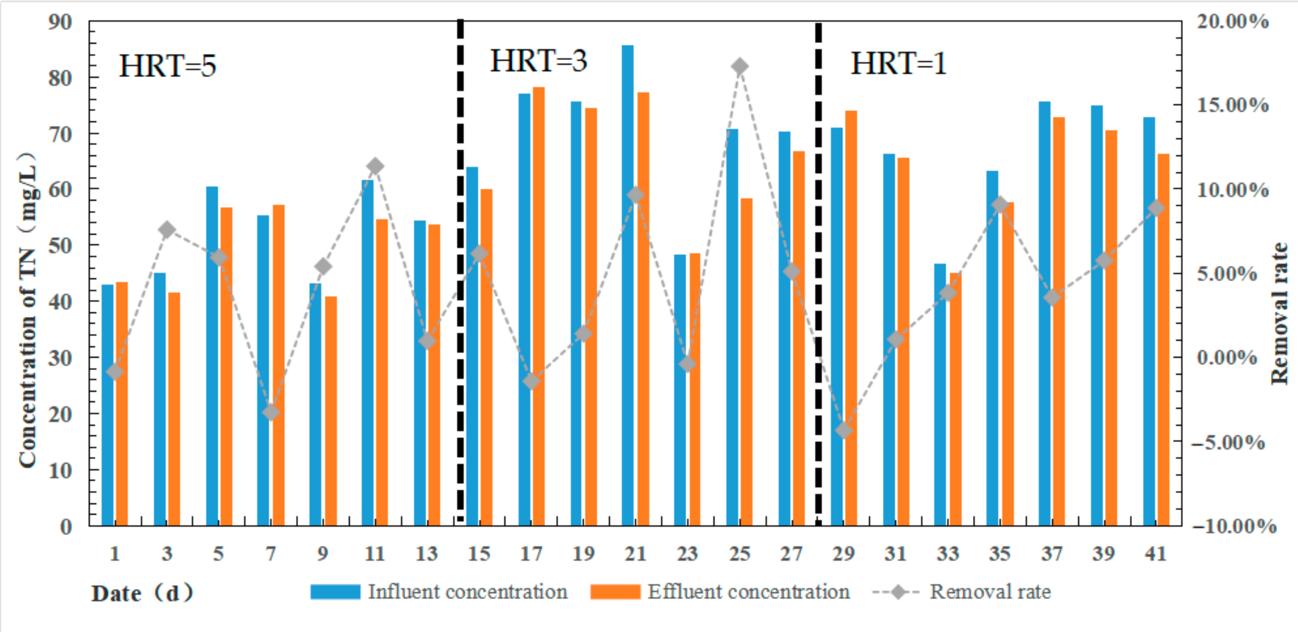


Figure 5. Effect of different HRT biofilms coupled with ABR septic tanks on TN removal.

As seen in Figure 5, the removal rate of TN by the ABR unit shows an increase and then a decrease during the stepwise shortening of the HRT from 5 d to 3 d and 1 d. This is mainly due to the change in the organic load of the influent water, which tends to decrease and then increase during the operation of HRT = 5 d, 3 d and 1 d. When the concentration of organic substrates in the influent water is low, the concentration of organic substrate that can be decomposed by anaerobic microorganisms also decreases, which makes the processes of growth and metabolism and the reproduction of anaerobic microorganisms slow down, and the demand for elemental nitrogen also decreases. At HRT = 1 d, the concentration of organic substrates in the influent water increases, the growth, metabolism and reproduction of microorganisms are good; therefore, the intake of elemental nitrogen increases and the ABR unit's rate of TN removal rate started to increase. During the experiment there were also cases where the TN concentration was higher than the influent concentration and the removal rate was negative. This may be due to the conversion of organic nitrogen compounds in the ABR unit into ammonia nitrogen, while the anaerobic microorganisms produced some ammonia nitrogen during the operation phase due to endogenous respiration and autolysis. Throughout the operation, the biofilm had limited performance in terms of removing TN from the ABR system, and the removal rate was low, with an average removal rate of only 3.99% for the whole stage, retaining the vast majority of nitrogen; therefore, it could be subsequently reused as irrigation water for farmland reclamation.

3.1.4. Analysis of the variation of TN(Total Phosphorus) at Different HRT during the Operational Phase

As can be seen in Figure 6, when setting HRT = 5 d, the TP concentration of the influent was 3.52~6.20 mg/L, and the effluent TP concentration of the biofilm-coupled ABR unit was 3.39~6.38 mg/L, corresponding to a removal rate of −2.93~4.98%, with an average TP removal rate of 1.56%. When the HRT = 3 d was adjusted, the influent TP concentration was 2.87~7.45 mg/L, and the effluent TP concentration was 2.80~7.25 mg/L, corresponding to a removal rate of 2.37~7.09% and an average TP removal rate of 4.57%. When the HRT = 1 d was further lowered, the TP concentration in the influent water was 2.87~5.28 mg/L, and the TP concentration in the effluent water was 2.77~4.98 mg/L, corresponding to a removal rate of 3.34~8.83% and an average TP removal rate of 5.77%.

