Article

A Modified Bio-Ecological Process for Rural Wastewater Treatment

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Abstract: Limited water resources and ensuring access to clean water are critical environmental challenges, especially for the developing world. In particular, rural domestic wastewater has become a significant source for the pollution of freshwater bodies. A modified bio-ecological A2O-wetland system for rural wastewater treatment consisting of a biological unit (anaerobic baffled reactor, anoxic tank and oxic unit, A2O) and an ecological unit (horizontal flow constructed wetland) was developed, and key performance indicators were identified. The bio-ecological treatment system showed high removal efficiency for pollutants, successfully achieving 91%, 85%, 78%, and 92% removal efficiencies for chemical oxygen demand (COD), ammonium (NH_4–N), total nitrogen (TN), and total phosphorus (TP), respectively. The concentrations of pollutants in the effluent from the system were lower than the Class 1 A regulated values of the Chinese National Standard GB18918-2002. The system offered high removal efficiency, simple operation, and low energy consumption. The A2O-wetland is a good alternative for rural wastewater treatment systems.

Keywords: wastewater treatment; constructed wetland; A2O; bio-ecological process

1. Introduction

Over the past few decades, the deterioration of freshwater has become a global phenomenon that will further intensify the demand for water reuse [1,2]. The inadequate supply of water also poses health risks to consumers because of its poor quality. The discharge of domestic sewage is a principal source of pollution for freshwater bodies [3]. Effective wastewater management and treatment is critical for maintaining public health and safe environments [4]. Domestic wastewater typically contains suspended solids, pathogen microorganisms, nutrients, and other pollutants [5]. For environmental safety and health hazards, these pollutants must be brought down to permissible levels for safe wastewater disposal [6]. Therefore, wastewater treatment is of paramount importance before discharging to the environment [7].

Lack of adequate sanitation system can be a source of pollution and a risk to the health of human beings and the environment as well. Hence, a significant worldwide effort has been made to implement and improve sanitation systems in the last few decades [8]. However, according to WHO (World Health Organization) [9] 2500 million people were still without access to appropriate sanitation systems. Therefore, it is critical to improve and implement basic wastewater treatment facilities in the affected populations, mainly in developing countries, where people live with extreme poverty conditions, particularly rural inhabitants or peri-urban dwellers [10]. Moreover, wastewater treatment is not only a problem concerning developing countries, different associated problems still have to be solved in industrialized and developed countries as well [11]. Recently, the primary focus of sanitation has changed to the reduction of environmental impacts [12]. Primarily centralized systems have been built to treat wastewater in urban or densely populated areas [13], and have required

large investment costs for sewer networks [14]. For rural areas there is a need to adopt decentralized wastewater treatment methods, because wastewater collection in the villages is difficult due to the dispersed layout, small-scale, and complex geographic conditions [15].

One of the main concerns regarding municipal wastewater discharge is the concentration of nutrient compounds [16]. These nutrients can stimulate the growth of aquatic vegetation in receiving water bodies, thereby decreasing the oxygen concentration [17]. Eutrophication of freshwaters bodies has gained increased attention, and a number of wastewater treatment methods have been developed to address this issue. Over the past few years some new technologies have been developed for rural or decentralized sewage treatments, such as the multistep A2O-H system [18], A2O-BAF system [19], five-step continuous flow activated sludge process (FSCFASP) [20], septic tanks [20], algal ponds [21], and soil trenches [22]. Most of these processes are selective or have operational issues. Molinos-Senante et al. [23] described an ANP (analytical network processes) approach to rank wastewater treatment technology set-ups for small communities by assessing multiple interdependences elements. Their results illustrated that constructed wetland is the most preferred alternative technology.

Decentralized sanitation systems can have great success in rural and peri-urban areas that lack sanitation coverage [24]. Conventional wastewater technologies are expensive to build, maintain, and operate [24], especially for scattered populations. Therefore, it is important to develop economical, environmentally sustainable, and socially acceptable wastewater treatment technologies for rural areas [25]. A modified simple bio-ecological (A2O-CW) wastewater treatment system was developed in this study. The biological system consists of an anaerobic baffled reactor (ABR), anoxic tank, and an oxic unit with an ecological unit consisting of a constructed wetland. The system offered simple operation, low energy consumption, and high treatment efficiency.

