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Organics removal from office wastewater in attached growth biological process of a packaged onsite wastewater treatment system

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ABSTRACT

Advancements in onsite wastewater treatment technology have attracted attention since various types of wastewater can be viably treated and reused at production. In the case of wastewater produced by buildings, including offices (including laboratories and workshops), wastewater is dilute and has particular characteristics warranting an investigation of the performance of onsite systems. This paper investigates the performance of an attached growth biological process in a full-scale onsite wastewater treatment system treating office wastewater. The organics removal efficiency of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of 93.0% and 93.3%, respectively, were achieved, and nutrient removal efficiency was 72.3 ± 0.7 and 25.9% ± 0.9% for total nitrogen (TN) and total phosphorous, respectively. The low nutrient concentrations and the presence of inhibitive chemicals such as phenols, metals, and high ammonia concentrations have caused unfavourable conditions for biomass growth, and caused washout (particularly heterotrophs) and reduced efficiency. Due to these factors, organics removal was as low as 5.2% and 4.8% for BOD and COD, respectively, and nutrient removal was as low as 65.4% and 0.0% for TN and TP, respectively. These performance limitations constitute essential guidance for using similar onsite treatment systems.

Keywords: In-situ; Wastewater; Office; Packaged units; Treatment

1. Introduction

Water deficiency is a significant challenge to sustainable development and is one of the drivers of decentralised wastewater treatment systems [1,2]. This challenge is compounded by rapid population growth, urbanisation, environmental pollution, and climate change [3,4]. Internationally, particularly in the Arabian Gulf region, the wastewater produced by a large portion of office buildings and satellite camps is stored in tanks and transported elsewhere by tankers for further processing. Peter-Varbanets et al. [5] reported that only a small fraction of mains water is used for potable consumption (i.e., drinking and cooking), with the majority used for non-potable applications, and in this case, wastewater reuse could play an important role. In areas where decentralised wastewater treatment plants are uncommon, decentralised wastewater treatment plants are faced with restricted budgets, a lack of local expertise, a lower wastewater collection rate, and a lack of performance knowledge [6,7]. Nonetheless, packaged wastewater systems have been reconsidered due to their technological advancement. They are regarded as a critical element in the urban water cycle, where they can provide a transitional solution to accommodate urban population growth [8]. Packaged water treatment and reuse systems can provide a sustainable and continuous source of high-quality potable and non-potable water for

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urban and suburban communities. Due to their relatively small spatial and carbon footprints and minimum effluent discharge into the environment, their environmental impact has been less, especially for the attached growth ones [9]. In addition, each packaged system can be tailor-made to suit local conditions, aesthetic requirements, water quality objectives, and end uses [10]. According to Mirra et al. [10], costs associated with connection to public sewerage networks, wastewater transportation, and treatment can also be reduced, which otherwise would be necessary for connecting to distant centralised treatment plants. Both options have their own capital and operating costs, while the latter provides the opportunity for onsite reuse while contributing significantly to providing tangible wastewater solutions [1,11]. However, regardless of the specificity of the onsite wastewater treatment system, three parameters follow similar increasing and decreasing trends—inflow rate, inflow pollution load, and oxygen demand in the reactor and could affect the wastewater treatment performance [10].

Commercial systems are available with different types of technology, capabilities, and specifications, and their operation is flexible. In many cases, manufacturers offer different versions of the same system to give different qualities and to suit different applications. The choice of a commercial packaged system could be achieved by using priori-established criteria. Tchobanoglus et al. [12] identified 23 essential factors to consider when selecting municipal wastewater treatment processes. This research can provide an opportunity to investigate these criteria further. Additionally, Mena-Ulecia and Hernández [11] have developed environmental, social, and economic assessment criteria for selecting decentralised systems.

However, there is a need for more scientific knowledge on packaged wastewater treatment and reuse systems concerning their suitability for some types of wastewater, technology efficiency, operational robustness, performance, reliability, operating costs, and greenhouse gas footprint.

