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Evaluation of an Outdoor Pilot Scale Hybrid Growth Algal-Bacterial System for Wastewater Bioremediation

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Abstract

Synergistic cooperation and interaction between algae and bacteria had made it easy by using one single step only to efficiently eliminate the impurities found in wastewater. High pollution levels triggered by the disposal of untreated wastewater and the harsh social and economic conditions, together with high construction and operation costs of conventional wastewater treatment systems, made it vital to find simple, efficient, cost-effective treatment systems. In this research work, a hybrid microalgae-bacteria pilot outdoor system comprised of a series of Algaewheel® rotating algae contactors (RACs) that receive preliminary treated domestic wastewater at a hydraulic retention time (HRT) of 8 hours was monitored for a period of 5 months. An average dissolved oxygen (DO) value of 3.04 ± 1.02 mgL^{-1} was obtained in the effluent-treated wastewater. While the average removal efficiencies recorded for the parameters monitored were 90.73% for BOD_5, 89.10% for COD, 93.45% for TSS, 77.05% for NH_3-N, and 70.40% for TN. All the effluent values for the parameters monitored were below the limits of both the local and international standards. The pilot system was found to be suitable and adaptable for small communities with low discharges of 5000 m^3/day or less due to its low operation and maintenance requirements, as its electricity consumption is 80% less compared with the conventional wastewater treatment systems.

Keywords: Algal-Bacterial; Wastewater Treatment; Removal Efficiency; Hybrid Attached Growth.

1. Introduction

Nowadays, it is a truism to say that wastewater pollution problems, both domestic and industrial, are of major concern for decision-makers, professionals, and laymen. Due to the escalating costs of wastewater treatment worldwide, the need for the production of clean treated effluent wastewater using very low energy requirements has become an urgent necessity. Third world countries are among the most affected communities due to many reasons that include economic, social, and lack of technical know-how (both design and operation & maintenance) and, finally, with a high significance, mismanagement. Microalgae and bacteria are widely used to significantly reduce the contaminants in wastewater, which essentially include the carbonaceous organic matter measured mainly by the chemical oxygen demand (COD) and nutrients; nitrogen (N) and phosphorus (P), prior to effluent discharge to the receiving water bodies [1-3]. Microalgae show diverse metabolic capabilities over bacteria that enable them to remediate a wide range of wastewater pollutants, including heavy metals, organic contaminants, and excess nutrients. By using the unique metabolic pathways of microalgae, innovative remediation strategies are currently being developed to effectively redress polluted environments [4]. Due to their metabolic flexibility, these microalgae systems have proved efficient in both domestic and industrial

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wastewater treatment with high nutrient recovery via the microalgae biomass, and they also have a high degradation capacity when compared with current existing conventional systems [5, 6]. These systems have proved to have high advantages over conventional systems for lower wastewater flow rates when comparing the per capita, the per cubic meter treatment costs, and the carbon and water footprints [7, 8].

Wastewater treatment using microalgae dates back to the sixties of the last century, with many factors affecting their growth rate, like sunlight, carbon dioxide, nutrients, etc. [9, 10]. Microalgae-based wastewater treatment plants (WWTPs) consume low energy, and in combination with bacteria, they provide an efficient integrated treatment system, as microalgae consume the carbon dioxide (CO_2) produced by the bacteria, and the bacteria consume the oxygen (O_2) produced by the microalgae, and due to this synergistic cooperation and interaction between them, in one single step, both the organic and inorganic impurities in wastewater can be efficiently eliminated [11-13]. Also, these systems have been reported to consume low energy and require minimum skilled operators for their management; thus, it is an affordable process with many benefits [14, 15]. Microalgae can be cultivated in many ways, either separately or in combination with conventional systems. It is an eco-friendly and cost-effective technology that presents an attractive solution for controlling pollution in developing countries [8, 16].

The efficiency of an algae-based lagoon sewage treatment plant was shown to reach 82% for carbonaceous matter and about 57.80% for nutrients for a retention time of 14.30 days [17]. Another study using an algae-bacteria-based system with a retention time of 96 hours recorded removal efficiencies of 91%, 68%, and 38% for chemical oxygen demand (COD), N, and P, respectively [18]. Mixing activated sludge with microalgae increased the removal efficiency of N & P to 94.90% and 76.36%, respectively, and reduced COD removal to 65.73% compared with the previous study [19, 20]. In a study with three different microalgae concentrations of 20, 30, and 40% and at a lower retention time of 24 hours and less, higher removal efficiencies exceeding 85% were recorded for both carbonaceous matter and nutrients [21].

The use of symbiotic microalgae and endophytic bacteria treatment systems and their high efficiency in the removal of N and P is widely documented due to the high ability of the microalgae to absorb nutrients in favor of biomass production by assimilation & phosphorylation for both N & P, respectively [22-24]. Nutrient uptake mechanisms, factors affecting the nutrient removal rate, and microalgae species are thoroughly attested in literature [25-27]. Using different species of microalgae, removal efficiencies of 93-96% and 73-86% were achieved for N & P, respectively [28]. Using one microalgae species (Chlorella vulgaris) and by increasing the quantitative concentrations from 1 to 10 mg/l, the removal efficiency increased for BOD from 80.41 to 82.92%, COD from 78.33 to 82.30%, N from 81.04 to 84.81%, and P from 32.26 to 36.12% [29].