2. Materials and Methods

2.1. Reactor Setup

A lab-scale novel bio-ecological setup consisting of an anaerobic baffled reactor (ABR), anoxic tank, oxic unit and constructed wetlands is shown in Figure 1.
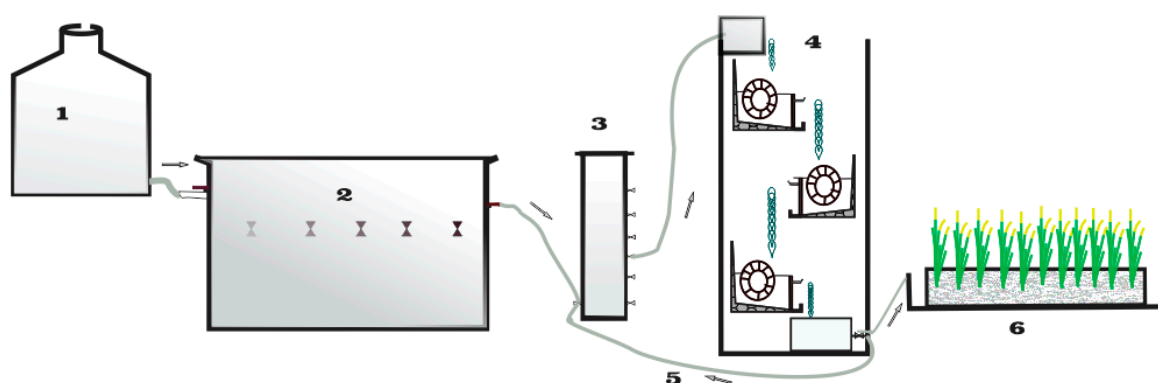

Figure 1. Schematic diagram of bio-ecological system; → wastewater flow directions; 1. Storage Tank for wastewater; 2. ABR (Anaerobic Baffled Reactor, equipped with DN10 sampling port); 3. Anoxic Tank (equipped with outlets for flow from different heights); 4. Oxic Unit (consisted of three sub-parts, each part consisted of a rectangular tank, a bio-wheel, and a rotating disc); 5. Return flow to anoxic tank from oxic unit; 6. Horizontal Flow Constructed Wetland

2.1.1. Anaerobic Baffled Reactor

The anaerobic baffled reactor (ABR) was 1 m × 0.2 m × 0.75 m (length × width × height) with an effective volume of 100 L. The reactor had vertical baffles dividing the reactor into five compartments and each compartment was filled with non-woven cloth. The outlet of each compartment had a DN10 sampling port.

2.1.2. Anoxic Tank

The anoxic tank was 1 m × 0.2 m × 0.2 m (height × length × width) with an effective volume of 32 L. The device was equipped with outlets at different heights.

2.1.3. Oxic Unit

The oxic part of the A2O-wetland system consisted of three cells, and each cell contained a rectangular tank (0.2 m × 0.2 m × 0.1 m in diameter), a bio-wheel, and a rotating disc working on the watermill principle. The wastewater dropped and pushed the blades of the wheel to rotate an axle that drove the bio-wheel in the reaction tank.

2.1.4. Constructed Wetland

The HFCW (horizontal flow constructed wetland) was a rectangular PVC (polyvinyl chloride) container 1 m long, 0.2 m wide, and 0.6 m deep. The constructed wetland was packed with 15 cm supporting layer of gravel (20–40 mm), 30 cm of cobblestone (0.5–2 mm diameter), and 5 cm of sand and soil mixture, planted with *Ipomoea aquatica* (water spinach). The hydraulic loading rate was set according to the biological unit effluent.

2.2. Experimental Procedure

The experimental reactor had been running for over four months after system start-up. The temperature during the experiment was 24–32 °C. First, the ABR received wastewater directly from the storage tank, where anaerobic degradation of the organic pollutants took place. The ABR effluent then flowed into the anoxic tank for denitrification and deodorization. Next, the sewage was pumped into the oxic unit. In the oxic unit, part of the wastewater dropped into the wheel, which was attached to a biological disc in the oxic unit through a shaft, rotating the biological disc. This unit was used primarily for nitrification and further degradation of organic pollutants. After the oxic treatment, a part of the effluent was pumped to the anoxic unit to maintain the reflex ratio, whereas the remaining effluent water was pumped to the constructed wetland for post treatment.

2.3. Sewage Characteristics

The wastewater for this research was obtained from the campus of the Southeast University at Wuxi. The wastewater originates from dormitories, restaurants, and laboratories of the university campus. The sewage quality is presented in Table 1.