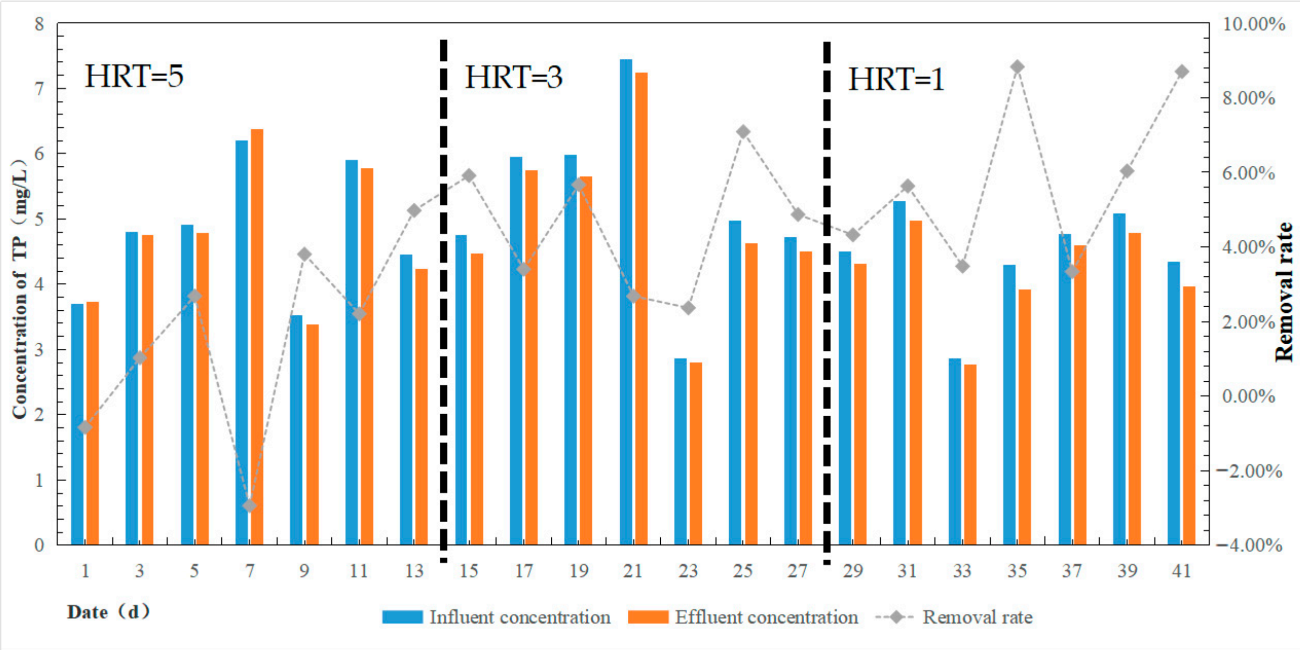


Figure 6. Effect of different HRT biofilms coupled with ABR septic tanks on TP removal.

From the analysis it can be seen that the limited TP removal capacity and low removal rate of the biofilm-coupled ABR device are mainly due to the inhibition of phosphorus uptake and phosphorus release by traditional phosphorus-polymerising bacteria in the fully anaerobic reactor, and the limited use of phosphorus by anaerobic microorganisms in the processes of growth, metabolism and reproduction. As the HRT decreases step-by-step, the organic load of the influent water increases, resulting in a higher concentration of organic matter substrates, providing sufficient nutrients for the microorganisms to grow and reproduce well and, therefore, a higher removal of phosphorus. Similarly, TP values were found to be higher than the influent values on some dates throughout the reaction process, and TP removal was negative, probably due to endogenous respiration and the autolysis of anaerobic microorganisms during the operation phase, resulting in higher TP concentrations in the effluent [16]. The vast majority of phosphorus was retained and, therefore, could be subsequently reused as agricultural irrigation water for reclamation.

3.2. Effect of Different Temperatures on the Operation of Anaerobic Biofilm-Coupled ABR Septic Tanks

After the start-up of the biofilm-coupled ABR septic tank was completed, power station domestic sewage was used as the feed water, and the feed water bucket was insulated to a certain extent through the addition of heating rods and insulation sponges. The internal temperature of the reactor was adjusted by adjusting the temperature settings of the heating rods, setting the hydraulic retention time to 3 d, setting the temperature to 35 °C, 25 °C and 15 °C, respectively, and each operating condition was run for 14 d. The effluent indexes of the ABR unit were monitored to study the changes in the indexes of the biofilm-coupled ABR septic tank operating under different HRT operating conditions, and the parameters of the feed water are shown in Table 6.

Table 6. Test feed water quality parameters.

Indicator	COD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	Temperature (°C)
Rang	201.11~298.89	52.40~173.29	34.89~68.24	2.87~6.18	15~35

3.2.1. Analysis of the Variation of COD at Different Temperatures during the Operation Phase

The COD influent concentration ranged from 205.56 to 280.68 mg/L at a set temperature of 35 °C, with an average COD influent concentration of 244.18 mg/L. The effluent COD concentration of the ABR unit coupled with the biofilm ranged from 83.33 to 120.29 mg/L, with a corresponding COD removal rate of 56.28% to 64.98% and an average COD removal rate of 59.92% and 64.98%, and the average COD removal rate was 59.92% (Figure 7). It can be seen that the ABR plant has a better performance in terms of COD removal, which is mainly because the suitable ambient temperature for the growth and metabolism and reproduction of the inoculated microorganisms is about 35 °C, and the biofilm filler can intercept the suspended matter in the influent water to a certain extent, and also intercept the organic pollutants attached to the suspended matter, and at a temperature of 35 °C, biofilm formation is more robust, and the microorganisms on the biofilm are in full contact with and degrade the organic pollutants in the influent water: therefore, the biomass in the biofilm-coupled ABR plant is also more than adequate.

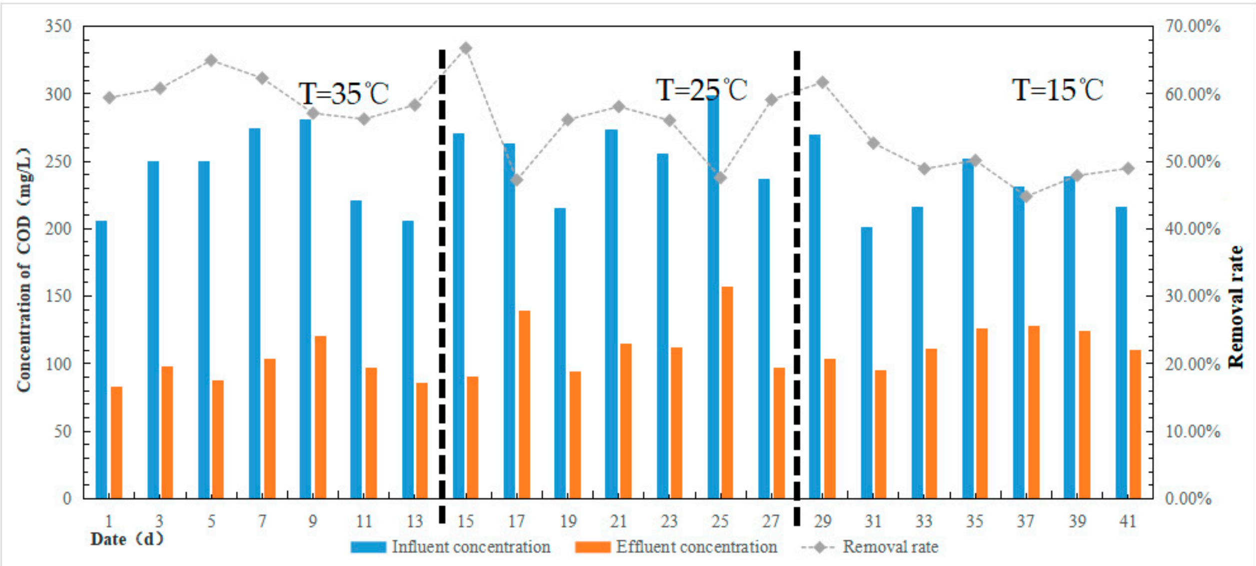


Figure 7. Effect of biofilm-coupled ABR septic tank on COD removal at different temperatures.