Previous research has investigated various packaged wastewater treatment systems for treating various types of wastewater [13,14]. For domestic or municipal wastewater, usually, a system composed of an aeration tank, clarifier, and a filter with disinfection (chlorination or UV) meets the regulatory requirements [15]. In the case of office wastewater, the quality differs as it is often very dilute compared with other types of wastewater and may contain relatively high amounts of specific contaminants depending on the business nature of the office buildings [16]. In many instances, office buildings are semi-industrial complexes. In this context, office wastewater is often more challenging to treat and reuse. Therefore, further research is vital to identify, modify, or design the appropriate packaged system that when used, can render treated water fit for reuse.

Many previous studies have addressed the onsite treatment of wastewater using biological processes [9,13,14,17–21]. Biological processes for wastewater treatment are widely used in packaged wastewater treatment plants due to their ease of operation and maintenance, low costs, and reasonable efficiency [14]. Biological treatment processes are available in many configurations, including the attached growth configuration, which is considered the most efficient [14,20]. Based on its onsite performance, the attached growth configuration with a simple design, easy operability, lesser maintenance, and lower energy requirement has an excellent potential to replace the conventional septic tank for domestic wastewater treatment in areas not connected to centralised wastewater treatment systems [18]. Karczmarczyk et al. [9] pointed out that many of the onsite systems surveyed in Poland still need to meet the 80% organics declared removal threshold.

Some challenges for office wastewater treatment stem from the uncertainty associated with wastewater characteristics such as nitrification inhibition, which could be caused by the unstable inflow of sewage with variable composition to the biological reactor chamber [10,22,23]. It was reported that the nitrification and denitrification efficiency could be significantly increased by introducing attached growth biological processes [24].

Nitrification in a biological treatment reactor can be inhibited by several substances in office wastewater from laboratories and other sources. If microorganisms are simultaneously exposed to several inhibitors, the effect of each of them is usually enhanced [25,26]. Another issue is the long hydraulic residence time requirement, which reduces biomass growth, and the low residence time, which hinders organic removal by heterotrophic bacteria [27]. Up to 96% organics removal efficiency could be achieved in attached growth biological reactors [17]. Nevertheless, it has to be noted that the filling ratio of the reactor or, alternatively, the porosity of the filling material could profoundly affect the performance of the attached growth process [28]. Gu et al. [28] concluded that a filling ratio of 50% may ensure optimal efficiency; however, they dealt with highly concentrated wastewater. If the influent had much lower concentrations of pollutants, the filling ratio effects might not be as pronounced [28].

This paper deals with the long-term performance of a bio-filter-based onsite wastewater treatment system under actual field conditions to assess its performance and to identify the constraints imposed by the characteristics of the wastewater generated by office buildings containing laboratories and technical support facilities. Specifically, this paper attempts to assess and understand the removal of organics from office wastewater using a packaged wastewater treatment system utilising an attached growth biological treatment reactor. The results of this study would enhance knowledge on dilute (office) wastewater treatment using attached growth biological reactors.

2. Methodology

The methodology to procure the wastewater reuse system consisted of a preliminary wastewater survey, identification of system requirements, procurement and installation of the *in-situ* wastewater reuse system, and system performance monitoring. Based on the wastewater survey, an appropriate packaged wastewater treatment system was selected and tested at a selected pilot site within the Kuwait Institute for Scientific Research (KISR) premises. A 30 m^3/d wastewater generation capacity was found suitable for the wastewater with the characteristics shown in Table 1.