Table 1. Main characteristics of the raw sewage.

Parameters	pH	COD	TN	NH$_4$–N	TP	TSS
		mg/L^{-1}				
Range	6.89–7.23	183.0–324.5	22.4–43.5	15.4–35.7	3.4–5.1	172–364
Mean	7.06	258.4	33.8	25.6	4.3	276

Here, COD = chemical oxygen demand; TN = total nitrogen; NH$_4$–N = ammonium; TP = total phosphorus; TSS = total suspended solids.

2.4. Analytical Methods

The water quality of the influent to and effluent from each stage was monitored regularly (three times per week). Chemical oxygen demand (COD), ammonium (NH_4–N), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) were analyzed according to standard methods (Table 2). pH and dissolved oxygen (DO) were tested by PH100 and DO200 probes (YSI), respectively.

Table 2. Test methods used for analysis [26].

No.	Parameters	Test Methods
1	COD	Closed reflux
2	TN	Potassium persulfate spectrophotometry
3	Ammonium	Salicylic acid spectrophotometry
4	TP	Molybdenum antimony anti points spectrophotometry
5	TSS	Gravimetric analysis

2.5. Data Analysis

Initially data and graphical presentation were performed in MS-excel (Office package-16) and then SPSS version-18.0 (SPSS Incorporation, Chicago, IL, USA) program was used to perform statistical analysis.

2.6. Start-Up Conditions

ABR start-up is a complicated process, during which the reactor needs to maintain full treatment capacity [27]. Many factors can affect the start-up of an ABR such as the concentration and composition of wastewater, pH, temperature, hydraulic retention time (HRT), reactor size, and structure [28]. Potential problems can arise during start-up because of plug flow, low pH, and accumulation of volatile fatty acids (VFAs) [29]. Some approaches such as feed dilution, organic loading rate (OLR), periodic feeding, and effluent recycling can help to overcome these difficulties [30]. Low loading start-up and reducing the concentration of organic matter promotes granular sludge growth [31]. For the start-up, the reactor operated for 50 days with HRT for 72 h, which was gradually reduced to 48 h and then 24 h until the COD removal efficiency stabilized at 60%, and the pH stabilized between 7.03 and 7.23 (Table 3).

Table 3. Operational conditions during ABR start-up.

Phase	Time (Days)	Temperature (°C)	HRT (Hours)	Volume Load (kg COD/m^3·day)	COD Removal Rate %
I	20	16–23	72	0.67–1.06	51
II	15	18–28	48	0.92–1.61	60
III	15	20–31	24	1.76–3.24	61

Here, COD = chemical oxygen demand; HRT = hydraulic retention time.

3. Results and Discussion

3.1. Performance Evaluation of ABR

Figure 2 shows HRT and COD removal relationship in the ABR. COD in the influent was between 180 and 330 mg/L^{-1}, and the variation of the COD concentration in the influent was impacted by the summer rain. In general, the COD removal efficiency increased with increasing HRT. The average COD removal efficiencies were 60%, 65%, 72%, and 74% for HRTs of 24 h, 48 h, 72 h, and 96 h, respectively.
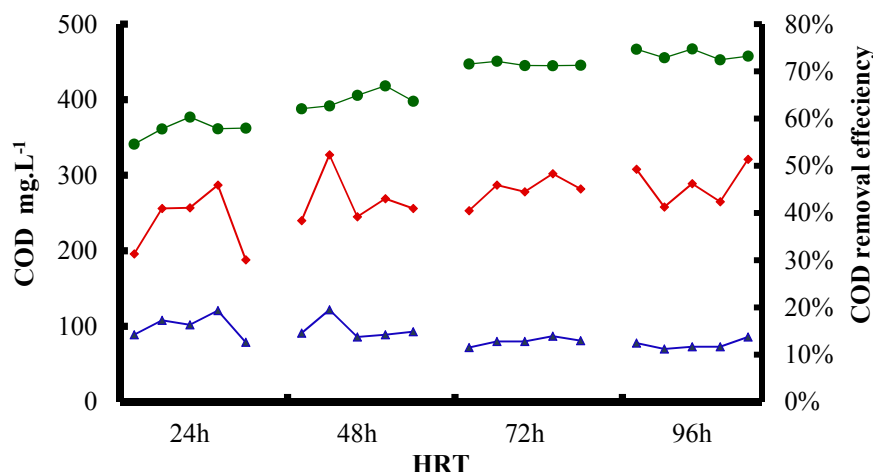
Figure 2. COD concentration and removal efficiency of ABR under different HRTs. ♦ Influent water; ▲ Effluent water; ● COD removal efficiency.