The range of the COD concentration in the influent water was 215.55~298.89 mg/L, with an average influent COD concentration of 259.21 mg/L, and the range of COD concentration in the effluent water was 90.00~156.67 mg/L, corresponding to a removal rate of 47.26~66.80% and an average removal rate of flat COD of 56.14%. By analyzing Figure 6, it can be seen that compared to the operating conditions where the other conditions were the same and only the temperature settings were changed to 35 °C, the ABR unit showed a decreasing trend in terms of COD removal, which was mainly due to the fact that the cellular metabolism of microorganisms was affected by the reduced temperature and the cellular activity of anaerobic microorganisms was inhibited to a certain extent at the operating condition of 25 °C; thus, the average COD removal rate decreased by 3% compared to that at the operating condition of 35 °C. The average COD removal rate decreased by 3.78% compared to 35 °C, but the overall average COD removal rate was still maintained at more than 50%, indicating that the ABR unit coupled with biofilm has some adaptability and resistance to changes in ambient temperature.

When the temperature was lowered again to 15 °C, the influent COD concentration of the ABR unit ranged from 201.11 to 270.00 mg/L, with an average COD concentration of 233.09 mg/L, and the effluent COD concentration ranged from 95.08 to 127.56 mg/L, with a corresponding COD removal rate of 44.81% to 61.73%, with an average COD removal rate of 50.74%. When the temperature was lowered to 15 °C, the decline in the biofilm-coupled ABR plant was more obvious, mainly because the activity of microorganisms received a greater impact under a low temperature, and their growth and metabolism and reproduction functions were inhibited, which made their degradation ability in terms of COD also weaken. When the temperature of the plant was 15 °C, the average COD removal rate decreased by 9.18% and 5.4% compared to 35 °C and 25 °C, respectively. It can be seen that the decrease in temperature directly affected the COD removal rate of the ABR plant, mainly because most of the dominant bacteria in the ABR anaerobic system are moderate-temperature-loving bacteria, and the low temperature will directly affect their growth, metabolism and reproduction. However, overall, the ABR plant with the coupled biofilm was able to maintain an average removal rate of >50% at lower temperatures, indicating that coupling the biofilm helped to improve the resistance of the ABR plant to low temperatures.

3.2.2. Analysis of SS Variation at Different Temperatures during the Operational Phase

The SS concentration of the influent water ranged from 81.79 to 140.57 mg/L, and the SS concentration of the effluent water ranged from 13.86 to 24.68 mg/L. The average SS effluent concentration was 18.10 mg/L, and the corresponding removal rate was 79.66% to 90.88%, with an average SS removal rate of 85.35% (Figure 8). It can be seen that under the operating condition of 35 °C, the biofilm-coupled ABR plant has a good effect on SS removal, mainly because the filler can retain most of the suspended solids in the effluent, and at the same time, at 35 °C, the biofilm hanging process is smoother, and the filler can be hung with a sufficient quantity of biofilm, which also directly enhances the interception ability of the ABR plant in terms of suspended solids.

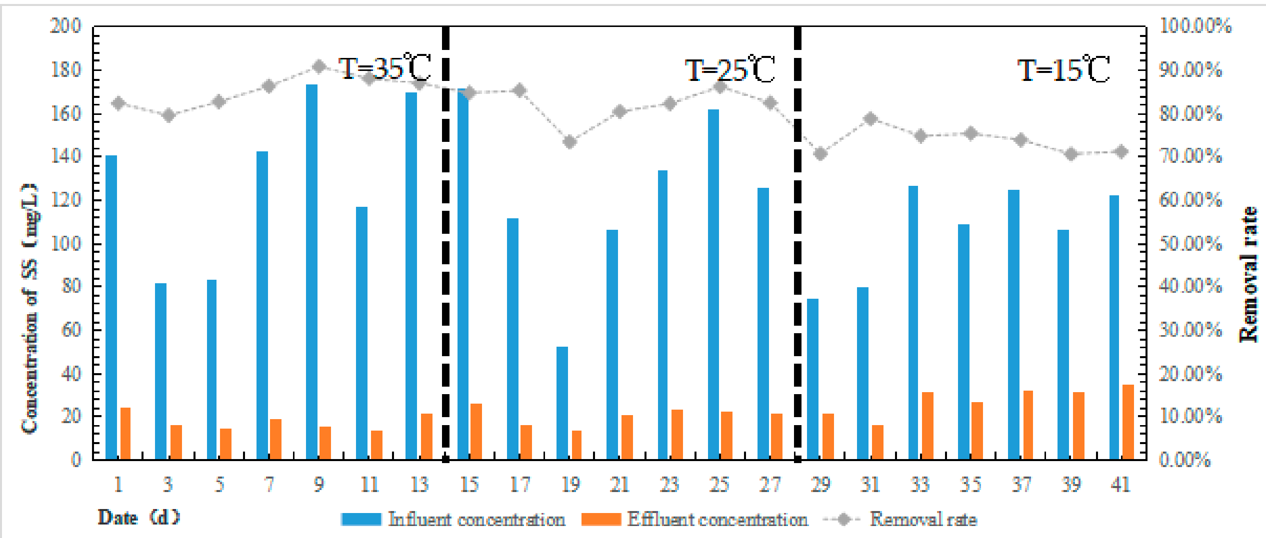


Figure 8. Effect of biofilm-coupled ABR septic tank on SS removal at different temperatures.

When the temperature was lowered to 25 °C, the SS concentration of the influent water ranged from 54.40 to 171.90 mg/L, the SS concentration of the effluent water ranged from 13.86 to 26.06 mg/L, the average SS concentration of the effluent water was 20.52 mg/L, the corresponding removal rate ranged from 75.54% to 86.30%, and the average SS removal rate was 81.70%. When the temperature continued to be lowered to 15 °C, the concentration of SS in the influent of the ABR unit ranged from 74.58 to 126.71 mg/L, the concentration of SS in the effluent ranged from 16.80 to 34.99 mg/L, the average SS concentration in the effluent was 27.49 mg/L, the corresponding SS removal rate ranged from 70.73% to 78.88%, and the average SS removal rate was 73.97%.

The analysis shows that the SS removal rate of the biofilm-coupled ABR plant decreased with the decrease in temperature, and the average SS removal rate at 15 °C decreased by 11.56% and 7.91% compared to 35 °C and 25 °C, respectively. The main reason for the decrease in the removal rate was probably due to the inhibition of microbial growth, metabolism and reproduction activities at low temperatures, resulting in a weaker interception and adsorption of suspended matter in the feed water by microorganisms [16]. Overall, despite the weakened retention capacity of the biofilm at lower temperatures, the removal rate remained above 70%, indicating that the coupled biofilm provided a certain guarantee for the SS removal rate of the ABR plant, contributing to the low temperature resistance of the ABR plant to SS removal and reducing the risk of blockage for further treatment.