Table 1
Overall statistics of the initial survey wastewater quality data

Parameter	Minimum	Maximum	Average	Standard deviation
Temperature (T), °C	17.5	22.6	20.3	1.3
pH	6.48	7.4	7.0	0.3
Electrical conductivity (EC), µS/Cm	234	1,550.0	1,001.7	368.4
Dissolved oxygen (DO), mg/L	0.15	3.2	1.0	1.1
Total suspended solids (TSS), mg/L	3.8	122.0	39.5	25.7
Volatile suspended solids (VSS), mg/L	3.7	119.0	37.3	25.2
Total dissolved solids (TDS), mg/L	124	488.0	304.5	99.6
Ammonia (NH_3N), mg/L	51	83.2	64.8	6.8
Nitrate nitrogen (NO_3^- N), mg/L	0.3	52.5	2.9	9.4
Nitrite nitrogen (NO_2^- N), mg/L	0	0.0	0.0	0.0
Total nitrogen (TN), mg/L	60	146.0	81.7	19.2
Total phosphate (TPO_4^{3-}), mg/L	0.35	56.7	19.5	15.2
Sulfide (S), mg/L	0.005	5.9	1.0	1.7
Fluoride (F), mg/L	0	2.7	0.8	0.6
Total oil and grease (TOG), mg/L	1.5	6.0	3.6	1.6
Chemical oxygen demand (COD), mg/L	12	305.0	171.2	72.8
Biological oxygen demand (BOD), mg/L	8	193.0	104.9	43.9
Aluminum (Al), mg/L	6.9	191.7	44.2	46.5
Arsenic (As), mg/L	2.14	2.8	2.5	0.5
Barium (Ba), mg/L	19.7	48.1	35.0	7.8
Boron (B), mg/L	31.64	319.0	143.5	67.8
Cadmium (Cd), mg/L	90.16	90.2	90.2	–
Cobalt (Co), mg/L	0.25	2.0	0.6	0.3
Chromium (Cr), mg/L	0.81	131.0	19.7	30.1
Copper (Cu), mg/L	8.69	65.1	23.7	13.5
Iron (Fe), mg/L	12.06	325.3	111.3	90.7
Mercury (Hg), mg/L	<1.0	<1.0	<1.0	–
Manganese (Mn), mg/L	0.41	212.4	108.9	64.3
Nickel (Ni), mg/L	0.65	11.8	5.2	2.6
Lead (Pb), mg/L	1.5	3.8	2.4	0.9
Antimony (Sb), mg/L	2.43	2.5	2.5	0.1
Zinc (Zn), mg/L	23.93	372.1	119.4	81.1
Total coliform (T.C.), mpn/100 mL	0	2,419.6	2,004.2	902.3
F-coliform (F.C.), mpn/100 mL	0	300.0	228.8	127.7
E. coli (EC), mpn/100 mL	7.5	2,419.6	2,118.4	823.1

2.1. Packaged system

A packaged wastewater treatment plant of 30 m^3/d was procured from ABRON, Denmark (Fig. 1). The selection of the system among bids was based on criteria set by Tchobanoglus et al. [12] and elaborated by Ahmed et al. [29]. The system was a Biokube, Jupitor-75, composed of a settling tank, biological treatment (attached growth, packing surface area 300 m^2/m^3), a clarifier, sand filter, and UV disinfection (Figs. S1–S3). The attached growth tank volume is approximately 2 m × 2 m × 2.5 m. The primary settling tank is a circular cylinder of 4.0 m^3 volume, and the secondary clarifier volume is 2.5 m^3.

The wastewater is collected from various buildings in a sewage well. The system is automated via a control panel, and the wastewater is pumped into the system automatically at 30 m^3/d. Wastewater flows in series through the settling tanks, the attached growth process's, the clarifier, the sand filter, and the UV disinfection. The flow is controlled by sensors at each stage of treatment.

2.2. Monitoring plan

A monitoring plan was executed to examine the wastewater treatability using the selected packaged wastewater system and the suitability of the final effluent for reuse in irrigation. Since the main objective of the priming period is to facilitate biological growth, only temperature, pH, biochemical oxygen demand (BOD), and VSS were observed daily to indicate the readiness of the attached growth process for long-term operation. The priming lasted for one month. Then, the wastewater was monitored for 6 months (from the first of April to the end of August 2020) to infer the attached growth process performance. Major parameters were measured before and after the attached growth process: daily for the first week, weekly for the next month and a half, biweekly for the next month, and monthly for the last three months.