HRT is one of the key factors affecting the operating results of the anaerobic reactor [32]. According to [33], higher HRT increases the wastewater contact time in the reactor and improves the removal efficiency of organic matter by promoting the growth of anaerobic microorganisms. However, longer HRT means a small flow rate and insufficiently stirred anaerobic sludge, resulting in an inability to maintain removal efficiency. Longer HRTs also require large areas and volumes of the reactor, which is not economically suitable. Selecting an accurate HRT for an anaerobic reactor is very important. The increase of the HRT from 24 h to 72 h increased the COD removal efficiency from 60% to 72%, however, when HRT increased from 72 h to 96 h no significant changes in the COD removal efficiency occurred. Excessively long HRTs reduce the up-flow velocity in each reactor compartment and the nutrition distribution for microbes; therefore, no significant changes occurred in the COD removal rate [34]. Extending HRT increased the reactor volume and construction costs [35]. An HRT of 72 h was optimal for the COD removal.

Figure 3 shows the COD removal rate in different compartments of the ABR at different HRTs. The first compartment showed a higher removal efficiency compared to all of the other compartments, followed by the second, third, fourth, and fifth compartments. As the HRT increases, the removal rate also increases. This result was possibly caused by the elevated substrate concentration, which also increased substrate flux into the bioaggregates, thereby increasing microbial growth [36]. The removal rates in compartments I, II, III, IV, and V at HRTs of 24 h to 96 h were 28%–42%, 12%–15%, 8%–11%, 5%–7%, and 2%–4%, respectively. Compartments IV and V showed low removal rates because most of the COD had been removed in the first three compartments and anaerobic microbes have low nutrients to consume [35].
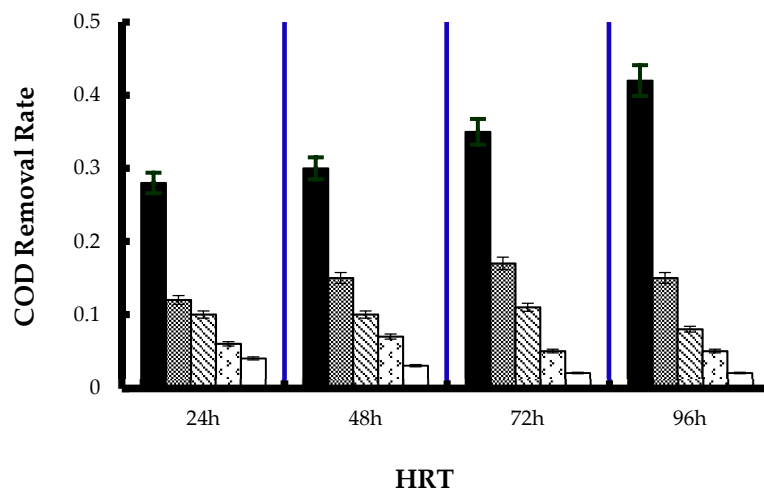
Figure 3. COD removal efficiencies in different compartments of ABR under different HRTs. ▉ Compartment I; ▤ Compartment II; ▨ Compartment III; ⬚ Compartment IV; ▭ Compartment V.

Organic loading rate (OLR) is a chief factor that indicates the amount of volatile solids to be fed into the reactor every day [37]. Figure 4 shows the relationship of OLR and COD removal efficiency. OLR fluctuates between 0.58 and 2.87 kg COD/m^3·day. At lower OLR, the removal efficiency was high. When the OLR was between 0.5 and 1.0 kg COD/m^3·day, the COD removal rate was above 70%. At the middle point between 1.5 and 2.0 kg COD/m^3·day, the removal efficiency dropped. Increasing OLR increased the substrate concentration and elevated microbial growth, resulting in a high COD removal rate [38]. However, further increases in the OLR dropped the removal efficiency. This result might be because high organic loadings decreased VSS (volatile suspended solids) and accumulation of inorganics, leading to subsequent destabilization of the reactor and processes, which affects the reactor performance [39].
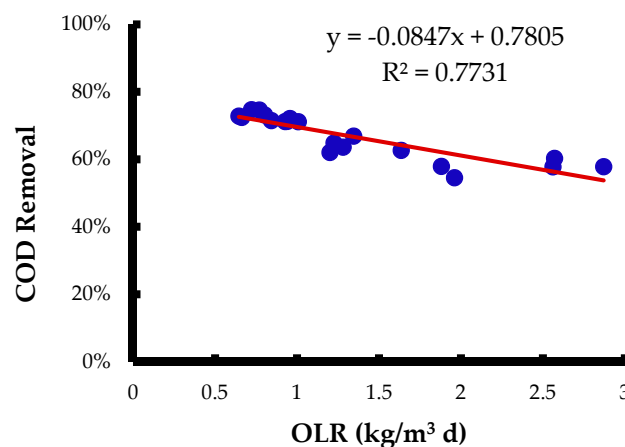