3.2.3. Analysis of the Variation of TN at Different Temperatures during the Operating Phase

When the temperature was set to 35 °C, the TN concentration of the influent water ranged from 42.76 to 62.05 mg/L. The effluent TN concentration of the ABR unit coupled with a biofilm ranged from 41.25 to 57.30 mg/L. The average TN concentration of the effluent water was 49.73 mg/L. The corresponding TN removal rate ranged from −2.03% to 12.19%. The average removal rate was 3.97% (Figure 9). The low removal rate of TN by the ABR unit is mainly due to the fact that nitrification reactions of biological denitrification do not easily occur in a completely anaerobic environment, and ammonification reactions are also limited. For decentralised wastewater treatment, an aerobic treatment process can be connected after the septic tank, as the ammonification of the ABR unit can further facilitate subsequent denitrification. In addition, some of the organic nitrogen compounds in the influent water are biohydrolysed to ammonia nitrogen; therefore, in some cases, the TN concentration in the effluent is even higher than the TN concentration in the influent water, and the removal rate is negative.

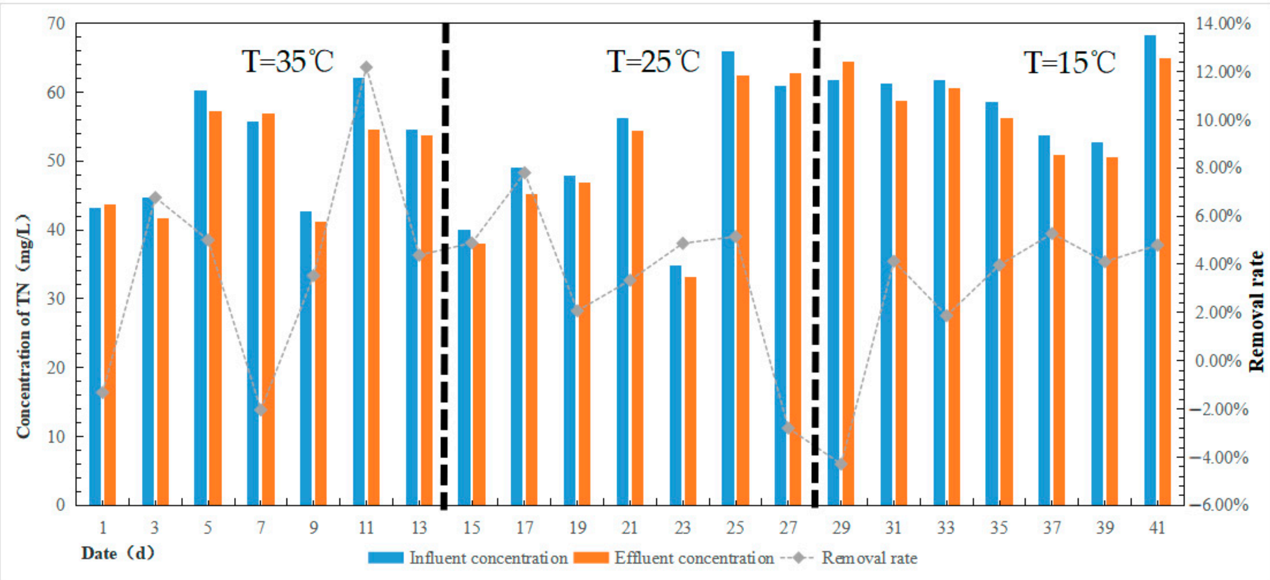


Figure 9. Effect of biofilm-coupled ABR septic tank on TN removal at different temperatures.

When the temperature was set to 25 °C, the TN concentration of the influent water ranged from 34.89 to 65.90 mg/L, the TN concentration of the effluent water from the ABR unit ranged from 33.18 to 62.69 mg/L, the average TN concentration of the effluent water was 48.75 mg/L, the corresponding TN removal rate was −2.79% to 7.80% and the average TN removal rate was 3.38%. When the temperature continued to be lowered to 15 °C, the TN concentration of the influent water ranged from 52.73 to 68.24 mg/L, the TN concentration of the effluent water from the ABR unit ranged from 50.56 to 64.96 mg/L, the average TN concentration of the effluent water was 57.98 mg/L, the corresponding TN removal rate ranged from −4.28% to 5.28%, and the average TN removal rate was 2.32%. The average TN removal rate was 2.32%.

An analysis of the data shows that the TN removal rate of the ABR unit also decreases after the temperature decreases, with the TN removal rate at 15 °C decreasing by 1.65% and 1.06%, respectively, compared to 35 °C and 25 °C. The main reason is that the lower temperature directly inhibits the growth, metabolism and reproduction of microorganisms on the biofilm, and some microorganisms may even enter a transient dormant state at lower temperatures [17]. At the same time, some anaerobic microorganisms will start endogenous respiration at low temperatures [18], releasing ammonia nitrogen externally, leading the TN removal rate of the ABR device to have negative values. During the whole operation stage, the TN removal rate of the biofilm-coupled ABR plant is limited. The promotion of TN removal by the biofilm in the ABR plant is not obvious under completely anaerobic conditions, and most of the nitrogen is still retained and can be directly reused for farm irrigation after some subsequent treatment.

3.2.4. Analysis of the Variation of TP at Different Temperatures during the Operating Phase

The concentration of TP in the influent water ranged from 4.17 to 5.89 mg/L at a temperature setting of 35 °C. The TP concentration of the effluent from the biofilm-coupled ABR unit ranged from 3.94 to 4.90 mg/L. The average TP concentration of the effluent was 4.42 mg/L. The corresponding TP removal rate ranged from 2.93% to 20.52%, with an average TP removal rate of 13.98% (Figure 10). TP removal by the ABR unit was still limited at higher temperature settings, mainly due to the inhibition of phosphorus release and phosphorus uptake by microorganisms in a completely anaerobic environment and the limited assimilation of phosphorus by film-mounted microorganisms.

