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Study on the Start-Up Phase of the Stabilization Lagoons System for Municipal Wastewater Treatment

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ABSTRACT

Worldwide, the transfer from the level of knowledge to operation at full scale is often difficult due to the expectation of some problems associated with new technologies that usually cannot be identified and solved on a full scale. Therefore, aspects of start-up times and methodologies become even more relevant when starting to implement any (or any project) processing system in wastewater treatment. Thus, this work aimed to develop and validate a concept for starting up a laboratory-scale lagoon system. This system typically contains a series of three continuous-flow lagoons to treat 50 Liters in the day from a municipal sewage facility in Al Rumaitha City, located north of Al Muthanaa Province in Iraq. Further, the influence of hydraulic detention time (HRT) on the hydraulic lagoon performance depending on site-specific conditions and determining factors influencing actual hydraulic residence time was evaluated by investigating the start-up of three different HRTs: 7 days, 14 days, and 21 days, as changing it altered the depth and, thus, the effective volume. The start-up experiment involved two different phases of experiments, and they were conducted for four months, distributed in two different periods: the first period of start-up experiments was characterized to develop a proper microbial floc as quickly as possible and also to select the appropriate HRT of the lagoon. The results from these experiments led to the selection of the best three-cell lagoons design, which had an HRT of 7 days because it remained more stable concerning COD removal. After that, the second period of the experiments began, devoted to helping performance assessment of these facilities in continuous mode via providing basic information about the treatment processes occurring in a lagoon and summarizing performance expectations until a steady state was reached. Throughout the period of this experiment, average removal efficiencies were found to be 73.34% for COD, 76.54% for NH_4^+-N, 36.06% for TN, and 38.30% for TP.

Keyboard: stabilization lagoons, start-up phase, hydraulic retention time, stable operation, wastewater treatment process.

INTRODUCTION

Over time, disorderly urban growth combined with the exploitation of the natural environment caused a large generation of wastewater, which soon led to the proliferation of diseases, reduced life expectancy, and environmental disasters; therefore, it is necessary to treat wastewater with adequate quality that meets ecological and human health standards set by many countries to avoid their adverse impacts on the ecology of the receiving waters. With the advancement of ecological awareness at the end of the 20th century, technologies were developed that enabled better control of pollutant emissions, in addition to the creation and development of basic environmental sanitation activities. Generally, municipal sewage is most commonly a waste product that is generated and treated within municipal sewage treatment facilities before being released into the water body (Msaki et al.,2023). Various methods can be used to treat this wastewater. All of these are based on physical, chemical, and biological methods. However, almost all domestic wastewater treatment plants are designed based on biological processes (Ahn 2006). In this context, in the search for solutions for the treatment of municipal wastewater, we can highlight the stabilization lagoons process by applying low-energy consumption technology within biological processes. Although stabilization lagoons are primarily employed to treat municipal sewage (Quiroga 2013; Msaki et al.,2023), they have also been used effectively to treat industrial sewage. This technology's main particularity is its ability to allow effective effluent treatment conditions based on the presence of microorganisms without the need for extensive construction costs (Von Sperling 2007; Quiroga 2013; Awad et al., 2023a; Msaki et al.,2023). Stabilization ponds present significant advantages for the economic context. They allow effluent treatability with minimal energy, construction, and maintenance resources. Also, it facilitates their implementation not only in developing countries (Nwankwo et al., 2022) but also in developed countries. Historically, stabilization lagoons have been employed to treat wastewater for over 3000 years (U.S. EPA 2011a; Ho et al., 2020).

Historical records show that the lagoon technique was invented in San Antonio, Texas, in 1901, the same year the first documented wetland treatment system was patented (Ho et al.,2020). Indeed, ponds are used for wastewater treatment worldwide. Many people today would be surprised to know that there are one thousand lagoon systems in Germany and two thousand pond systems in France (U.S. EPA 2011b), while Canada accounted for 1244 lagoons in 2016. In contrast, the United States has approximately 8,000 lagoon facilities, and lagoons account for approximately 50% of wastewater treatment facilities in both countries. This distribution has remained remarkably stable in Canada and the United States since the 1980s (U.S. EPA 2011b; Mavinic et al., 2018; Statistics Canada 2018). Wastewater treatment by lagoon technologies is often viewed as an optimal approach to harnessing natural processes to improve sewage discharges in tropical and subtropical climates. This is mainly attributed to the domination of elevated temperatures and sunlight, which effectively kill pathogens (Dias et al., 2017; Liu et al., 2018), additionally facilitating extensive oxidation of organic matter (Denisi et al., 2021). However, its use is not restricted to tropical climates (Faleschini et al., 2011) but under different climatic conditions, even in the Arctic (Von Sperling 2002; Recio-Garrido et al., 2018). Of particular note, they are an essential' appropriate technology'; excellent levels of pathogen removal can be achieved without the dosage of chemical products (Liu et al., 2018), as in the case of chlorination, that is used in other wastewater treatment techniques, which is questionable due to the possibility of generating toxic byproducts. Most generally, stabilization lagoons can be classified into three categories: anaerobic, facultative, and aerobic, depending on the type of biological activity occurring there, which is a function of the amount of dissolved oxygen (DO) present in them (Faleschini et al., 2011; Nwankwo et al., 2022, Awad et al., 2023a), and despite these methods being commonly referred to as "low-tech," they utilize numerous complicated mechanisms and processes to treat and stabilize contamination, comparable to those of traditional technologies. It is believed that these processes exist within ponds that, if understood better and operated, could be optimized to enable effective wastewater treatment with limited construction and maintenance costs, which justifies their great acceptability where they are implemented, especially when it is desired to reuse the treated water in crop irrigation, without posing health risks. In this way, it is possible to alleviate the problem of scarcity of water resources in the region (El-Kamah et al., 2011).