Parameters monitored include temperature, the logarithm of hydrogen concentration (pH), electric conductivity (EC), dissolved oxygen (DO), BOD, chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), total nitrogen, total phosphorous, biomass (VSS), cadmium, chromium, nickel, mercury, cobalt, iron, antimony, copper, manganese, zinc, lead, boron, barium, arsenic, and aluminium.

2.3. Laboratory analysis

Laboratory analysis was conducted at KISR-WRC Sulaibiyah Research Plant (SRP) laboratories, which are ISO 9001:2015 certified in the fields of quality assurance (QA) and quality control (QC). Analysis was conducted using standard procedures outlined in the Standard Methods for Water and Wastewater Examination [30]. All the necessary equipment was calibrated, inspected, and quality assured routinely as per the ISO9001: 2015 certification of the laboratories.

2.4. Biomass characterisation

The attached biomass was estimated using the methodology described by [31], where some of the packing material in the aeration tank was collected and gently rinsed with distilled water, then dried in the oven at 105°C for 24 h. The dried carriers were allowed to cool and then weighed. The attached biomass was removed from the random packing carriers by soaking the carriers in 0.25 N NaOH for 24 h. The carriers were then rinsed well with water, dried for 24 h at 105°C, and reweighed to determine their dry weight. The difference in weight was used to determine the amount of biomass on the carriers.

2.5. Data analysis

An independent samples *t*-test, or its non-parametric equivalent Mann–Whitney test [32,33], was performed for each of the variables comparing inflow and outflow concentration levels of the attached growth process during the operation of the wastewater treatment unit. Since the statistical analysis was based on the assumption that the distributions were normal, skewness and kurtosis coefficients were also calculated to identify the nature of the distributions [34]. It is important to note that some parameters were normally distributed, normally distributed by log-transformation, or do not follow normal distribution by log-transformation. The statistical analysis was conducted using Excel (2016).

3. Results and discussion

During the operation of the packaged wastewater treatment system, the wastewater temperature, pH, and DO in the attached growth tank were relatively stable at 23.2°C ± 0.5°C, 7.2 ± 0.7, and 2.7 ± 0.3 mg/L, respectively. These temperature and pH values are reportedly within the optimum range for organics removal and nitrification–denitrification [7,16,35]. Under these conditions, the oxygen solubility is reasonable, as it decreases at higher temperatures [16]. The effluent BOD and COD concentrations differed significantly (p exact 0.007 and 0.006, respectively). While the BOD is mainly associated with easily degradable organics, which respond well to natural removal processes, the COD could be associated with pollutants that may have complex interactions within the biological treatment system and, therefore, only logarithmic transformation produced a normal distribution for COD.

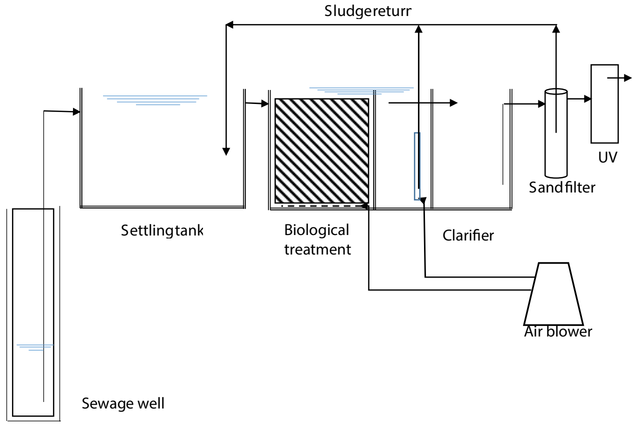

Fig. 1. Wastewater treatment system components.