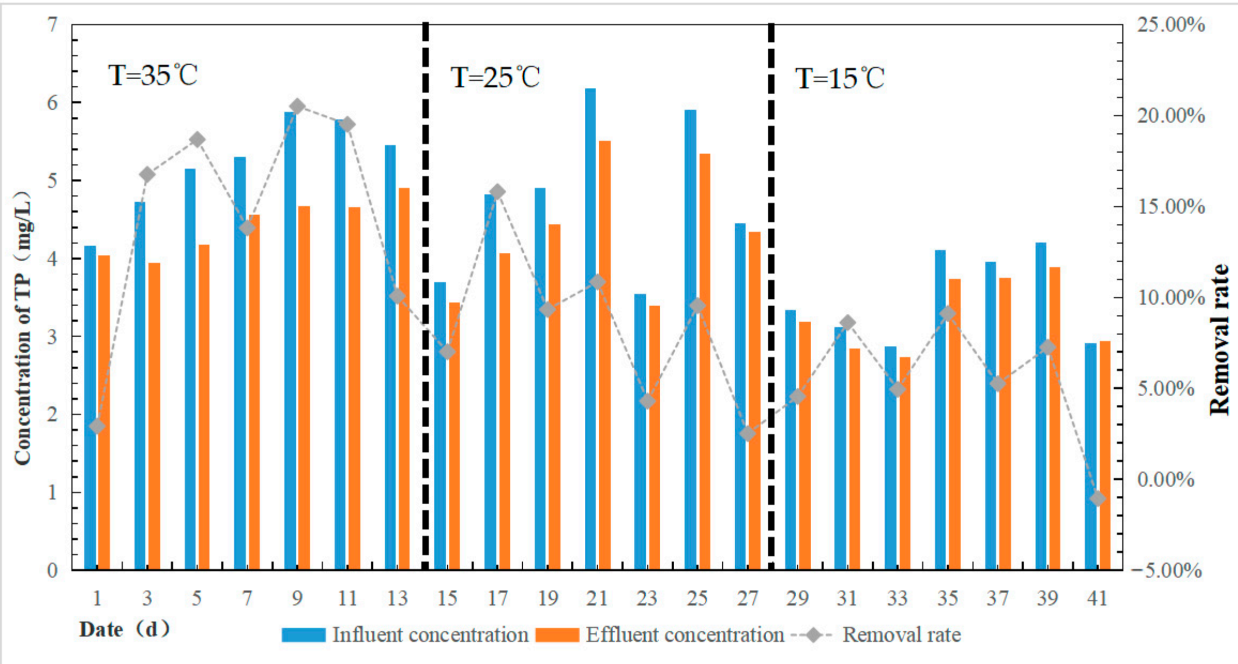


Figure 10. Effect of biofilm-coupled ABR septic tank on TP removal at different temperatures.

When the temperature was regulated to 25 °C, the TP concentration of the influent water ranged from 3.54 to 6.18 mg/L, and the TP concentration of the effluent water from the biofilm-coupled ABR unit ranged from 3.39 to 5.51 mg/L. The average TP concentration of the effluent water was 4.38 mg/L, and the corresponding removal rate ranged from 2.53% to 15.82%, with an average TP removal rate of 8.64%. When the temperature was further lowered to 15 °C, the TP concentration of the influent water ranged from 2.87 to 4.20 mg/L, and the TP concentration of the effluent water from the biofilm-coupled ABR unit ranged from 2.73 to 3.89 mg/L. The average TP concentration of the effluent water was 3.30 mg/L, and the corresponding removal rate ranged from −1.05% to 9.13%, with an average TP removal rate of 5.21%.

Analysis of the data showed that the removal rate of TP from the ABR unit also showed a significant decrease after the temperature was lowered. The TP removal rate at 15 °C was 8.77% and 3.43% lower than that at 35 °C and 25 °C, respectively, mainly because the microbial activity was inhibited to a certain extent after the temperature was lowered, and the intake of phosphorus was reduced. In addition, the organic load of the influent water can promote the growth, metabolism and reproduction of anaerobic microorganisms within a certain range. Under different temperature conditions, the concentration of organic load increased at 25 °C compared to 35 °C and decreased compared to 15 °C, and it can be found that the removal rate of TP by the ABR unit also showed a certain degree of fluctuation in the range around the turning point [19]. When the temperature was lowered to 15 °C, the TP removal rate of the biofilm-coupled ABR unit decreased significantly and, in some cases, was negative, which was probably due to the release of phosphorus by phosphorus-polymerising bacteria at low temperatures when endogenous respiration and the biological activity of the microorganisms are mainly inhibited.

The ABR plant outperformed the conventional ABR septic tank mainly because its biofilm adhered to the filler and increased the number and abundance of microorganisms in the reactor, indicating that the biofilm helped increase the resistance of the ABR plant, even though the ABR plant showed weaker TP removal at low temperatures than at high temperatures, indicating that the biofilm was of limited help in TP removal in the ABR plant. The totally anaerobic ABR plant, in general, has a lower TP removal rate and nevertheless retains a significant amount of TP, which can be processed and repurposed right away for agricultural irrigation.

3.3. Effect of Different Fillers on the Operation of Anaerobic Biofilm-Coupled ABR Septic Tanks

After the start-up of the biofilm-coupled ABR septic tank was complete, domestic sewage from the power station was used as the feed water, and heating rods and insulation sponges were added to the feed water bucket to provide a certain degree of insulation, and the internal temperature of the reactor was adjusted by adjusting the temperature of the heating rod settings and setting the hydraulic retention time to 3 d and the facility temperature to 25 °C~35 °C. Furthermore, three types of hanging film materials, namely elastic packing, fluidised bed packing and floating-ball, were selected. The ABR unit was operated for 14 d, and the effluent indexes of the ABR unit were monitored to study the changes in the indexes of the biofilm-coupled ABR septic tank operating under different HRT conditions. Gao Hongfu et al. investigated the role of ABR fillers in the early stages of operation and concluded that the influence of the filler material on the length of the start-up period was small [20]; the difference in removal effectiveness during the operation phase was the focus of the study (see Table 7).

Table 7. Test feed water quality parameters.

Indicator	COD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	Temperature (°C)
Range	210.65~489.31	76.05~190.63	34.70~67.36	2.95~7.75	25~35

The main direct costs associated with ABR projects are labor, supplies and the usage of construction machinery. The cost disparity between the three types of ABR, which is largely due to the limited amount of rural sewage, may be seen in two aspects: the price of the filler and the cost of the supporting infrastructure needed for filler installation. Due to the fact that three-dimensional elastic filler is typically installed as square installation, which necessitates the creation of steel frames, the filling of a three-dimensional elastic filler will result in some expenses due to the required supporting facilities. It is possible to add floating balls and fluidised bed fillers directly to the unit without paying any additional supplementary fees. The price of filler per cubic metre for each ABR and the cost of ancillary facilities are shown in Table 8.

Table 8. Fill prices and ancillary facility charges.

Type	Prince (CNY·m^{-3})	Facilities Fee (CNY)	Total (CNY)
Elastic packing	33	45	78
Fluidised bed filler	600	0	600
Floating ball	1200	0	1200

According to the relevant information, the cost of each ABR project from large to small is floating ball ABR > fluidised bed filler ABR > elastic packing ABR, and the cost of elastic packing is about 1/8 and 1/15 that of floating ball and fluidised bed packing, respectively.