But most generally, startup, followed by operation and well-monitored, are forgotten phases not only in sewage treatment systems using stabilization lagoons but in most existing types. Therefore, aspects of startup times and methodologies become even more relevant when starting to implement any (or any project) processing system in wastewater treatment. The lack of consistent, practical research and studies in this area has generated a gap regarding the influence of these phases on the efficiency of treatment systems. Therefore, this paper aims to add a puzzle piece to the cumulative knowledge of the sewage treatment process and, more specifically, the startup of the treatment process on municipal sewage for a lab-scale lagoons system, which typically consists of a series of three facultative lagoons, followed by its stable operation. The facultative lagoon was selected in this study from among stabilization lagoon systems because the facultative pond process is the simplest (Von Sperling 2005), in which natural activities of algae and bacteria occur associated with the environment's physical and chemical conditions, favoring the stabilization of mainly the matter organic and even removing nitrogen, phosphorus, and pathogens.

MATERIALS AND METHODS

Description of three-celled lagoons treatment system and setup

The system proposed for this study was composed of a preliminary stage with the aim of removing coarse solids, followed by a primary sedimentation tank where the sedimentation of suspended solids was achieved; downstream of this tank were the lagoons that served as studies for the present work. The experimental laboratory system consisted of three identical facultative lagoons operated in series; this implies that the outflow from lagoon #1 serves as the inflow for lagoon #2, and the outflow from lagoon #2 serves as the inflow for lagoon #3. After the last lagoon, most of the effluent is sent by gravity to the settling cell. A three-cell lagoon treatment system was built and implemented in an open environment subject to climate variations over a land area inside a municipal sewage facility located in Al-Rumaitha City, situated in the northern region of Al-Muthana Province in Iraq. The treatment system was implemented to process 50 liters per day of wastewater. Because the ground conditions were considered, each lagoon's bottom and walls will be lined with high-density PVC plastic and securely embedded at the barrier's top to prevent leakage. Figure 1 shows a schematic representation of three lagoon systems. The internal dimensions for each lagoon were 1 m long by 1 m wide. The ponds were designed and constructed with a 1:1 ratio of length to width. It should be noted that the lagoons were operated in series in this study because they would produce better quality effluent than those operated in parallel, as reported in the literature.

This study evaluated the geometric characteristics and determined the three-cell lagoons' operational conditions, which favour optimal effluent quality, algae growth, and microbial community in terms of hydraulic detention time and useful depth. More generally, hydraulic retention time is among the main factors affecting the performance of lagoons. It is employed in many design methodologies (Nascimento 2001), considering the effect of physical and climatic conditions on determining actual hydraulic residence time. It was determined as a function of a lagoon volume required to accommodate the incoming lagoon flow. Therefore, the start-up of three different hydraulic retention times (HRTs) for this study was investigated, as changing it altered the depth and, thus, the effective volume. Therefore, the experiment was divided into three sets; each set consisted of three lagoons arranged in a series and independent of each other. The difference between the three sets is the HRT; runs were undertaken on three different HRTs: 7 days, 14 days, and 21 days, as changing it altered the depth to 35 cm, 70 cm, and 100 cm, respectively, and thus, the effective volume. The lagoon inflow is constant in each group with a 50 L/day, as the HRT variation is connected to the lagoon volume. Of particular note is that the chosen range of HRT corresponds with the hydraulic retention time reported in the literature for treating domestic sewage in facultative lagoons, which has a wide range of values. In contrast, Von Sperling in 2002 highlights that shorter retention times can be adopted in regions with higher liquid temperatures. Furthermore, the same author elucidates that the necessary retention time as a function depended on removing organic carbon matter and the hydraulic regime of the lagoon.

Startup strategy and operational procedure

The purpose of a startup procedure for a new lagoon is to promote and increase the growth of the population of bacteria and algae as quickly as possible, expressed as mixed liquor-suspended solids (MLSS), which are used to treat (digest) waste and established the overall efficiency of the lagoon.