Fig. 2 shows the attached growth process's COD, BOD influent, and effluent concentrations. As can be seen, the influent COD and BOD concentrations (79.7 ± 1.6 and 130.3 ± 2.0, respectively) are low for this office wastewater compared with domestic wastewater, and the average COD/BOD ratio was 1.64 ± 0.05. In Fig. 2, the low values of COD and BOD towards the end of the monitoring period could be related to the increased use of water by employees for disinfection purposes towards the end of the monitoring period when the COVID-19 lockdown was eased and return to work was allowed as found by Ahmed et al. [32]. On average, the attached growth process's COD and BOD removal efficiency were 80.8 ± 3.0 and 81.0 ± 2.9, respectively. A sharp decrease in efficiency was noticed on day 149, probably attributed to low nutrient concentrations leading to higher biomass washout [27]. The COD and BOD removal efficiencies reached a maximum of 93.0% and 93.3%, a typical performance for the biological attached growth process [24,36]. Fig. 2 also demonstrates that the process produced relatively stable effluent BOD and COD concentrations despite the variation of the influent concentrations.

The DO and VSS variations in the aeration tank and the VSS washout in the effluent from the aeration tank are shown in Fig. 3. Once again, the increased use of cleaning and disinfecting agents during the COVID-19 pandemic could have produced unfavourable conditions for biomass growth, resulting in an increased F/M ratio and the residual disinfection products leading to higher biomass washout [32]. While the DO was maintained at stable values, the attached growth tank's suspended VSS increased and stabilised at values close to 60 mg/L. The VSS washout in the effluent experienced two peaks on days 20 and 149 (Fig. 2). The corresponding COD and BOD efficiency in the 2 d was 52.0 and 5.2 for BOD and 54.7% and 4.8% for COD, respectively. Evidently, the increase in VSS in the effluent is related to increased nutrient concentrations and a decrease in COD and BOD removal efficiency, as noticed in Fig. 2. Conceivably, the low loading and low nutrient levels contributed to a higher VSS washout due to heterotroph decay [27]. However, the suspended biomass VSS did not vary abnormally during the operation despite the change in influent concentrations, and its variation seemed quite logical given the stable oxygen concentration (DO) and reasonable influent BOD [10]. Therefore, the washout is concluded to be primarily related to the attached biomass decay. This fact can be easily deduced from Fig. 3, where the attached growth plateaued at around 450 mg/L, indicating equal growth and decay rates.

Fig. 3 also demonstrates that the ratio of attached growth to suspended growth was in the range of 6.3–10.7, with an average of 7.8 ± 0.3 and a ratio of 7.9 when the attached growth plateaued. A slightly lower average was observed previously [37]. Other parameters did not significantly affect the attached growth performance, while the suspended growth fluctuated, indicating sensitivity to nutrient concentrations. In Fig. 3, the initial variation of both suspended and attached growth can be seen to be proportionate to the s/M ratio (Fig. 3) despite their instability during the first four months. In wastewater treatment, the F/M ratio should be maintained below 0.25 [16,38], which was not the case during these four months. After that, the F/M ratio stabilised, and the process seemed well controlled. Therefore, in addition to the nutrient concentrations, the food-to-microorganisms ratio (F/M) was found to correlate better with the suspended growth (R^2 = 0.73) than the attached growth (R^2 = 0.21). This correlation indicates that, broadly, the variation of suspended growth could also be explained by the variation of the F/M ratio.

The attached growth process achieved TN and TP removal efficiencies of 72.3 ± 0.7 and 25.9% ± 0.9% (Fig. 4). Minimum removal efficiencies were observed to be related to the high inflow concentrations of TN and TP. The low TP removal is mainly due to low microorganism uptake of TP in the organic degradation process. Also, low uptake could be due to higher TP concentrations, inhibition, or an imbalanced organics-to-nutrient ratio. Other reasons could include the speciation of phosphorous; in case where orthophosphate is dominant, microorganisms' uptake is higher than the polyphosphates [16]. Also, these minimum removal efficiencies were found to be related to a higher washout of VSS, as reported in Fig. 2. This finding confirms the washout of heterotrophs as observed in the organics removal (Fig. 1) [27]. The low removal efficiencies could also be related to detecting phenol concentrations of (0.134 to 0.141 mg/L) during days 27–48. The effect of phenol on nitrification inhibition has been documented by Wang and Wu [39], although it is more pronounced in the suspended biomass than in the attached biomass. On day 41, the ammonia concentration was also the highest (70.3 mg/L), reported as toxic to biomass [40]. In addition to phenol and nutrients, metals of high concentrations were detected (Table 1). These metals could be inhibitory even at lower concentrations [40].