3.3.1. Analysis of COD Variation under Different Fillers during Operation Stage

Figure 11 shows that, during the stable operation of the plant, under the condition that the elastic filler was selected as the hanging film carrier, the COD concentration of the influent water of the biofilm-coupled ABR plant ranged from 210.65 to 296.80 mg/L, the COD concentration of the effluent water ranged from 94.18 to 133.12 mg/L, the average COD concentration of the effluent water was 115.94 mg/L and the corresponding COD removal rates ranged from 50.75% to 60.07%, with an average COD removal rate of 54.73%.

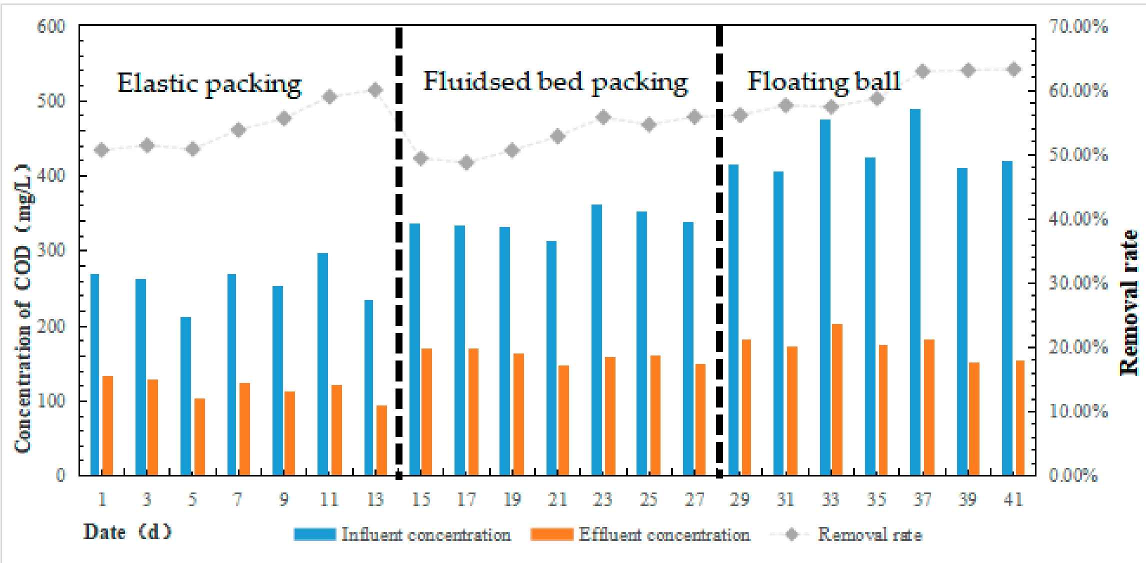


Figure 11. Effect of biofilm-coupled ABR septic tank on COD removal under different fillers.

After replacing the hanging film filler with a fluidised bed filler, the influent COD concentration of the biofilm-coupled ABR plant ranged from 312.95 to 360.93 mg/L, the effluent COD concentration ranged from 147.49 to 170.76 mg/L, the average effluent COD concentration was 160.13 mg/L and the corresponding COD removal rate was 48.77% to 55.90% The average COD removal rate was 52.54%.

After replacing the hanging film filler with a floating ball again, the influent COD concentration of the biofilm-coupled ABR plant ranged from 404.68 to 489.31 mg/L, the effluent COD concentration ranged from 151.63 to 202.10 mg/L, the average effluent COD concentration was 174.54 mg/L and the corresponding COD removal rate ranged from 56.18% to 63.28%, with an average COD removal rate of 59.88%.

In the operation process, the microorganisms on the filler hang the film sufficiently, increasing the effective contact area between the microorganisms and the wastewater. The specific surface area of the fluidised bed filler and floating ball were 348 m^2/m^3, 460 m^2/m^3

and 300 m^2/m^3, respectively, and the corresponding engineering filling ratios were 100%, 70% and 100%, respectively, and the increase in effective surface area was beneficial to increase the hanging film biomass of the microorganisms.

The main reason for this is that the COD concentration of the rural wastewater is not high and the population of anaerobic or partly anaerobic microorganisms has a certain upper limit and cannot fully utilise the surface area of the filler, in addition to the fact that the COD removal effect is slightly better than that of the fluidised bed filler due to the larger three-dimensional space of the suspended spheres and elastic filler, which makes it easier for the ageing biofilm to shed and settle.

3.3.2. Analysis of SS Variation under Different Fillers during Operation Phase

When elastic packing was selected as the biofilm carrier, the SS concentration of the influent water ranged from 95.70 to 171.36 mg/L, the SS concentration of the effluent water ranged from 17.10 to 36.59 mg/L, the average effluent concentration of SS was 24.58 mg/L, the corresponding removal rate was 78.65% to 84.12% and the average SS removal rate was 81.56%. When replacing the hanging film carrier with a fluidised bed filler, the SS concentration in the influent water ranged from 76.05 to 166.02 mg/L, the SS concentration in the effluent water ranged from 10.65 to 22.81 mg/L, the average SS concentration in the effluent water was 16.53 mg/L, the corresponding removal rate ranged from 83.26% to 86.26% and the average SS removal rate was 84.94%. When the biofilm filler was replaced by a floating ball again, the SS concentration in the influent of the ABR unit ranged from 96.65 to 190.63 mg/L, the SS concentration in the effluent ranged from 10.30 to 19.31 mg/L, the average SS concentration in the effluent was 14.10 mg/L, the corresponding SS removal rate ranged from 86.77% to 90.21% and the average SS removal rate was 88.89%. The average SS removal rate was 88.89% (Figure 12).