Furthermore, microalgae wastewater treatment systems have proven their high capabilities in the bioremediation of heavy metals from wastewater [30]. They provide a high potential for establishing many ecofriendly and cost-effective technologies that can be adopted for heavy metal removal from wastewater, as they pose a high risk if discharged to the environment or the treated wastewater is used for irrigation [31-33]. The use of microalgae-based systems for the treatment of high-strength wastewaters has many potential merits and is promising for implementation [34-36]. On the contrary, with bacteria, harvested microalgae can provide a good source of bioenergy due to their high photosynthetic conversion rates and increased biomass productivity; biofuels produced by the cultivation of microalgae are considered as third-generation biofuels and can contribute to meeting the future energy demands [37, 38]. Food supplements and bio-fertilizers are also among the potential benefits that can be withdrawn for microalgae wastewater treatment [39, 40], thus adding another add-up value to its numerous advantages. However, before microalgae can be adopted in large-scale commercial applications for sustainable feedstock and bioenergy production, there are many obstacles that need to be addressed. These include choosing the right microalgae strains, creating methods for pre-concentrating biomass, and using wet microalgae biomass to produce biofuel [41].

The main aim of this research work is to assess the efficiency of domestic wastewater degradation using an integrated microalgae and bacteria pilot treatment system. This system is the first of its type to be introduced in the Egyptian wastewater industry; thus, thorough monitoring with regards to startup, factors affecting operation, removal efficiencies, and energy consumption was investigated. The system is commercially marketed by *OneWater*, Inc., with previous research conducted on a similar plant for the removal of ammonia [42] with removal efficiency exceeding 95%.

2. Material and Methods

This section presents the study site, description of the pilot plant, experimental procedure, parameters monitored, and the analytical measurements.

2.1. Site Study

The pilot Algaewheel® rotating algal contactor (RAC)™ plant was constructed and operated at the Badrashin WWTP in southern Giza between June and December 2021. The influent wastewater for the system was collected after the headworks of the main WWTP (after screening and grit removal) via a 100 mm plastic pipe. Construction of the system started on the 19th of June 2021 and lasted for 21 days, while raw wastewater started to flow in the system continuously from the 10th of July 2021. The start-up period for seeding took 21 days before the commencement of sampling for laboratory analysis (31st of July 2021). Operation of the system was terminated on the 30th of December 2021, and the system can be viewed in aerial photographs using Google imagery. October 10, 2021, at coordinates 29°49'52.94" N 31°14'10.21" E. The study area location is presented in the map shown in Figure 1.

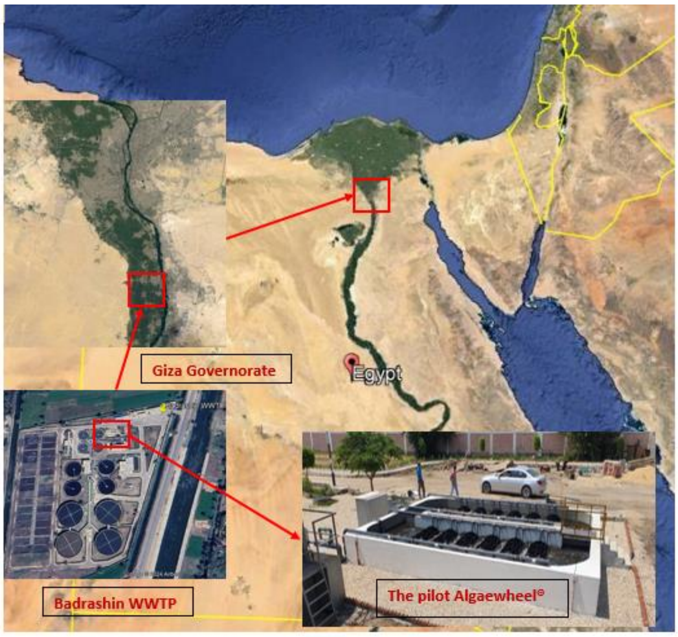


Figure 1. Location of the pilot plant

2.2. Pilot Microalgae Bacteria Treatment Plant

The patented pilot Algaewheel® RAC™ plant was designed to accommodate an average flow of 100 m^3/day with twelve Algaewheel® shafts (five shafts * 900 mm diameter wheels) placed in series. The raceway was constructed in a U-shape configuration using plain concrete and bricks to reduce costs. The total tank depth was 1.90 m and was approximately 1.20 m below ground and 0.70 m above ground with a water depth of 1.0 m. Together with the 12 Algaewheels, each with five wheels, two small (0.5 hp) mixers were attached at the base of the tank to provide both mixing and circulation of flow around the raceway (approximately 1 cycle/hour). A 2.60 kW air blower (on VFD) was installed to provide air to the diffusers located below each wheel log to rotate the buoyant wheels at approximately 1.50 rpm.

The pilot plant had no secondary clarifier due to a lack of adequate space. Effluent samples were collected and placed in an Imhoff cone and allowed to settle in a dim area away from sunlight for a period of about 45 minutes. This roughly duplicated the conditions of a covered large-scale secondary clarifier, which will have a settling time of (2-3) hours in the darkness; darkness is required in the secondary clarifiers to inhibit algal growth, which produces oxygen that bubbles upwards in the tank and reduces the clarification efficiency. Details of the Algaewheel® dimensions, surface area, mode of operation, etc., are fully discussed by Johnson et al. [42], while Figure 2 shows the schematic diagram of the pilot plant flow chart diagram.

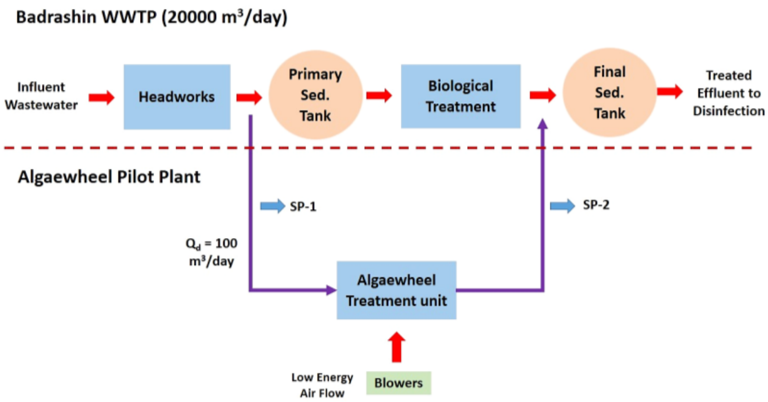


Figure 2. Schematic diagram of the pilot plant flow chart diagram

2.3. Reactor Design

The pilot scale reactor for this study consists of two channels 7.0 meters long, 2.40 meters wide and 1.0 water depth. Figure 3 shows photographs of the pilot Algaewheel® pilot plant. The following steps summarize the design of the pilot plant:

Average discharge = 100 m^3/day

Volume of reactor = 33.60 m^3

Area of reactor = 33.60 m^2

Retention time = 33.60/100 = 0.336 day = 8.0 hours

BOD = 500 mg/lit

Number of shafts = 12

Number of wheels = 5 × 12 = 60

Diameter of wheel = 900 mm

Surface area of wheel = 75 m^2

Total surface area of wheels = 75 × 60 = 4500 m^2

Specific area of MBBR media inside the Algaewheels = 450 m^2/m^3

Total area (75 m^2) includes the MBBR media – 63 m^2 for media and 12 m^2 for actual external wheel surface area.

BOD load = 100 × 500 = 50,000 gBOD/day = 50 kgBOD/day

BOD loading rate = 50,000/4500 = 11.11 gBOD/m^2/day

Aeration calculations:

Oxygen diffusion from atmosphere = 25 nmolO_2/cm^2/min

Oxygen produced by photosynthesis = 75 nmolO_2/cm^2/min

Diffusion oxygen from atmosphere (24 hours) = 0.360 molO_2/m^2/day

Oxygen produced by photosynthesis (12 hours) = 0.504 molO_2/m^2/day

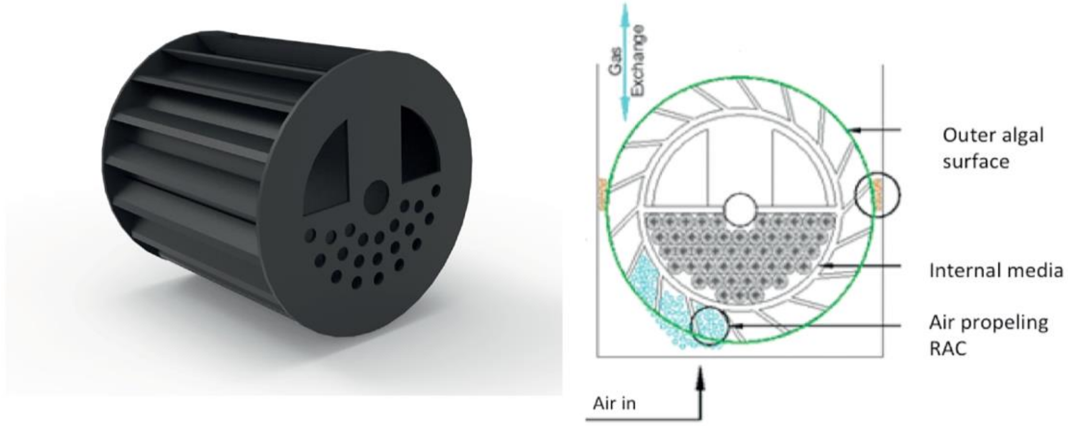
Amount of oxygen diffused from atmosphere = 0.36 × (33.60 + 63 × 60) = 1372.896 molO_2/day

Amount of oxygen produced by photosynthesis = 0.504 × 12 × 60 = 362.88 molO_2/day

Total amount of oxygen produced = 1372.896 + 362.88 = 1735.776 molO_2/day

Figure 3. Photographs of the pilot Algaewheel plant

The drums in the reactor basin act as rotating biological contactors (RBCs) as shown in Figures 3 and 4. The RACs in this pilot plant are driven by air bubbles, as shown in Figure 4-b, thus reducing the cost of the rotating mechanism when compared with the conventional RBC systems. Algal photosynthesis helps to increase the oxygen production together with the sequestration of the CO_2 produced by the bacteria, and this supplements the oxygen flow with a direct reduction in electricity consumption, as aeration devices consume about 45-75% of the energy supplied to WWTPs [43]. The air bubbles not only rotate the RAC but also aerate the water, scour the biofilm, and reduce its thickness. This promotes algal growth and increased exposure to the sunlight.



(a) (b)

Figure 4. Reactor components. a) Algaewheel™ rotating algal contactor (RAC), b) RAC showing interactions with air bubbles and water [42]

2.4. Raw Domestic Wastewater Characterization

The influent wastewater for the pilot plant was collected after the headworks of the main Badrashin WWTP. The following parameters shown in Table 1 were monitored and analyzed during the operation period.

Table 1. Influent wastewater characteristics

Parameter	Minimum value (mg/L)	Maximum value (mg/L)	Average value (mg/L)
Total Suspended Solids (TSS)	375	580	500
Chemical Oxygen Demand (COD)	650	900	800
Biological Oxygen Demand (BOD_5)	425	650	500
Ammonia Nitrogen (NH_3-N)	35	80	50
Total Nitrogen (TN)	62	105	80

2.5. Analytical Experimental Measurements

All samples were collected from the influent and effluent streams of the system at approximately 10:00 a.m. according to the operation schedule. All the samples were analyzed in the laboratories of the Badrashin WWTP using Standard Methods [44]. Parameters monitored include chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), and ammonia nitrogen (NH_3-N). Dissolved oxygen (DO) concentrations, pH values, and temperature were recorded daily using a multi-channel analyzer (Topac Consort C932). BOD was measured using 300-mL incubation bottles and Hach HRI3P-2 (220V) incubator, while COD was measured using the closed reflux colorimetric method using a UV-VIS DR6000 benchtop Hach spectrophotometer with a wavelength range from 190 to 1100 nm and a resolution of 1 nm; this spectrophotometer was also used in the analysis of the remaining parameters. All the data were statistically analyzed using one-way analysis of variance (ANOVA) using JMP®, Version 13.2.1 (SAS® Institute Inc., Cary, NC) with application of the Tukey-Kramer test for post hoc comparison if needed.