$$y = -0.0847x + 0.7805$$
$$R^2 = 0.7731$$

Figure 4. Effects of organic loading rate (OLR) on the removal rates of COD under HRT on 3 h in ABR.

3.2. Optimization of the Anoxic Tank Configuration

The flow ratio from the oxic unit to that from the anaerobic reactor in the anoxic unit is called the reflux ratio. This ratio determines the carbon source and nitrate quantity in the anoxic tank, and both these parameters can affect the denitrification process [40]. Therefore, the reflux ratio is one of the most significant parameters affecting the treatment efficiency. The reflux ratio was adjusted to 25%, 50%,

100%, and 150%, which resulted in HRTs in the aerobic unit of 8 h, 6.5 h, 5 h, and 3.5 h, respectively. The removal efficiencies of COD, NH$_4$–N, and TN were also investigated (Figure 5).
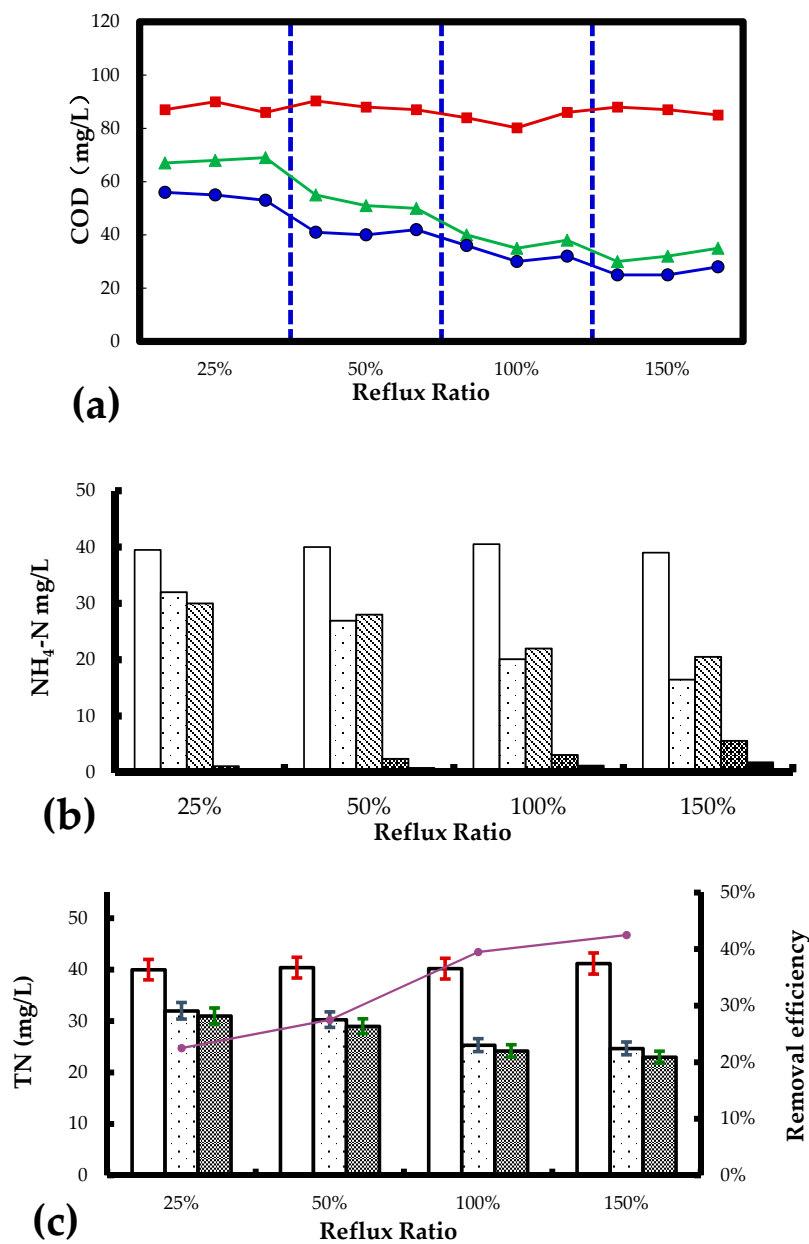