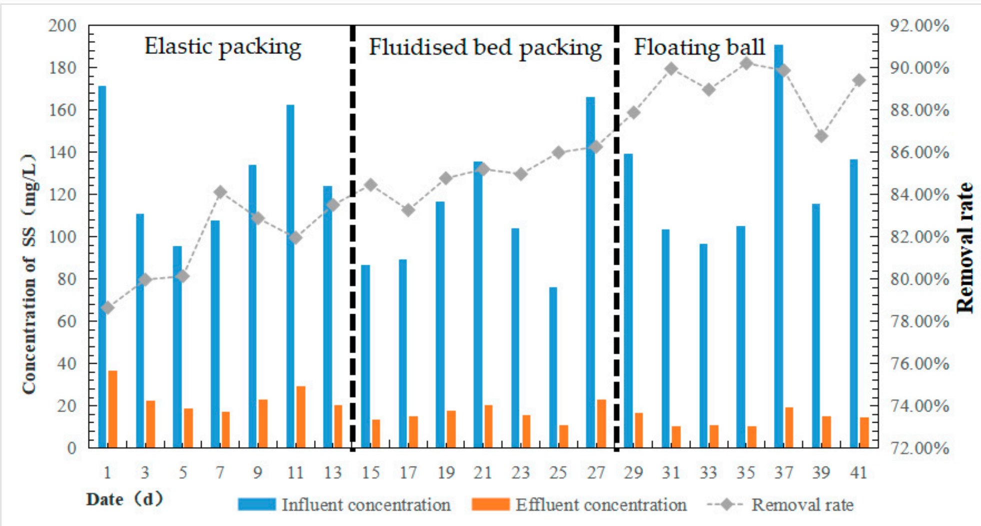


Figure 12. Effect of biofilm-coupled ABR septic tank on SS removal under different fillers.

The main reason is that the filler increases the interception area of SS in the ABR unit, and the filler structure in the ABR unit helps to improve the solid–liquid separation efficiency, and at the same time, under a suitable temperature, the biofilm hanging process is smoother, and the filler is able to hang a sufficient quantity of biofilm. This also directly enhances the interception capacity of the ABR unit for suspended solids. The highest SS removal rate was achieved using an ABR that had suspended ball packing, which was 7.33% and 3.95% higher than that of elastic packing and fluidised bed packing, respectively, which was mainly due to the fact that the surface area of the suspended ball packing is larger and, therefore, the retention area is larger than that of the other two fillers. The main reason is that the annular structure of the fluidised bed is more favourable to the removal of SS than the elastic packing.

3.3.3. Analysis of the Variation of TN under Different Fillers during the Operation Phase

According to Figure 13, when the elastic filler is selected as the biofilm carrier, the TN concentration of the influent water ranges from 42.83 to 62.22 mg/L, the TN concentration of the effluent water ranges from 40.52 to 57.05 mg/L, the average effluent concentration of TN is 47.96 mg/L, the corresponding TN removal rate is −0.22% to 12.59%, and the average TN removal rate was 5.51%. When replacing the hanging film carrier with fluidised bed filler, the TN concentration in the influent water ranged from 34.71 to 66.11 mg/L, the TN concentration in the effluent water ranged from 33.67 to 60.35 mg/L, the average TN concentration in the effluent water was 47.84 mg/L, the corresponding removal rate ranged from 1.52% to 8.71%, and the average TN removal rate was 4.98%. When the biofilm filler was replaced by floating ball again, the concentration of TN in the influent of the ABR unit ranged from 52.09 to 67.36 mg/L, the concentration of TN in the effluent ranged from 46.15 to 58.83 mg/L, the average concentration of TN in the effluent was 53.12 mg/L, the corresponding TN removal rate ranged from 4.30% to 15.49%, and the average TN removal rate was 9.91%.

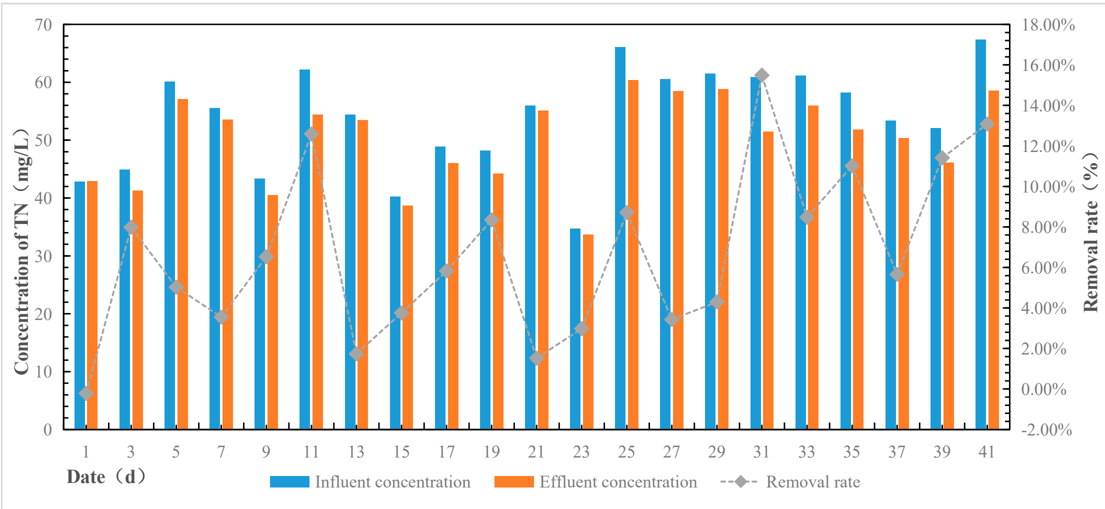


Figure 13. Effect of biofilm-coupled ABR septic tank on TN removal under different fillers.

On the whole, the ABR of the three fillers had an average total nitrogen concentration of 53.93 mg/L in the influent water, and the removal effect of TN was relatively average. The reasons for this are mainly analysed as follows: on the one hand, the fillers of the ABR device help to carry out part of the retention; on the other hand, due to the small demand for nitrogen during the growth and metabolism and reproduction of microorganisms in a completely anaerobic environment, the anaerobic or partly anaerobic type of The removal of nitrogen by microorganisms is mainly based on their own assimilation. The removal effect was ranked as floating ball (9.91%) > elastic filler (5.51%) > fluidised bed filler (4.98%), while a small peak in the TN removal effect was observed at d 11, d 25 and d 31, mainly because the organic load of the influent water on these dates was increased within a certain range, which indirectly promoted the growth, metabolism and reproduction of the anaerobic microorganisms and enhanced their ability to remove ammonia. However, it is clear that the effect is still very limited, as the completely anaerobic environment inhibits the further conversion of ammonia to nitrate and nitrite nitrogen in the ABR plant, resulting in a relatively low removal rate of total nitrogen.

The bio-phase analysis revealed that the microbial concentrations in the ABR plant showed a similar pattern to the TN removal by the three fillers, i.e., the microbial concentrations on the floating ball were slightly greater than those on the elastic and fluidised bed fillers, while the elastic filler was slightly higher than those in the fluidised bed filler. In a few cases the effluent TN concentration of the biofilm-coupled ABR plant was higher than the influent and the TN removal rate appeared negative, which may be due to the partial conversion of nitrogenous organic compounds in the influent water to ammonia nitrogen, while the endogenous respiration of some anaerobic microorganisms and autolysis in a completely anaerobic environment produced ammonia nitrogen. The vast majority of the nitrogen in the influent water is retained and can be subsequently regenerated for direct reuse in agricultural irrigation after some treatment.