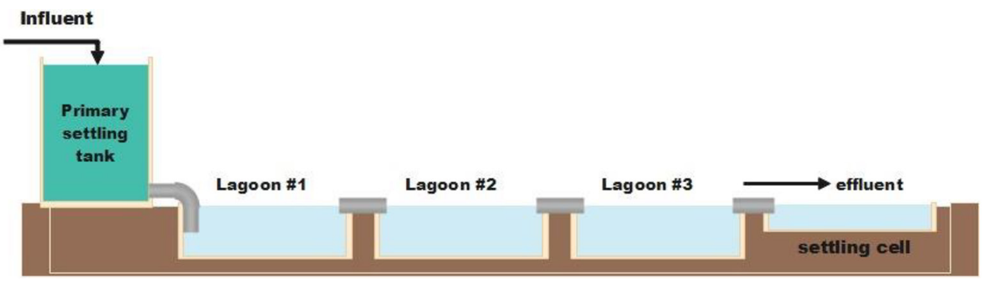

Figure 1. Schematic of the three lagoons treatment system

This is necessary because the raw sewage does not contain sufficient organisms to stabilize the organics present in the wastewater properly. In this phase of the study, external seeding was not used, so it may take longer for the bacteria to become established, and the ponds will be filled with raw sewage from the Al Rumaitha sewage treatment plant and left in batches for developing algal and bacterial populations. Therefore, the experiments on lagoons were started in early summer to take benefit of the heightened activity of bacteria linked with warm temperatures. As reported in the literature, bacterial activity is greater in the summer than in winter (Mama et al., 2011). Generally, the warmer the pond's contents, the more efficient the treatment. It's important to acknowledge that a temperature rise would lead to a corresponding increase in the growth of bacteria, resulting in heightened utilization of oxygen. The experimental stages of this work were carried out in an open environment in the Al-Rumaitha sewage treatment facility located at Al-Rumaitha City, north of Al-Muthanaa Province in Iraq. A startup experiment involved two different phases of experiments, and they were conducted for four months, distributed in two different periods: the first period from the beginning of June 2022 to late June 2022 and the second period from the end of July 2022 to late September 2022. As mentioned previously, the three lagoons for this study were operated based on the concept of hydraulic retention time, which optimizes the presence of algae in the lagoon's liquid medium to achieve an appropriate balance between bacteria and algae involved in the treating process (Von Sperling 2007). The applicability of this method is interesting because the three-cell lagoon system for this study is dug and implemented in an open environment subject to climate variations. Indeed, determining the actual HRT is difficult, but once it is defined, the depth of the lagoons can be fixed.

That is, in the first period of experiments, each set of lagoons was operated in batch mode; this period was characterized by the startup of the lagoon system as well as the selection of the appropriate HRT for the lagoon. So, the lagoons in each set were filled with real raw sewage for the Al-Rumaitha municipal wastewater treating plant and left to climatic conditions in the batch culture to evaluate the microbial community and Algal, but with various hydraulic detention times (HRT) of 7, 14 and 21 days, creating three different effective volume: V1, V3, and V4, respectively. The lagoon inflow is constant in this case, as the HRT variation is connected to the lagoon volume. All sets were filled with raw sewage simultaneously but with different HRTs to ensure consistency in all experiments, where environmental conditions such as temperature and influent wastewater were identical for each set. This experimental procedure allowed the startup of lagoons in conjunction with a better comparison for choosing the suitable hydraulic retention time and, in turn, selecting the best design among the three sets. There are several possible criteria for choosing the best design: the one with the overall efficiency, the one with the minimal HRT, the one with the minimal required area, etc. Since the three sets occupy the same surface area, this study aims to select the best design using removal efficiency, specifically COD and NH_4^+-N as the screening mechanism. The results from the first phase of startup experiments resulted in the decision being made to make the first set, which operated the lagoons with a detention time of seven days in lagoons #1, #2, and # 3, with depths (h) of 35 cm; the appropriate lagoons design for this study, which will be proposed in the next step, with an HRT of 7 days because it remained more stable concerning COD removal. A good layout for a lagoon with a small depth will minimize the quantity of earthwork required and maximize the flexibility of the operation. After that, the second period of the experiments began, which was conducted for 67 days, out of which the first seven days were assigned to a startup phase. This phase was devoted to achieving the second purpose of the startup phase; namely, it is intended to help performance assessment of these facilities in continuous mode by providing basic knowledge on the treating processes occurring in a lagoon and summarizing performance expectations until reaching a steady state. The biological process has been stabilized, and all contaminants, mainly COD, NH_4, TN, and TP, have been treated. Therefore, in this phase of the experiments, a lagoons system consisting of a series of three facultative lagoons was operated continuously to reach a steady state. Although the three experimental lab-scale lagoons installed in series are the same in formes, employing identical surface geometry of 1 m long by 1 m wide, a depth of 0.35 m, and hydraulic retention times equal to 7 days, the qualities of the effluents are different due to the lagoons' microbial activities. The incoming municipal wastewater for the laboratory plant was directly withdrawn after the preliminary treatment process of the Al-Rumaitha treating facility onsite, which consisted of roughing, sieving, sandblasting, and defatting. The pre-treated wastewater was continuously pumped into the 150-liter primary sedimentation tank, where the sedimentation of suspended solids took place. It was subsequently directed to the first cell, which is performed as facultative ponds and is followed by two lab-scale facultative ponds. This tank is located above the laboratory plant, allowing wastewater to flow by gravity to the stabilization lagoons without using a pump through a pipe that extends the feed to its base. For this stage, during the assessment of the lagoon system, considering a constant flow system, the last lagoon, already existing, was operated as a maturation lagoon, a fact proven due to the high rates of dissolved oxygen found in samples collected there with average DO value equal to 10.47 $mg \cdot L^{-1}$. Where waste discharges are large, combining these two types of ponds may be a realistic wastewater treatment method.

Characteristics of lagoons system inflow wastewater

This study aims to assess the efficacy of lagoon technology and its resilience to fluctuations in influent composition during startup experiments. Therefore, the characterization of raw wastewater is paramount to understanding the proposed treatment approach. To ensure data reliability, actual effluent from municipal wastewater treatment, with varying pollutant concentrations, was utilized as the influent flow. Few laboratory-scale studies have operated lagoon systems with real effluent for prolonged durations. The use of actual sewage is preferred due to its easier biodegradability compared to synthetic wastewater and its diverse microbial community. Key parameters for effluent quality assessment included chemical oxygen demand, ammonium, total nitrogen, and total phosphorus. Throughout the entire operational period of the biological system, regular sewage characterizations were conducted, recognizing that its composition may fluctuate over time. Table 1 presents the characteristics of primary contaminants in municipal wastewater .