2.6. Start-up and Operational Schedule

Start-up of the system took a duration of 21 days to allow for the algae growth to flourish on the surface of the wheels and the reactor was seeded for bacteria from the main Badrashin WWTP. Samples were collected from the inlet and outlet of the reactor with the frequency shown in Table 2. Figure 5 shows photographs of the algae growths on the wheels surface and the effluent samples before and after sedimentation.

Table 2. Operational schedule and sampling frequency

Run		Run duration = 154 days						Sampling frequency
		Number of samples						
Monitored parameters	TSS	40	40	40	40	40	40	Twice/week
	COD	30	30	30	30	30	30	Every 5 days
	BOD_5	30	30	30	30	30	30	Every 5 days
	NH_3-N	10	10	10	10	10	10	Once/2 Week
	TN	30	30	30	30	30	30	Every 5 days

Figure 5. Photographs showing the algae growth on the wheels and treated water

3. Results and Discussion

The pilot scale Algaewheel® RAC™ treatment system was operated under steady flow conditions for one trial only and samples were collected after reaching steady state and full growth of bacteria and algae was noticed on the media. Summary of the monitored parameters is discussed in the following sections.

3.1. pH Value and Temperature

pH monitoring is not only an essential parameter for observing the growth and health of a culture, but it also gives us a clue for algae demand of carbon. Carbon is the essential nutrient required for algae production, as it composes about half of the algae dry weight. Algae consumption of carbon dioxide and release of oxygen during photosynthesis was found to slightly increase the pH during the daylight compared with the night, and this was attributed to the presence of bacteria that produces carbon dioxide to compensate for that consumed by the algae. During night time the algae and bacteria respiration releases carbon dioxide, which accounts for the reduction of pH. In our research work, pH was measured more than once a day as an indicator of the pilot plant's steady and healthy operation. The average pH readings for the five months of monitoring ranged between 7.07 ± 0.17 and 8.19 ± 0.23.

Furthermore, temperature has a significant impact on the microalgae/bacteria process in terms of the pace of reaction, microorganism growth rates, and death. The difference in liquid average temperature between the wettest and driest months of the year as recorded in the main Badrashin WWTP is around 22 °C. While in our research work, the maximum temperature recorded was in summer in the month of August with an average value of 31 ± 3.08 °C. The lowest temperature recorded was 14 ± 2.11 °C in December. Average monthly recorded data for temperature and pH are as shown in Table 3. The climate in Egypt has a slight effect on algae growth as temperature is in the range of (14-31) °C, and the hours of daylight are in the range of (10-13) hours. Literature documents that the maximum algae growth is at 23 °C and the lowest is at 7 °C [45], while the optimal growth is in the range of (20-30) °C [46].

Table 3. Average monthly pH and temperature values

Month	pH	Temperature (°C)
July	7.60 ± 0.18	28 ± 4.70
August	8.19 ± 0.23	31 ± 3.08
September	7.44 ± 0.33	24 ± 5.22
October	7.07 ± 0.17	22 ± 3.15
November	7.51 ± 0.41	18 ± 4.18
December	7.42 ± 0.27	14 ± 2.11

3.2. DO Concentrations

The rotating shafts, the diffused air supply for rotating the contactors together with the presence of algae were the three mechanisms providing oxygen to the pilot system. Pumped-in, diffused air supplies both oxygen and rotates the wheels upon which the algae sunlit biofilm grows synchronously, producing oxygen. DO concentrations were daily recorded at the inlet and outlet of the bioreactor during the monitoring period to monitor the changes and the efficiency of the algae for oxygen production. The average value of DO concentration recorded was 0.98 ± 0.58 mgL^{-1} at the inlet, while the average concentration recorded at the outlet was 3.04 ± 1.02 mgL^{-1}. The percentage of DO increase was calculated to range from 7 to 700%, and influent and effluent values are as shown in Figure 6. These results are similar to those reported by Johnson et al. [42] and Kuenen et al. [47], as they showed an oxygen increase of about 500%. In another study by Su et al. [48], a DO increase from 2.0 mgL^{-1} to 5.50 mgL^{-1} (175% increase) was reported.