Figure 5. (**a**) Reflux ratio effect on COD removal in anoxic tank. ▮ anaerobic inflow; ▮ anoxic effluent water; ▮ oxic inflow; (**b**) Reflux ratio effect on NH$_4$–N removal in anoxic tank. ▮ anaerobic ammonia; ▮ anoxic ammonia; ▮ anaerobic nitrate; ▮ anoxic nitrate; ▮ oxic nitrate; (**c**) Reflux ratio effect on TN removal in anoxic tank. ▮ anaerobic flow; ▮ anoxic effluent; ▮ oxic flow; ▮ TN removal.

The average ABR influent concentrations of COD and NO$_3$-N were 85.2–92.3 mg/L^{-1} and 39.2–40.5 mg/L^{-1}, respectively, while the influents to the oxic unit were 25.5–54.7 mg/L^{-1} and 2.1–3.25 mg/L^{-1}, respectively. Increasing the reflux ratio increased the removal efficiency. When the reflux ratio was greater than 100%, the influence on TN removal was more significant than that for the removal of COD and NH$_4$–N. TN removal in the anoxic tank was largely dependent on the concentration of NO$_3$-N, which was mainly drained from the oxic unit [41].

At the reflux ratios of 25%, 50%, 100%, and 150%, TN removal rates were 22.5%, 27.5%, 40.1%, and 42.5%, respectively. For 25% to 100% reflux ratios, the TN removal rate increased significantly, but when the reflux ratio increased to 150%, the increase in TN removal efficiency was not remarkable. This result may be caused by nitrogen limitation in the anoxic zone [35]. Therefore, a reflux ratio of 100% was optimal.

3.3. Overall Reactor Performance

The complete A2O-wetland unit consisted of an anaerobic baffled reactor, anoxic tank, oxic unit, and constructed wetland as a combination of biological and ecological processes, was operated as a consecutive flow model. The HRTs in the ABR, anoxic tank, and oxic unit were 3 days, 5 h, and 4.4 h, respectively. The reflux ratio in the anoxic tank was 100%, and the hydraulic loading of the wetland was 0.2–0.4 m^3/day. Water spinach was selected for the constructed wetland due to its easy survival and well developed root system.