Sampling and laboratory analysis

To test the lab-scale systems' efficiency. Wastewater samples were collected throughout the study period, always at midday, over four months from three sites:

Table 1. Properties of the municipal inflow wastewater that enters the lagoon system

Parameter	Unit	Range
COD	($mg \cdot L^{-1}$)	175–500
NH_4^+-N	($mg \cdot L^{-1}$)	25–50
TN	($mg \cdot L^{-1}$)	35–55
TP	($mg \cdot L^{-1}$)	4–8

- raw sewage,
- outflow from each individual lagoon,
- the outflow from the final lagoon.

The study samples were analyzed for COD, NH_4^+, TN, and TP. These analyses were carried out on the premises of the laboratory set up of the Al-Rumaitha wastewater treatment plant according to the methods described in Standard Methods (APHA, 2005). At the same sampling time, liquid temperatures were recorded using a thermometer, and the dissolved oxygen was measured using an OHAUS portable meter, ST300D model, and a WTW portable pH meter, model 3110, at the study site.

RESULTS AND DISCUSSION

First period (start-up phase)

Monitoring of basic parameters

During this experiment period, the DO, pH, temperature, and MLSS were measured in each of the three lagoons; testing was conducted randomly throughout the day, and occasionally twice daily, in the morning and afternoon, and finally, the average value was used for the three lagoons system. The experimental lagoons sets' average influent and effluent temperatures ranged from 26 °C to 31 °C. These values of temperature were in the ideal biodegradation range from 20 °C to 35 °C (Chan 2011; Wang 2019). However, it should be noted that the temperatures in the lagoons for the first and second sets were higher than those in the third sets of lagoons. On the other hand, during the first work period, the pH values for the sample taken from each set of the three lagoons system were consistently higher than the input raw wastewater pH values. The pH was measured throughout HRT, with average values of 7.87 for raw wastewater, 8.69 for the lagoons of the first set, 8.75 for the lagoons of the second set, and 8.81 for the third set. In each set of the three lagoons system under study, it was observed that the effect of depth or hydraulic detention time was not perceived for the pH measured over HRT. Also, the concentration of mixed liquor suspended solids (MLSS) was determined within the lagoons' first, second, and third sets to be 1661 mg·L^{-1}, 1323 mg·L^{-1}, and 600 mg·L^{-1}, respectively. When the concentration of MLSS is observed to be low, this means that long HRT has affected the microbial community size, which is the decrease in biomass growth rate, and the algae population will usually be reduced. The low concentrations observed may be because there is usually no nutrient supplied to these lagoons from the raw sewage since these stages are in batch mode. Typically, when one or more nutrients or the substrate is completely exhausted, the growth rate in batch culture starts decreasing (Hoang, 2013), which can be seen in HRT 14 days followed by 21-day HRT. The death rate keeps on increasing until all bacterial cells die off. Cell death and lyses release some soluble organics, leading to increased organic matter, which is the reason for decreased efficiency removal in the third stage. It should be noted that the average values of DO observed in lagoons system sets first and second were greater than 2.0 mg·L^{-1}. In contrast, the DO in the third set was lower than 2.0 mg·L^{-1} because the algae population will usually notice reduction, reducing oxygen production; this is normal after 21 days of batch mode because nutrients or the substrate is exhausted.

Removal of COD during start-up

Since all lagoons created in each set were filled with wastewater simultaneously and then left in batch mode, the influent COD value in all cells during this experimental stage was 287.70 mg·L^{-1} concentration. Concentrations of COD in the effluent varied between 90.00, 156.70, and 274.40 mg·L^{-1} in the first, second, and third sets, respectively. The increase in total COD concentration is due to the conversion of inorganic carbon into algal biomass. The presence of organic matter evaluated by the COD parameter indicates a higher biomass concentration. It was observed, therefore, that as the HRT of the ponds increased, the total COD removal efficiency also decreased. Figure 2 presents the COD removal: first set with HRT = 7 days, second set with HRT = 14 days, and third set with HRT = 21 days, where a high value of COD removal was observed for the lagoons (first set) operated with 35 cm in depth and a hydraulic detention time equal to seven days. It can be seen in Figure 2 that the lagoons with depths of 35 and 70 cm, run with a hydraulic retention time equal to 7 days and 14 days, respectively, provided good stability of organic matter, favoring efficiencies of nearly 68.71% and 45.54 in the removal of COD.

This value is still a good result, but it should be noted that the temperatures in the first and second sets were higher than in the third set. Set #3, lagoons with a depth of 100 cm, had the lowest average COD removal efficiency, with a value close to 5%, as shown in Figure 2. This behavior is probably related to environmental conditions

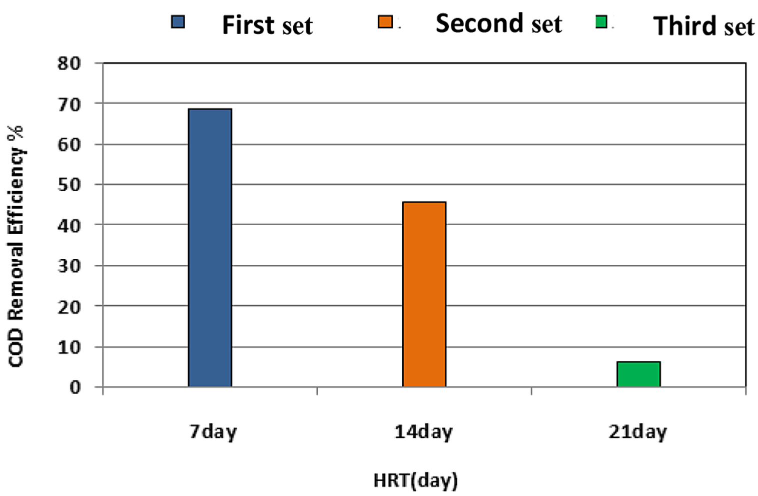

Figure 2. The COD removal: first set with HRT = 7 days, second set with HRT = 14 days, third set with HRT = 21 days

unfavorable to the activity of heterotrophic organisms (bacteria) in this lagoon, particularly the higher pH values found in these lagoons (100 cm). According to Couto (2016), the high pH values, such as those observed in lagoon HRT of 21 days, are harmful to removing organic matter.