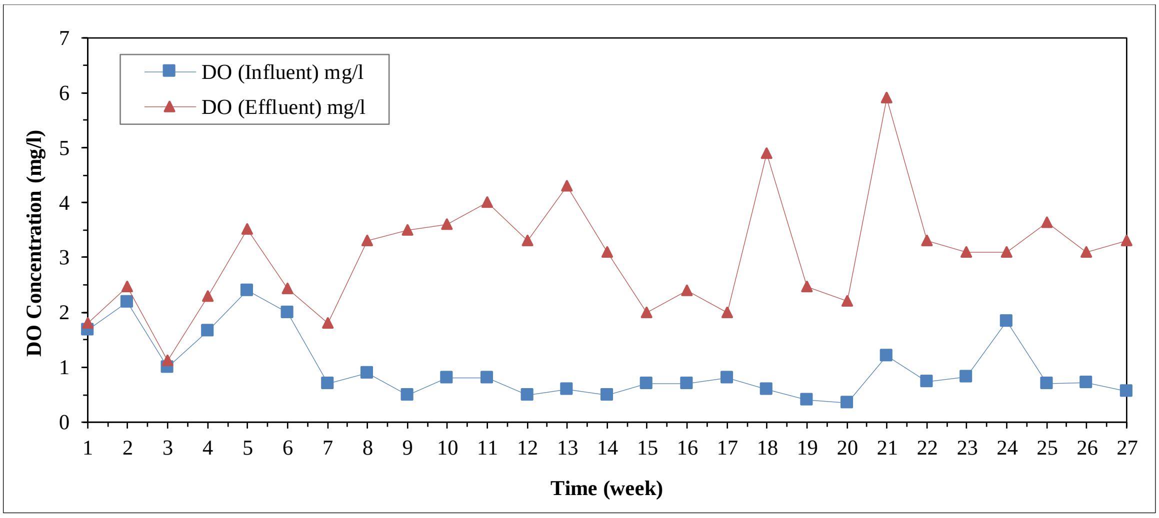


Figure 6. DO influent and effluent concentrations

3.3. TSS and TDS Removal Efficiencies

The TSS removal efficiency of the pilot plant was high compared with that of TDS, which was negligible. Figure 7 shows the TSS and TDS influent and effluent values during the monitoring period of the system. The average recorded influent and effluent values for TSS were 245.11 ± 77.56 mgL^{-1} and 14.44 ± 6.54 mgL^{-1}, respectively, yielding an overall average TSS removal percentage of 93.45 ± 3.73%. TSS removal percentages are similar to those reported by Su et al. [48], as they reported in TSS values from 1.89 gL^{-1} to 0.016 gL^{-1}, giving about 99.13% removal efficiency. Also, the TSS removal efficiencies obtained in this study are similar to those reported by Mahapatra et al. [17] from other studies, which were in the range of (90-93)% and (89-94)%.

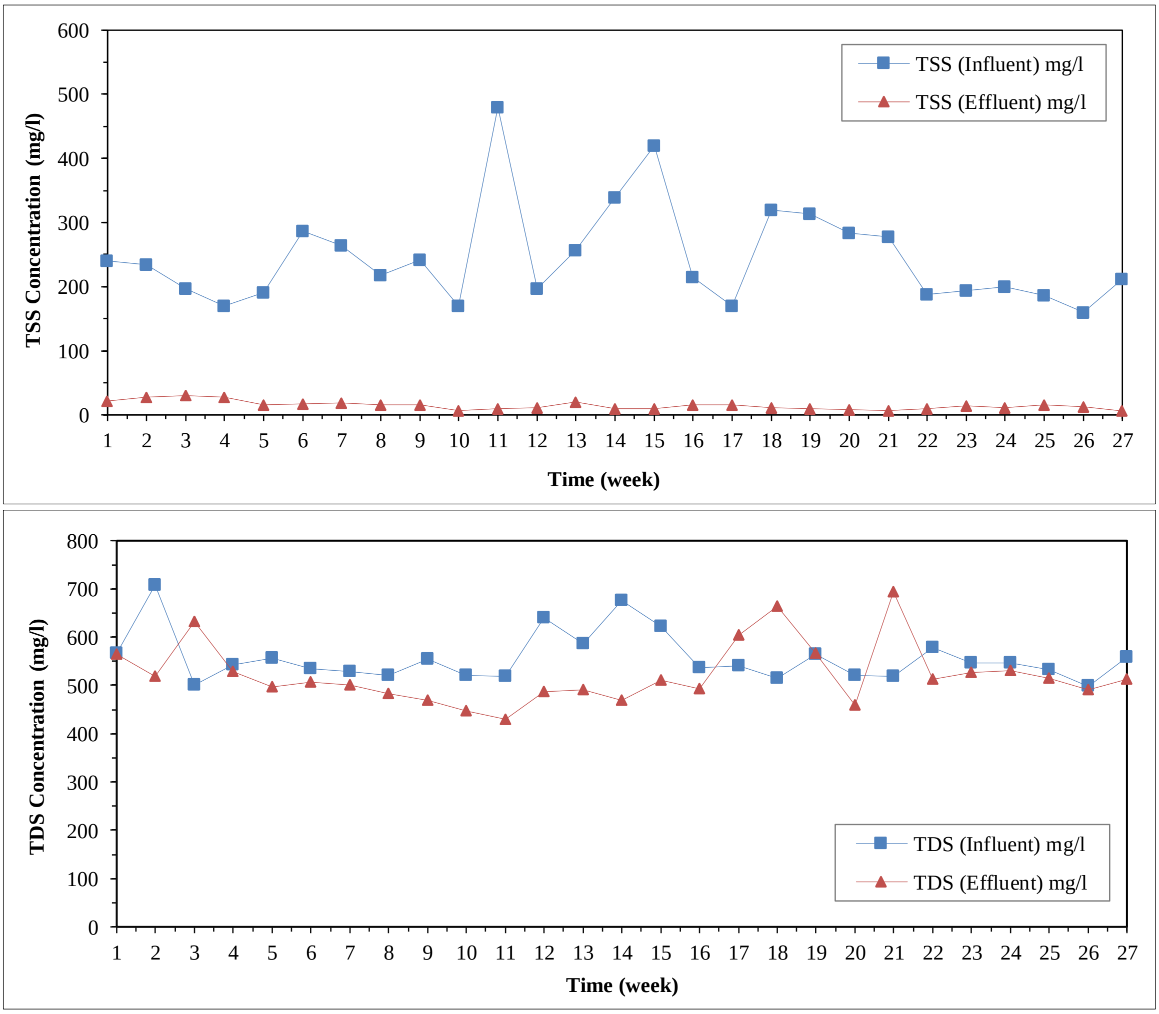


Figure 7. TSS and TDS influent and effluent values

On the other hand, the TDS influent and effluent average recorded values were 556.70 ± 51.21 mgL^{-1} and 522.26 ± 63.03 mgL^{-1}, respectively, with a removal percentage of 5.31 ± 15.53%, respectively. The deviation in the effluent removal efficiency for TDS was very high, with about 15% on average, and this was contrary to what was obtained for the other parameters monitored, and the results obtained were rather disappointing and reflect the failure of the system for TDS removal. However, the percentage of dissolved solids remains within the permissible limits. This low removal efficiency is attributed to the low TDS influent concentrations and maybe the type of algae species grown in the system. Literature reports high TDS removal efficiencies of 27% for influent concentrations of 2700 mgL^{-1} and above [49]. Another study showed that increasing the TDS levels reduces the microalgae growth and consequently the removal efficiencies. For TDS concentrations of (2000-4000) mgL^{-1}, the removal efficiencies were (76-47)% [50].