Figure 6 shows the concentration and removal efficiencies of COD, TN, NH_4–N, and TP in a bio-ecological system. The combined overall removal efficiency of the A2O-wetland system during the monitored period was 91% for COD, 78% for TN, 85% for NH_4–N, and 92% for TP. The mean, minimum, and maximum for the concentration and removal efficiencies of COD, ammonia, TN, and TP are shown in Table 4. The influent COD concentration was between 185.3 and 321.2 mg/L^{-1} and after treatment, the effluent COD concentration was 10.4–28.7 mg/L^{-1}. The removal efficiency for COD reached up to 90%. TN concentrations in the influent and effluent were 22.4–42.1 mg/L^{-1} and 3.6–11.5 mg/L^{-1}, respectively, and the total nitrogen removal efficiency was 75%–85%. Whereas, the average effluent concentration of NH_4–N and TP were 2.35 ± 0.99 and 0.36 ± 0.10 mg/L^{-1} with removal efficiency of 85% and 92%, respectively.
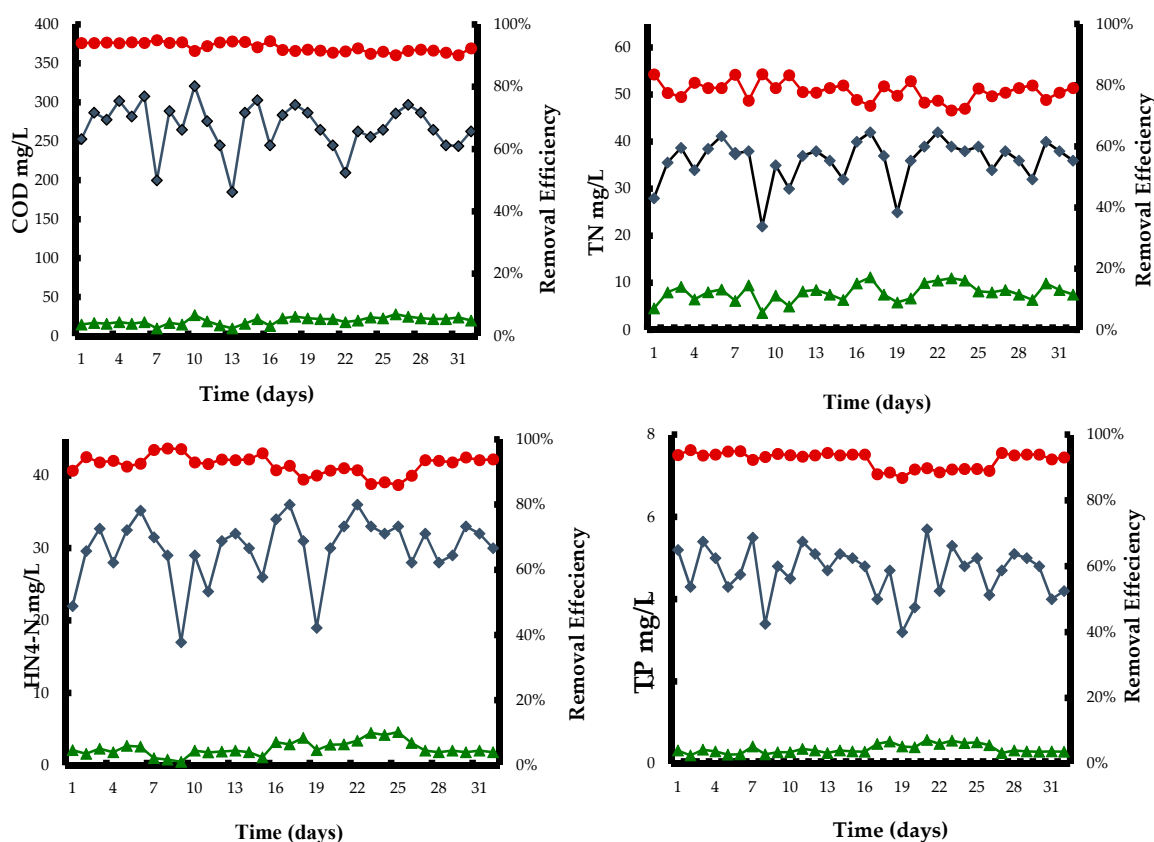

Figure 6. Removal efficiency of COD, TN, NH_4^+–N, and TP in A2O–wetland system. ◆ Influent water; ▲ Effluent water; ● COD removal efficiency.

Table 4. Removal efficiencies were achieved by A2O-wetland system.

Parameters	Influent			Effluent			Efficiency		
	Min	Max	Mean ± SD **	Min	Max	Mean ± SD **	Min	Max	Mean
	mg/L^{-1}						%		
COD	185.3	321.2	268.2 ± 30.75	10.4	28.7	19.6 ± 4.6	0.87	0.95	0.91
TN	22.4	42.1	36.01 ± 4.59	3.6	11.5	7.96 ± 1.84	0.75	0.85	0.78
NH$_4$–N	17	36	29.9 ± 4.42	0.5	4.6	2.35 ± 0.99	0.81	0.94	0.85
TP	3.2	5.7	4.7 ± 0.59	0.2	0.58	0.36 ± 0.10	0.87	0.95	0.92

Here, COD = chemical oxygen demand; TN = total nitrogen; NH$_4$–N = ammonium; TP = total phosphorus. ** is the probability value >0.001.