Removal of NH_4^+-N during start-up

The main nitrogen removal mechanisms in stabilization lagoons include volatilization (of ammonia), assimilation by algae (of ammonium and nitrates), bacterial activity (nitrification–denitrification), and sedimentation (of organic nitrogen particulate) (Rockne et al., 2006; Camargo Valero and Mara 2007; U.S. EPA 2011b; Mayo et al., 2014). Most of these mechanisms depend largely on pH, temperature, and the presence of algae. Bacteria oxidize organic matter in wastewater with oxygen produced by algae growth, releasing nutrients and CO_2; the algae then use the CO_2 through photosynthesis, absorbing the nutrients in the algae biomass and releasing O_2. The algae are then settled or physically or chemically removed before being discharged. On the other hand, it is also clear that CO_2 consumption by algae is increasing. This consumption occurs more rapidly than replacement by bacterial respiration. This causes the existing bicarbonate ions (HCO_3^-) to dissociate and produce not only more CO_2 but also the hydroxyl ion (OH^-), which is alkaline and increases the pH of the medium, which in turn can serve as an indicator of the reaction system performance (Moreira et al. 2009; Mayo et al., 2014). Therefore, the predominant mechanism of nitrogen removal within lagoons depends on lagoon pH levels, a relationship also observed by Park and Craggs (2011). However, in terms of treatment only, volatilization can be considered more critical for nitrogen removal than nitrification since its transformation to nitrate does not constitute effective removal, as stated by Garcia and collaborators in 2000.

For this phase of startup, lagoons tend to present variability in results, which is, in a way, typical of open systems subject to local climate variations (Couto 2016). In this experiment period, all lagoons in each set were filled with wastewater simultaneously and then left in batch mode; the influent NH_4^+-N value in all cells during this experimental stage was in a concentration of 31.21 $mg \cdot L^{-1}$. When evaluating the concentrations and removal of NH_4^+-N, it was observed that the average concentration of the values for the effluents of the three sets first, second, and third sets varied between 23.86 and 18.32 and 9.87 $mg \cdot L^{-1}$, respectively. The concentration of NH_4^+-N was observed to be lowest in the effluent lagoons with an HRT of 21 days and 100 cm deep, which presents the third set, reaching removal levels of up to 68.39%. The greater efficiency in the removal of NH_4^+ for these lagoons could be explained, in large part, by the higher pH values observed in the lagoons, which reach values nearly 8.81, where favored the transformation of the ammonium ion (NH_4^+), which is soluble, into free ammonia (NH_3), which, being volatile, is released from the liquid column – additionally, the impact of the assimilation by biomass due to microalgae. Therefore, the primary removal mechanism was volatilization, followed by biomass assimilation, possibly influenced by higher pH values.

The lagoons system, with depths of 70 cm and worked with a hydraulic retention time equal to 14 days, provided good stability of ammonium removal, favoring efficiencies of nearly 41.30% in removing NH_4^+-N. For the seven-day HRT, the 35 cm deep lagoons (first set) had the lowest efficiency, equal to 23.55%, with a significant difference concerning the second and third sets, as shown in Figure 3. The low concentrations observed are related to lower pH values, which have been observed in this case. Furthermore, the biomass assimilation process had less impact because the algae started to develop and grow after this period of waste introduction.

Second period (operation strategies and steady state)

Physical parameters across the lagoons system

The DO, pH, and temperature were monitored in three lagoons, #1, #2, and #3, and the sedimentation tank from the period 1/8/2022 to 30/9/2022; testing was carried out at various intervals of the day and occasionally twice daily in the morning and afternoon, and then the average value was used. During the continuous operation mode, the average value and standard deviation of the temperature, pH, and DO across the system were (average = 29.18 ºC and SD = 0.85), (average = 8.64 and SD = 0.60) and (average = 7.69 $mg \cdot L^{-1}$ and SD = 4.49), respectively. The results from measurements of physical parameters are shown in Figures 4 to 6, respectively. The dissolved oxygen across the system experienced

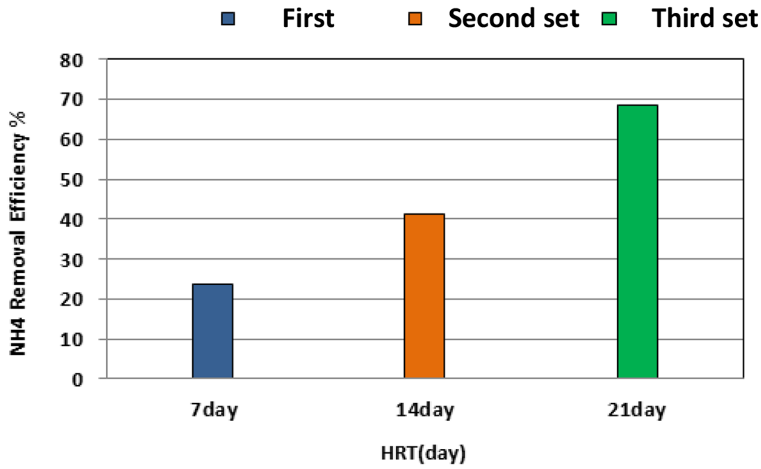

Figure 3. The NH_4^+ -N removal: first set with HRT = 7 days, second set with HRT = 14 days, third set with HRT = 21 days

an average concentration of 7.69 mg·L^{-1}. Dissolved oxygen is lowest in the sedimentation tank, where it can be assumed entirely devoid of dissolved oxygen, characterizing it as anaerobic or anoxic. The deficient DO in the sedimentation tank is within normal expectations because feed wastewater carries high organic loading and, therefore, a high COD. This manifests itself physically in a low DO value.