3.4. BOD_5 and COD Removal Efficiencies

Analysis of the samples collected during the monitoring period for the remediation of the carbonaceous pollutants in the influent wastewater showed very promising results. With very low energy requirements, the removal of BOD_5 and COD reached 90.73 ± 4.61% and 89.10 ± 5.18%, respectively. The average recorded influent and effluent BOD_5 concentrations during the monitoring period were 224.67 ± 52.17 mgL^{-1} and 19.63 ± 8.51 mgL^{-1}, respectively. While those recorded for COD were 436.07 ± 124.14 mgL^{-1} and 44.20 ± 19.30 mgL^{-1}, respectively. Figure 8 shows the average influent and effluent values recorded for both parameters.

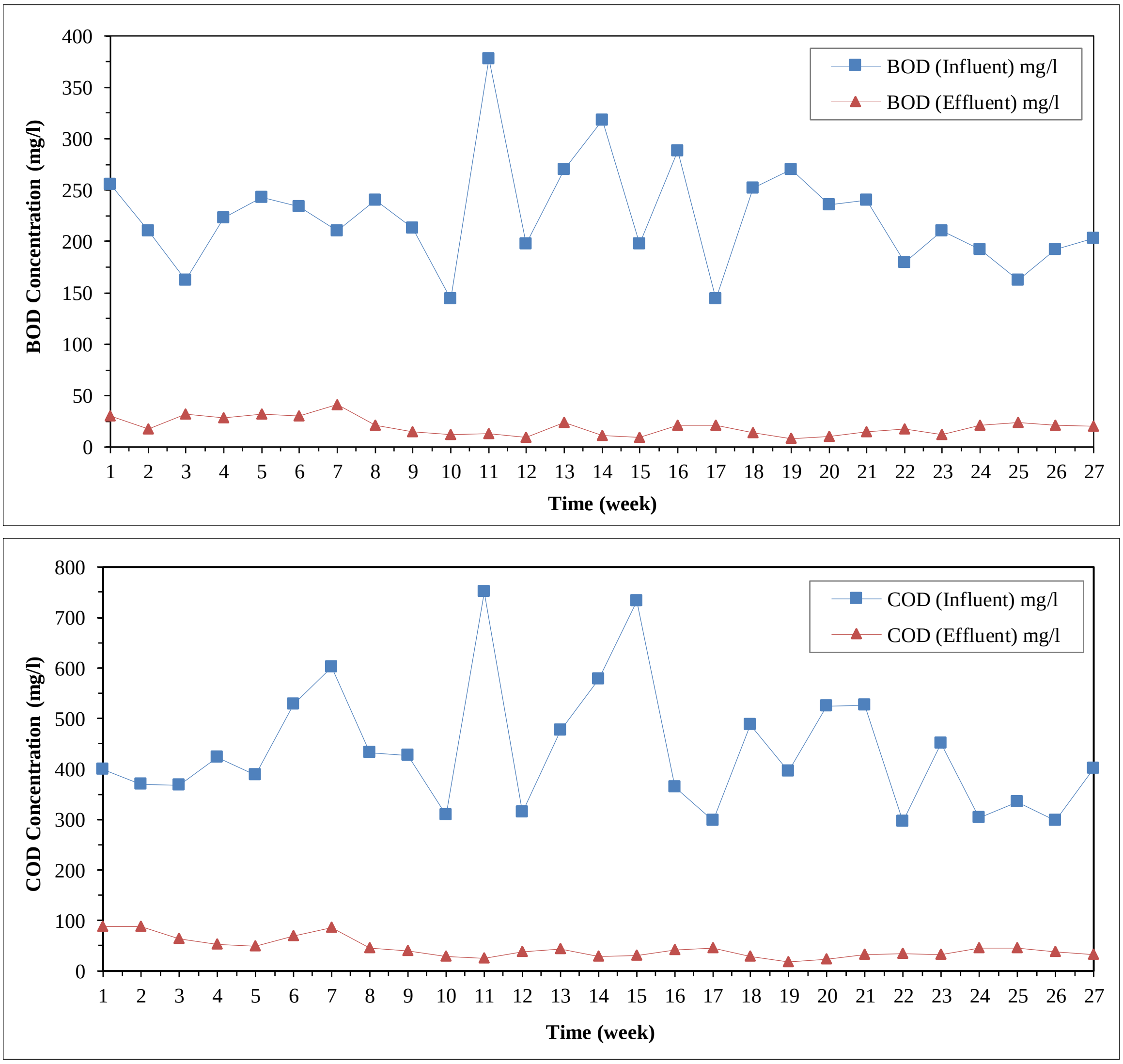


Figure 8. BOD_5 and COD influent and effluent concentrations

This high removal efficiency by the hybrid algae/bacteria system is attributed to the three different mechanisms involved in the bioremediation process [14]. Removal efficiencies obtained in this study are similar to those documented in literature for previous studies; a 91% removal efficiency was documented by Tricolici et al. [18], while Khaldi et al. [19] recorded a COD removal rate of 65.73%. For different microalgae concentrations and retention times, the COD removal efficiency was recorded to range from (93.47-97.92)% [21]. Choi and Lee [29] reported a BOD removal rate in the range of (80.41-82.92)% and COD from (78.33-82.30)% by using different concentrations of *Chlorella vulgaris*. A 84% BOD and 89.00% COD removal efficiency using both *C.vulgaris* and *Scenedesmus sp.* in a batch system was documented by Hammouda et al. [51]. Treating domestic wastewater using microalgae was reported by Aslan and Kapdan [52] with removal efficiencies of 68.40% and 67.20% for BOD and COD, respectively.