Figure 7 illustrates the removal efficiencies of the bio-ecological system for tested parameters in different stages of the A2O-wetland system. The most effective COD removal took place in the ABR under an HRT of 3 h, and it was supposed that the chief quantity of the organic matter was removed by heterotrophic bacteria [42]. The average TN removal efficiency in the anoxic tank was 40.1%, and the other major part was constructed wetland for TN removal. Nitrogen removal can occur through nitrification, denitrification, and volatilization, and nitrogen can also be taken up by plants and become part of plant biomass [43]. Nitrogen uptake by plants is an important function of CW (constructed wetland) [44]. TP removal efficiency was between 87% and 95%. The main part of TP was removed by the CW. The processes that can remove nitrogen in constructed wetlands are nitrification, denitrification, nitrogen fixation, NH$_3$ volatilization, plant and microbial uptake, nitrate reduction to ammonium (nitrate-ammonification), mineralization (ammonification), anaerobic ammonia oxidation (ANAMMOX), sorption, fragmentation, desorption, burial, and leaching, whereas phosphorus removal processes in constructed wetland are adsorption, desorption, dissolution, precipitation, plant and microbial uptake, leaching, fragmentation, sedimentation, and mineralization [45,46].
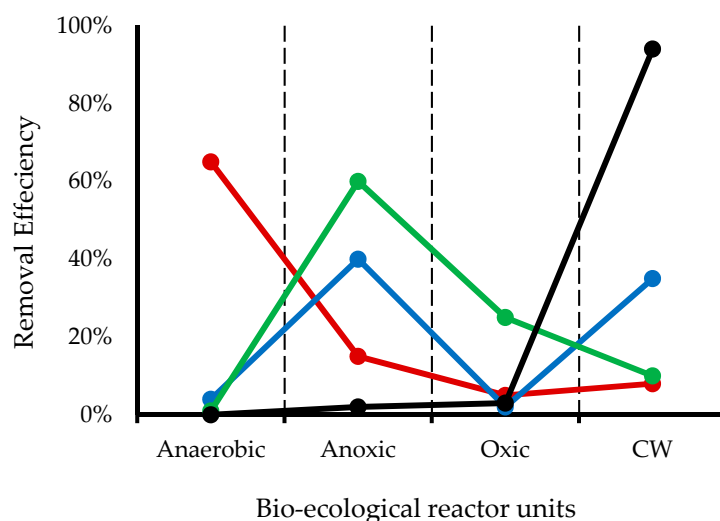
Figure 7. Removal efficiencies of COD, TN, NH$_4^+$–N, and TP in different units of A2O–wetland system. —— COD; —— TN; —— NH$_4$–N; —— TP.

The bio-ecological reactor was proposed for rural domestic wastewater treatment. In comparison with other decentralized or on-site technologies, such as intermittently aerated MBBR (TN = 47%–55%; COD = 42%–67%) [47], filter packed with recycled glass (TN = 10%–26%; COD = 72%–83%) [48]; step feed biofilm process (TN = 25%–75%; COD = 80%) [49]; hybrid bioreactor (TN = 59.1%; COD = 93%) [50]; reed bed (TN = 33%–66%) [51]; and integrated A/O biofilm reactor (TN = 66%–84%; COD = 62%–85%) [52], the organic pollutant removal efficiency of A2O-CW was higher.

The bio-ecological system showed a highly significant effect ($p < 0.001$) for COD, TN, ammonium, and TP.

According to [53], aeration, pumping, and material flow are the most important units in WWTPs (wastewater treatment plants) regarding energy consumption, and aeration consumes more than a half of the total energy consumption in WWTPs. In the bio-ecological system, there was no other energy consumption equipment other than a water pump. Thus, the average cost of wastewater could be kept to a minimum. An important approach for bio-ecological processes is the treatment and reuse of domestic wastewater in a decentralized manner, especially in rural areas [54]. Ecological wastewater treatment often leads to decentralized treatment, and considers the wastewater as a resource for irrigation and fertilizer [24].

4. Conclusions

The main findings are the following:

The bio-ecological treatment system of A2O (anaerobic baffled reactor, anoxic tank, and oxic unit) and wetland showed a high removal efficiency for nutrients. The system successfully achieved 92%, 96.7%, 83.6%, and 95.3% removal efficiencies for COD, ammonium, TN, and TP, respectively. The concentrations of organic matter and nutrients in the effluent from the system were lower than the Class 1 A regulated values of the Chinese National Standard GB18918-2002. The most effective COD removal took place in the first three compartments of ABR under a HRT of 3 h by heterotrophic bacteria. For anoxic nitrification the optimum reflex ratio was 100%. The major part of TN removal occurred in the anoxic tank and CW, whereas TP removal took place in the constructed wetland. Aeration is an important part of biological units; more than half of the total energy consumed in wastewater treatment plants is used in aeration and pumping. The A2O-wetland is an energy saving alternative for wastewater treatment and an appropriate technology, especially for the rural regions of the developing world.

Author Contributions: Haq Nawaz Abbasi, Fang Xu, and Xiwu Lu conceived and designed the project, materials, and analysis tools. Haq Nawaz Abbasi and Fang Xu performed the experiment works and data analysis, however, Xiwu Lu supervised them during all stages. All authors wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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