The DO begins to increase in lagoon #1 and decreases and then increases in cell #3, respectively, showing that the effluent has become aerobic, a fact also confirmed by the presence of algae in this lagoon, with the characteristic greenish color. In the lagoons #1, #2, and #3, the DO varied between maximum and minimum of 13.70 to 4.71, 12.61 to 4.72, and 13.64 to 7.71 mg·L^{-1}, respectively. The resulting average was 10.20, 9.10, and 10.47 mg·L^{-1} for the lagoons #1, #2, and #3, respectively. These concentrations of DO are considered expected in the literature for effluents from facultative lagoons. As seen in Figure 4, DO concentration showed significant variability, as evidenced by the standard deviation (SD = 4.49), which is more than one-half the average. Dissolved oxygen levels depend on high temperatures and commonly demonstrate an inverse correlation with temperature. Thus, when the temperature is high, lagoon #1 should expected to have a lower concentration of oxygen. However, this is not the case because the first lagoon actually had a higher oxygen level. This seeming anomaly is easily explained. In the Lagoon system, microalgae produce oxygen, which heterotrophic bacteria use to decompose organic matter. However, according to Moreira

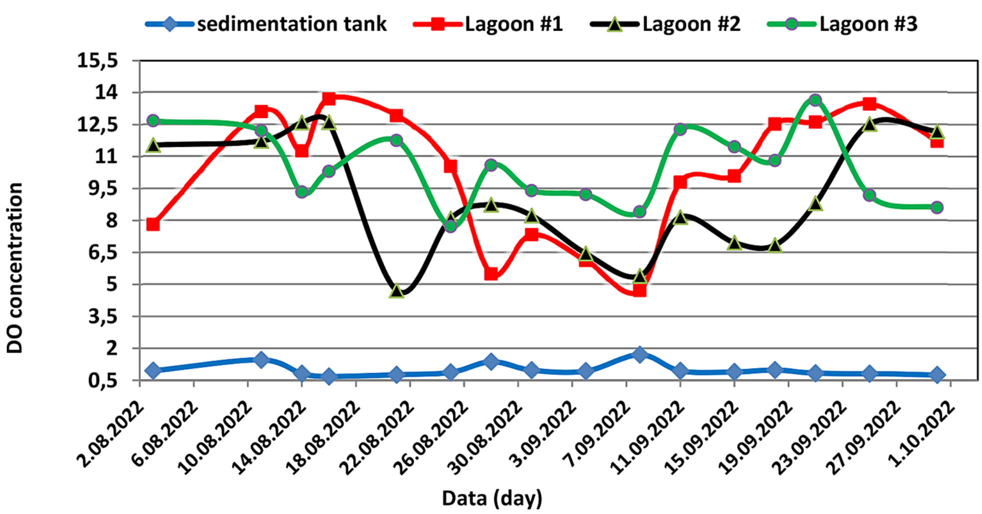

Figure 4. Dissolved oxygen concentration variation across the system

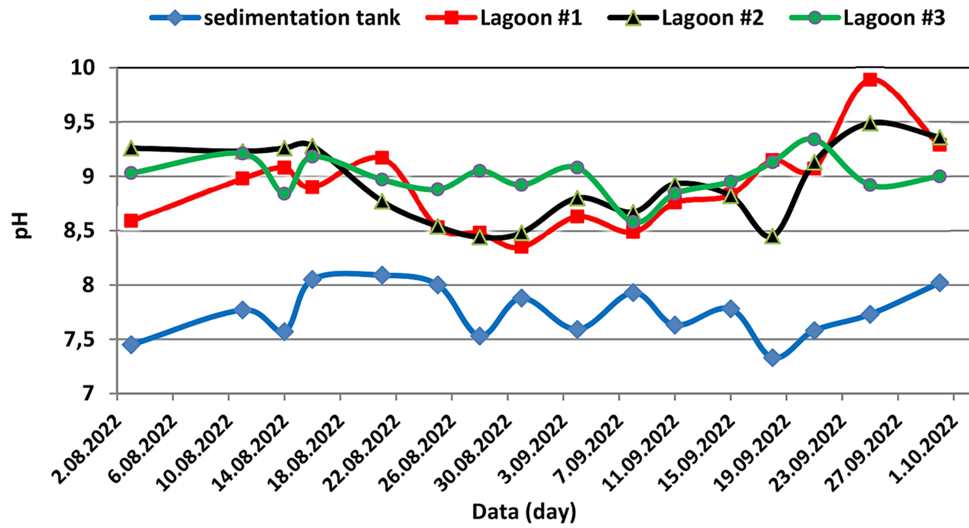

Figure 5. pH variation across the system

et al. (2009), bacteria use a tiny portion of all the oxygen produced, with the vast majority being disposed in the medium as dissolved oxygen. Therefore, increased algal metabolism due to high temperatures will lead to higher photosynthetic activity, resulting in high dissolved oxygen levels. Meanwhile, as mentioned previously, the CO_2 produced by heterotrophic metabolism is dissolved as bicarbonate ions (HCO_3^-). When photosynthesis is more accentuated, the removal of CO_2 from the liquid mass exceeds its replacement by heterotrophic bacteria and, in this way, the bicarbonate ions present react with free H^+ ions, producing CO_2 (carbon source used by algae) and OH^- and increasing the pH.