3.5. NH_3-N and TN Removal Efficiencies

NH_3-N and TN removal in algae-bacteria hybrid systems is much more efficient in comparison to separate algal and conventional wastewater treatment systems due to the multiple routes available through the algal-bacterial mutual relationship. NH_3-N and TN removal in the algal-bacterial pilot system under study took place through several different pathways. Nitrification-denitrification is also a very important process for the efficient removal of nitrogen from wastewater. Oxygen produced by the photosynthetic action of microalgae helped the nitrifying bacteria together with the presence of anoxic zones in the reactor of the pilot plant in the denitrification process. Although phosphorus is a major essential nutrient for the algal growth, the effect of microalgae on its removal was not measured in our research work due to technical issues. The weekly sample collected for determining the efficiency for nitrogen removal in the pilot system was taken after four weeks of the system start-up after reaching the steady state with nitrification of ammonia taking place. The analysis revealed that the average influent and effluent load recorded was 22.26 ± 3.52 mgL^{-1} and 5.13 ± 4.11 mgL^{-1} for NH_3-N, with an average removal efficiency of 77.05 ± 18.60%. Similarly, the pilot system showed higher removal efficiency for TN, with the average influent and effluent load recorded being 71.41 ± 11.41 mgL^{-1} and 21.84 ± 9.08 mgL^{-1}, with an average removal efficiency of 70.40 ± 8.84% (Figure 9). The ability of the microalgae-bacteria in the pilot system to absorb and use nutrients for growth drastically lowered the amount of nutrients in wastewater, improving the quality of the effluent wastewater together with biomass accumulation.

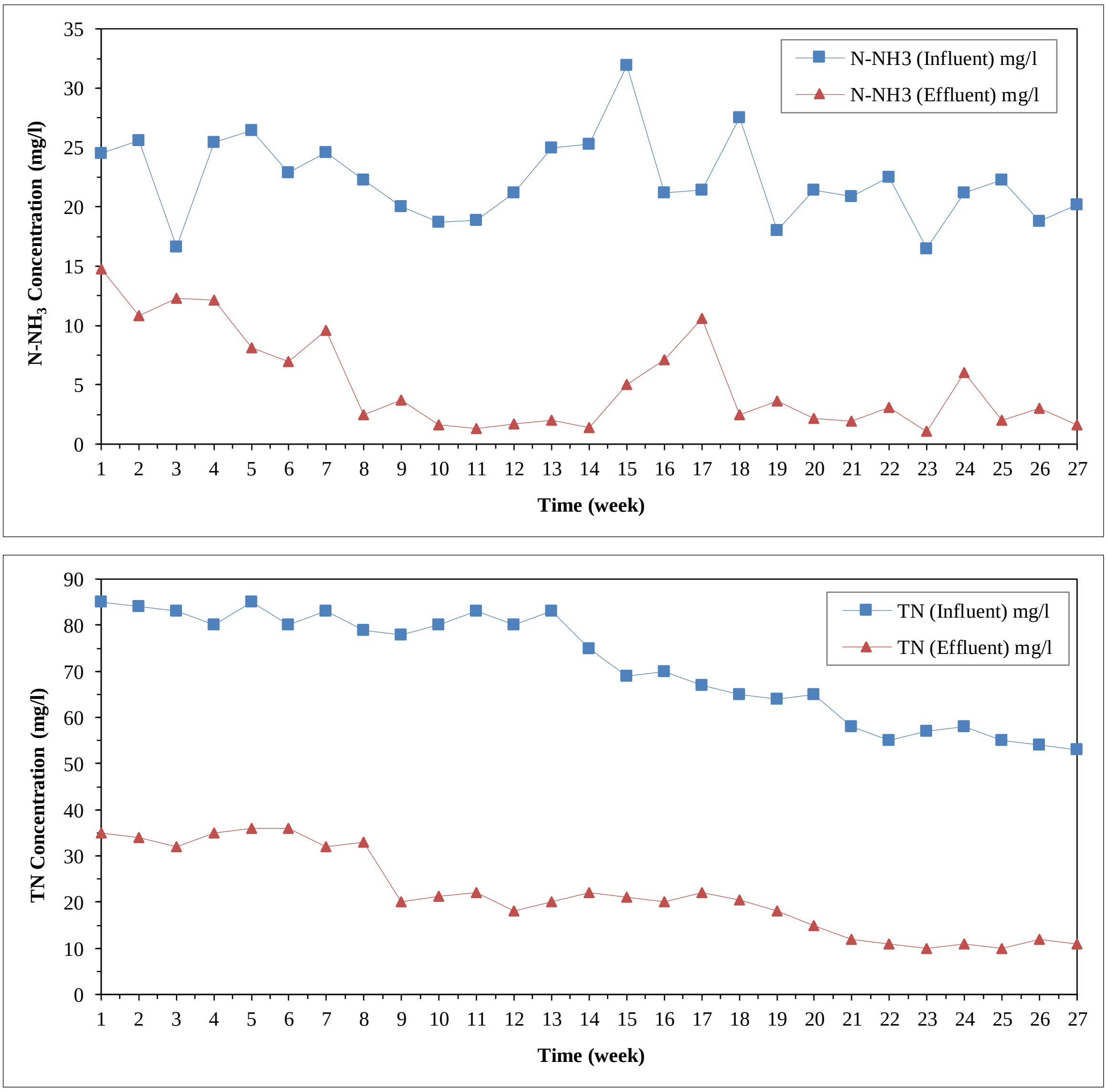


Figure 9. NH_3-N and TN influent and effluent concentrations

Removal efficiencies reported in previous studies for NH_3-N and TN are similar to what was obtained in this study. Alazaiza et al. [27] reported 95.00% ammonia nitrogen removal. While Choi and Lee [29] using different algae concentrations documented removal efficiencies ranging from (96.90-97.26)% and (81.04-84.81)% for NH_3-N and TN, respectively. Su et al. [48] reported a TKN removal efficiency of 88.3±1.60% using algal-bacterial culture consortia. Fard et al. [53] using *Scenedesmus* microalgae obtained a TN removal efficiency of 93.00%. Also, many studies in the literature linked the efficiency of the nutrient removal with the type of algae species grown in the system, but in our case, we didn't determine the type of algae cultures.