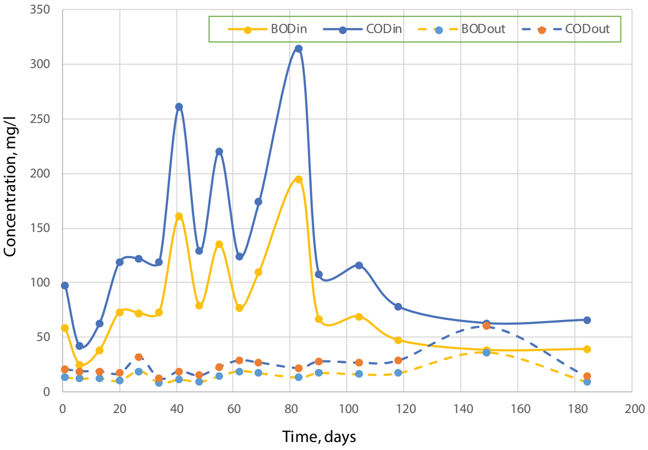

Fig. 2. Influent and effluent concentrations of biochemical oxygen demand and chemical oxygen demand.

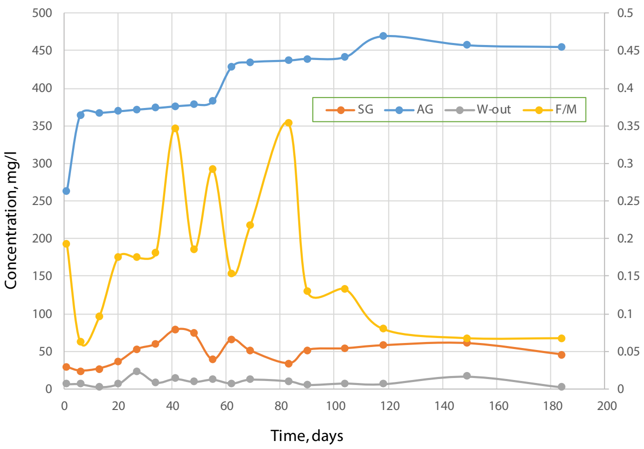

Fig. 3. Suspended growth, attached growth, washout, and food-to-microorganisms ratio (F/M) variation. F/M is plotted on the minor axis.

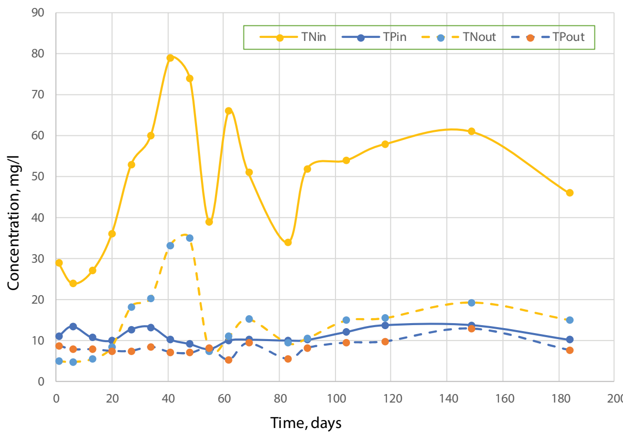

Fig. 4. Influent and effluent concentrations of total nitrogen and total phosphorous.