3.3.4. Analysis of the Variation of TP under Different Fillers during the Operation Phase

As can be observed in Figure 14, when the elastic filler was selected as the biofilm carrier, the concentration of TP in the influent water ranged from 2.95 to 5.91 mg/L. The TP concentration in the effluent of the biofilm-coupled ABR plant ranged from 2.73 to 4.35 mg/L. The average TP concentration in the effluent was 3.62 mg/L, and the corresponding TP removal rate ranged from −2.13% to 28.78%, with an average TP removal rate of 13.51%. When replacing the hanging film carrier with a fluidised bed filler, the TP concentration of the influent water ranged from 3.55 to 6.21 mg/L, the TP concentration of the effluent water from the biofilm-coupled ABR unit ranged from 3.40 to 5.48 mg/L, the average TP concentration of the effluent water was 4.37 mg/L, the corresponding removal rate ranged from 1.26% to 15.75%, and the average TP removal rate was 8.78%; again When the biofilm filler was replaced with Floating ball, the TP concentration of the influent water ranged from 5.31 to 7.75 mg/L, and the TP concentration of the effluent water from the biofilm-coupled ABR unit ranged from 4.16 to 5.21 mg/L. The average TP concentration of the effluent water was 4.81 mg/L, and the corresponding removal rate was 20.15% to 35.79%, with an average TP removal rate of 25.75%.

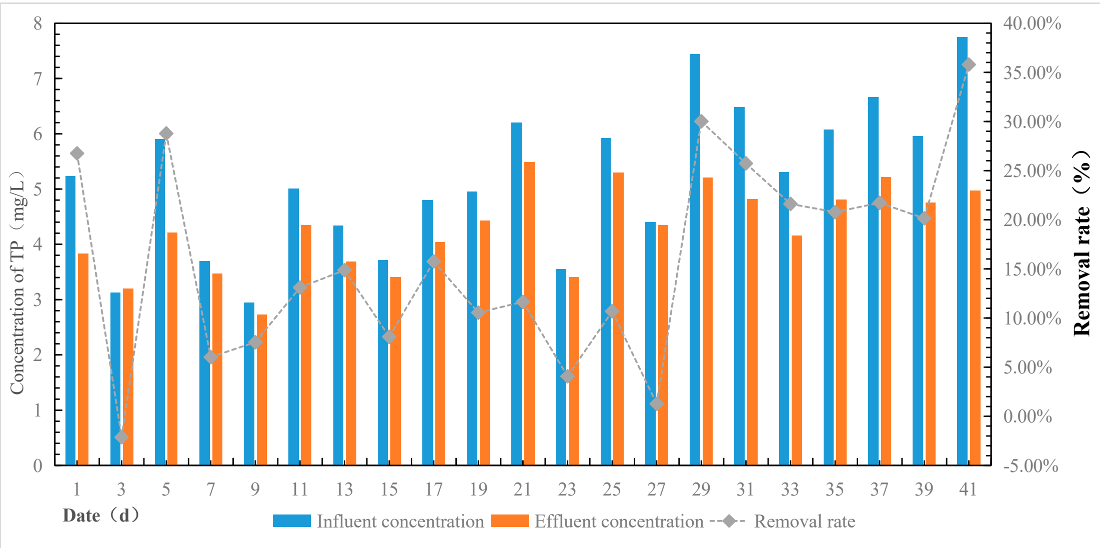


Figure 14. Effect of biofilm-coupled ABR septic tank on TP removal under different fillers.

Overall, the TP removal effect of all three filler biofilm-coupled ABR devices was limited. This was primarily due to the fact that microorganisms' growth, metabolism, and reproduction process essentially did not take in phosphorus in a completely anaerobic environment, and anaerobic conditions hindered the traditional denitrification and phosphorus removal reaction. Phosphorus-polyphosphorus bacteria started to release phosphorus under these circumstances, and anaerobic microorganisms under conditions of lower organic loading will engage in endogenous respiration. As a result, in some cases, the TP concentration of the effluent is higher than the influent and the TP removal is negative. It can be seen that the effect of suspended ball packing is better than that of elastic packing and fluidised bed packing, the main reason for this is basically similar to the reason for the difference in TN removal effect, and after further increasing the organic load of the influent water, the removal rate of TP by the ABR plant tends to increase again, mainly because the increase in organic load indirectly promotes the growth, metabolism and reproduction process of anaerobic microorganisms, which makes its uptake of phosphorus increase However, the overall phosphorus removal rate is still low and most of the phosphorus is retained in the effluent; therefore, it can also be regenerated and reused in the farm after some treatment.

4. Conclusions

In this study, single-factor control was used to study the operation of the ABR plant under different conditions with different influencing factors after the successful start-up of the biofilm-coupled ABR septic tank. By exploring the regulation stages of HRT at 5 d, 3 d and 1 d, temperature at 35 °C, 25 °C and 15 °C, respectively, and filler selection as an elastic filler, fluidised bed filler and floating ball, the effect of the biofilm-coupled ABR septic tank on the removal of COD, SS, TN and TP was analyzed, and the following conclusions were reached.

(1) During the regulation HRT of 5 d, 3 d and 1 d, respectively, the removal rates in terms of COD and SS in the biofilm-coupled ABR septic tank fluctuated above and below 55.52% and 78.75%, respectively, and the best removal performance was maintained at a stable level of about 60% when the influent COD concentration ranged from 248.05 to 469.95 mg/L and HRT = 3 d. The removal rates of both TN and TP in the ABR septic tank were low and did not vary greatly, and its COD and SS effluent concentrations met the Water Quality Standard for Agricultural Irrigation (GB5084-2005), and the biofilm was beneficial in terms of improving the performance of the ABR against hydraulic impact.

(2) During the regulation process of decreasing the temperature step-by-step, the removal rates of COD, SS, TN and TP of the biofilm-coupled ABR septic tank decreased. However, at lower temperatures, the removal rates in terms of COD and SS of the biofilm-coupled ABR septic tank still performed better, remaining above 44.81% and 70.43%, respectively. It conforms to the Water Quality Standard for Agricultural Irrigation (GB5084-2005), and it can be concluded that the biofilm filler can ensure the removal rates of COD and SS when using the ABR as well as the performance of the body constant ABR device against low temperatures. At the same time, the retained nitrogen and phosphorus elements can be regenerated for use in irrigation after a certain treatment of agricultural land.

(3) In the case of biofilm-mounted fillers using elastic fillers, fluidised bed fillers and floating balls, respectively, floating balls performed best regarding the average removal rate in terms of COD and SS in the biofilm-coupled ABR septic tank, and there is a small increase in the removal rate of TN and TP but the overall performance is still low.

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