The pH is influenced by the activity of algal and bacteria, which carry out photosynthesis and consume the carbon dioxide present in the medium, increasing the pH level. As seen in Figure 5, pH levels in individual sampling points and throughout the system showed, in general, minimal fluctuations. As expected, the sedimentation tank had the lowest pH values; there was a fluctuation between values of 7.33 and 8.09, with an average of 7.75. The pH tended to increase as the wastewater flowed through the lagoons, with cell #3 having the highest average pH, highlighting the influence of the photosynthetic process triggered during the day by algae in the facultative reactors. This increase is associated with the demand for CO_2. Furthermore, when the pH is high, nutrients are removed by physical and chemical processes. Nitrogen, for example, can be physically removed from the liquid phase by volatilization by releasing ammonia gas. Phosphorus can precipitate in the form of hydroxyapatite or struvite crystals, depending on the physicochemical characteristics of the liquid medium (Torres, 2014). The average expected pH for the lagoons #1, #2, and #3 would be 8.89, 8.93, and 9.00, respectively.

In terms of temperature, it showed a slight fluctuation within the system regarding the other parameters, as evidenced by the standard deviation (SD = 0.82), ranging from 27.77 ºC to 31.03ºC. The overall trend is a rise in temperature from the primary sedimentation tank to lagoon #1, followed by a decline after that. Notably, the first lagoon consistently exhibited the highest temperature within the system. Higher temperatures typically indicate an elevated metabolic rate and greater algae production and activity. Consequently, further COD reduction and subsequent variation of other temperature-dependent parameters are expected to support this hypothesis, as depicted in Figure 6. Therefore, a temperature increase leads to a corresponding rise in the activities of algal photosynthetic, thereby increasing the concentration of dissolved oxygen and pH. Consequently, it explains the observed relations between temperature and dissolved oxygen values, DO and pH, and consequently, temperature and pH.

Chemical parameters across the lagoons system

Removal of COD

Table 2 summarizes the results of concentrations of COD parameters expressed as the mean, standard deviation, and efficiency obtained in

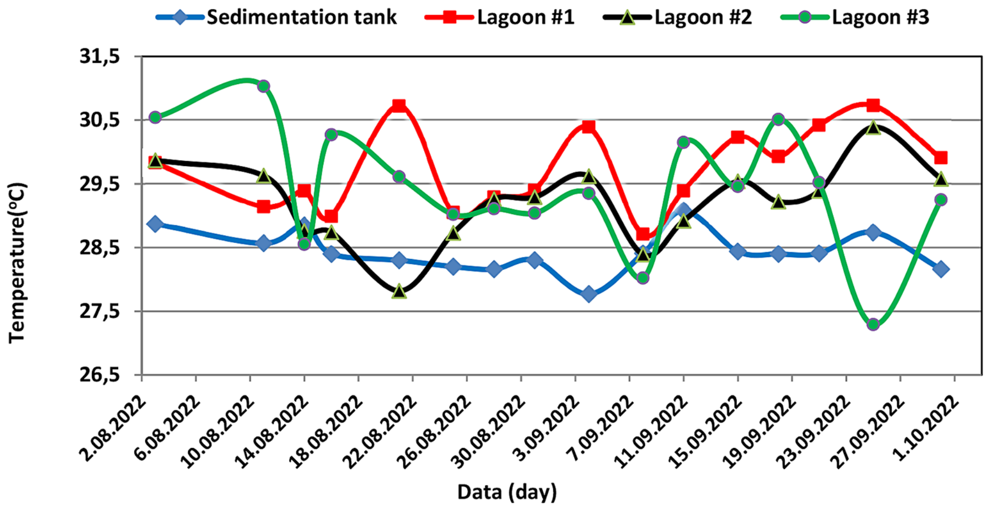

Figure 6. Temperature variation across the system

each lagoon in the system. At the same time, Figure 7 presents variations in the COD concentration for raw sewage and effluents from lagoons #1, #2 and #3. When observing the standard deviation values demonstrated in Table 2, it becomes evident that there is a wide variation in the COD values of raw sewage. The influent COD value throughout the study period varied in concentration between 189 and 430 mg·L^{-1} (with an average of 319.20 mg·L^{-1} and SD = 65.73). The series promoted gradual removals of organic matter; there was a reduction in the average COD from 319.20 mg·L^{-1} (SD = 65.73) for raw wastewater to 83.60 mg·L^{-1} (SD = 11.99) for the effluent of the last lagoon, representing an overall removal efficiency of 73.34% (SD = 3.48) of COD, with greater removal in the facultative lagoon #1 series – 66.08% (SD = 4.49), followed by 9.23% (SD = 4.65) and 13.15% (SD = 5.87) for lagoon #2 and #3, respectively. However, lagoons #2 and #3 promoted additional COD removal in a small percentage compared to the first lagoon.