3.6. Comparison with Standards Requirements

During the monitoring period, all the recorded effluent values were below the required effluent values as per the Environmental Protection Agency (EPA) and the Egyptian Code of Practice (ECP) standards for disposal to agricultural drains, as shown in Table 4.

Table 4. Comparison with ECP & EPA standards

Parameters	Average influent	Average effluent	Removal efficiency (%)	ECP	EPA
BOD_5 (mgL^{-1})	224.67 ± 52.17	19.63 ± 8.51	90.73 ± 4.61	60	50
COD (mgL^{-1})	436.07 ± 124.14	44.20 ± 19.30	89.10 ± 5.18	80	250
TSS (mgL^{-1})	245.11 ± 77.56	14.44 ± 3.54	93.45 ± 3.73	50	50
pH	7.38 ± 0.32		N/A	6-9	6-9
Temperature	23.37 ± 6.67		N/A	< 30	< 30
TDS (mgL^{-1})	556.70 ± 51.21	522.26 ± 63.03	5.31 ± 15.93	< 2000	1000
TN (mgL^{-1})	71.41 ± 11.41	21.81 ± 9.08	70.40 ± 8.84	N/A	50
NH_3-N (mgL^{-1})	22.26 ± 3.52	5.13 ± 4.11	77.05 ± 18.60	N/A	N/A

3.7. Economic Advantages, System Scalability and Operational Conditions

The easy operation and the high removal efficiencies for the parameters monitored prove that the hybrid microalgae-bacteria-fixed-film systems are highly capable of removing the organic carbonaceous compounds and nutrients from wastewater. The high nutrient removal efficiency, reaching more than 70%, in one single reactor is a result of a series of processes as documented in a study undergone for the same pilot reactor [42]; (3-11)% of NH_3-N is oxidized to nitrate while (27-36)% is lost to the atmosphere as N_2 and the majority is oxidized to nitrite. Also, electricity consumption studies conducted in the same study proved the algae bacteria RAC pilot system consumes less electricity by about 80% when compared with conventional systems giving the same removal efficiencies [42]. Also, the system can be scaled to meet both domestic and industrial requirements with no flow capacity limits; the system provider has modules that serve up to 750,000 GPD. Earlier documented literature reports that the microalgae-bacteria systems are suitable for domestic, high-strength, and industrial wastewaters. No economic analysis was done for this pilot system as it was constructed and operated by the system provider; data is currently being collected to conduct the analysis for the large-scale 1000 m^3/day treatment plant.

During operation of the system, we realized that algal productivity seemed to be more impacted by the high sunlight intensity in summer months compared with winter months, but with no excess overgrowth in both seasons. The rotation of the wheels helped in the mixing of the MBBR media placed inside the RACs.

Easy operation and almost maintenance-free requirements by the system during our monitoring period, together with its high removal efficiencies, nominates the system for adoption for use in decentralized remote systems with small discharges. We also see it as suitable, as remote areas lack highly qualified operators, and the availability of electricity is always low. The hybrid system operates in the same manner as conventional systems with regard to the removal of excess algal and bacterial overgrowth (washout) as the effluent wastewater from the system is clarified prior to disinfection and final disposal. The only difference is that the final clarifiers should be covered to block sunlight and terminate algal growth; collected algae can be harvested and used as previously discussed. Consequently, a new large-scale wastewater treatment plant with a capacity of 1000 m^3/day was constructed in Egypt with two Algaewheel® reactors, each with a capacity of 500 m^3/day, and it is currently in its initial start-up phase, and full documentation of the operation of this plant will be published in another research work.

4. Conclusions

Microalgae has proven its exceptional efficiency in the production of oxygen by photosynthetic activities yielding higher growth rates. The higher biomass productivity by microalgae can be grown without the need for large land areas. In one single step and by combining the merits and marvels of both algae and bacteria, the pilot treatment plant was able to assimilate the carbonaceous pollutants and nutrients found in the domestic wastewater. The output of monitoring the pilot plant in this research work can be concluded in the following points:

- An average DO level of 3.04 ± 1.02 mgL^{-1} was maintained in the effluent of the reactor basin.
- BOD_5 removal rates recorded were above 90% with effluent values as low as 19.63 ± 8.51 mgL^{-1}.
- The average effluent COD value recorded was 44.2 ± 19.3 mgL^{-1} marking a removal efficiency of 89.10%.
- TSS removal was very high, recording 93.45%, with an average effluent value of as low as 14.44 ± 3.54 mgL^{-1}.
- TDS removal by the system was negligible.
- The removal of the nutrient (N) was measured as NH_3-N and TN, and the removal efficiencies were well above 70% for both parameters with average effluent values of 5.13 ± 4.11 mgL^{-1} and 21.81 ± 9.08 mgL^{-1} respectively.
- One of the main benefits of Algaewheel® RAC™ treatment systems is the reduced consumption of electricity compared with other conventional bacterial systems.
- Rapid system installation with easy operation and very low maintenance requirements are among the many merits of the system.
- Algal-bacterial hybrid systems are still in the preliminary steps of large-scale commercialization, and future research work must focus on the types of algae strains that are well-suited to the wastewater treatment requirements, taking into consideration the seasonal effects, retention time, pollution load, algae-bacteria ratio, etc.

5. Declarations

5.1. Author Contributions

Conceptualization, K.H. and M.Heg.; methodology, A.K.; software, M.Heg.; validation, K.H., M.Heg., and M.Hel.; formal analysis, K.H.; investigation, M.Heg.; resources, M.Hel.; data curation, M.Hel.; writing—original draft preparation, K.H.; writing—review and editing, K.H. and M.Heg.; visualization, M.Hel.; supervision, K.H. and A.K.; project administration, A.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Data sharing is not applicable to this article.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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