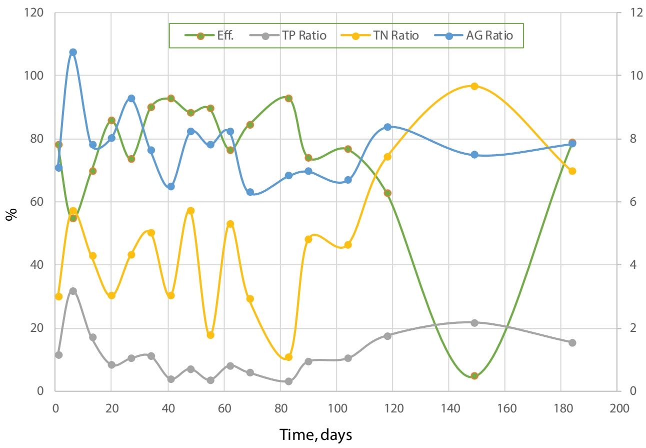

Fig. 5. The efficiency, COD:N, COD:P, and attached growth ratio (AG) variation. AG is plotted on the minor axis.

Fig. 5 shows the COD removal efficiency variation with the COD/TN, COD/TP, and the attached growth ratio. As can be seen from Fig. 5, the efficiency was stable (days 20–80) despite high COD:N:P ratios (above 100:5:2); however, during a significant increase of the ratio (100:2:0.5, days 104–149), a noticeable decrease in the efficiency was observed. An associated impact on TN and TP effluent concentration was observed (Fig. 4), with more noticeable effects on TP [41].

Fig. 5 demonstrates that organics removal efficiency depends on COD/TP below 2%, COD/TN below 8% and organic loadings of concentrations above 100 mg/L. As discussed earlier, these conditions did not significantly affect the bacterial population but affected the washout, particularly heterotrophs' washout. However, maximum removal efficiencies were achieved at a COD/TP/TN ratio of 100/1/5 and under these conditions, the AG/SG ratio was approximately 7. Conceivably, a higher AG/SG ratio would increase VSS washout and thus not optimum for process performance. In general, these values suggest guidance for the operation of aerobic onsite wastewater treatment systems for the type of wastewater considered in this research. They also raise a flag on nutrient ratios and initial organic concentrations.

Towards the second month, poor nitrification was due to a slump in VSS, while attached growth was not fully developed and was probably caused by an increase in the TP:TN ratios. This observation was reported by Wang and Wu [39], where the efficiency of nitrification and denitrification was slightly better due to biofilm biomass than the suspended biomass.

While the system considered in this study achieves mostly reasonable performance to meet water quality requirements suitable for water reuse, low concentrations of nutrients, along with inhibiting compounds introduced from the inclusion of laboratory wastewater, led, in many instances, to poor performance. These conditions led to the washout of the mostly heterotrophic biomass, which, in turn, led to poor nitrification and denitrification. The technology used here is widely used in packaged wastewater treatment units, and therefore, these findings shall be considered as technical guidance when similar units are used. Finally, maintaining suitable conditions for healthy biofilm growth shall include segregation of laboratory wastewater and maintaining optimum organics to nutrient ratio, namely operating under days 104–120 conditions in Fig. 5.

4. Conclusions

The performance of an attached growth biological process in a full-scale onsite wastewater treatment system has been investigated in this paper. Office (including laboratories) wastewater was treated successfully, and organics removal efficiency of BOD and COD of 93.0% and 93.3%, respectively, were achieved. While nutrient removal was satisfactory, the efficiency was 72.3 ± 0.7 and 25.9% ± 0.9% for TN and TP, respectively. The main performance limitations of the dilute wastewater considered in this work were the low nutrient concentrations leading to biomass loss and lower organic removal efficiency during operation. Another factor affecting biomass is the presence of inhibitive compounds such as phenols, metals, and elevated ammonia levels in some instances due to laboratory discharges. These findings constitute essential guidance for operating onsite systems, particularly since their use is of utmost importance globally and in arid and semi-arid regions for safe water reuse.

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Supporting information

Fig. S1. Side view image of wastewater treatment unit representing (1) aeration tank, (2) secondary settling tanks, and (3) inlet flow stream.

Fig. S2. Side view image of the treatment unit representing (1) primary setting tank, (2) aeration tank, (3) filtration/disinfection processes room, and (4) effluent storage tank.

Fig. S3. Side view image of the treatment unit representing (1) filtration/disinfection processes room and (2) back-up power generator.