Table 2 shows that in the system, the facultative lagoon was the reactor responsible for the greatest organic matter removal, meeting

Table 2. The results of concentrations of COD parameter expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system

COD								
Data	INF	Lagoon #1		Lagoon #2		Lagoon #3		System
		EFF	R%	EFF	R%	EFF	R%	R%
2/08/2022	298	102	65.77	94	7.84	92	2.13	69.13
9/08/2022	386	121	68.65	95	21.49	85	10.53	77.98
15/08/2022	283	92	67.49	85	7.61	78	8.24	72.44
21/08/2022	189	76	59.79	69	9.21	54	21.74	71.43
27/08/2022	333	106	68.17	98	7.55	87	11.22	73.87
2/09/2022	270	117	56.67	110	5.98	88	20.00	67.41
8/09/2022	325	109	66.46	97	11.01	85	12.37	73.85
14/09/2022	337	101	70.03	96	4.95	78	18.75	76.85
20/09/2022	341	113	66.86	105	7.08	92	12.38	73.02
27/09/2022	430	125	70.93	113	9.60	97	14.16	77.44
COD, average, mg/L	319.20	106.20	66.08	96.20	9.23	83.60	13.15	73.34
Standard deviation, SD	65.73	14.54	4.49	12.59	4.65	11.99	5.87	3.48

Note: INF – total influent, EFF – effluent, R – removal efficiency.

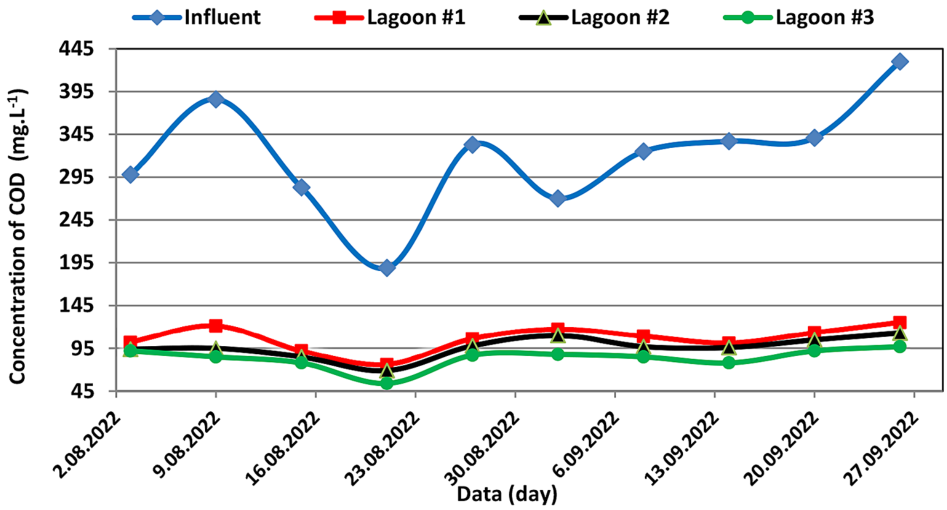

Figure 7. The COD concentration for raw wastewater and outflows from each lagoon throughout an analysis period

a primary objective of its use in a series of lagoons where the effluent from the facultative lagoon presented an average value of 106.20 mg·L^{-1}, offering an average efficiency of 66.08% for facultative lagoons are approximately within the range reported by von Sperling (2002), from 65 to 80%. This is linked with the higher algal activity observed in the facultative lagoon, elucidating the seemingly abnormal dissolved oxygen levels despite the lagoon's higher temperatures. For this stage, during the assessment of the lagoon system, considering a constant flow system, the second pond's different behavior (to a lesser extent) regarding the removal of organic matter is observed when compared to the following ponds in the series. This fact should be the subject of specific and more in-depth studies, mainly in the biological aspect, to better understand this phenomenon. This reactor probably represents a transitional environment, when the effluent passes from the optional lagoon to the second lagoon, causing a replacement of the existing biota by another more adapted to the characteristics of the lagoons (lower organic load, smaller amount of nutrients for algae, increase of DO, etc.). This can lead to the fact that the third lagoon operated as a maturation lagoon for a large part of the study period. Therefore, according to the literature, such comparisons allow us to assume the facultative lagoon's good efficiency in removing COD and keeping it within what is expected. Meanwhile, the average efficiency of the entire system, 73.34%, is within the best expected.

Removal of ammonium nitrogen

As mentioned previously, the nitrogen removal mechanisms are highly dependent on pH and temperature and the presence of algae, more pronouncedly on the first, where higher values result in greater removal. The pH variation in stabilization ponds occurs naturally due to a dependent relationship between algal biomass and sunlight. The increase in pH causes the production of free ammonia. As it is subject to volatilization, this form of ammonia is released into the atmosphere. Therefore, Table 3 summarizes the results of concentrations of NH_4^+-N parameter expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system. At the same time, Figure 8 presents variation in the NH_4^+-N concentration for raw sewage and effluents from lagoons #1, #2 and #3. As illustrated in Figure 8 and Table 3, NH_4^+-N concentration showed a downward trend throughout the lagoon series. These low concentrations of effluent ammonium likely stemmed from the impact of nitrification and volatilization; there was a reduction in the average influent raw sewage NH_4^+-N from 38.26 mg·L^{-1} (SD = 5.75) to 8.78 mg·L^{-1} (SD = 1.03). The results in Table 3, which presents the average removal efficiency for each individual unit and the entire system, showed that the three lagoon systems showed an overall efficiency of 76.54 mg/L (SD=5.01) of NH_4^+-N removal. The highest removal was in lagoon No. 1 – 41.78% (SD = 7.99) – followed by 32.10% (SD = 14.38) and 39.15% (SD = 10.43) for the lagoon #2 and lagoon #3 series, respectively. As expected, the most significant portion of algae productivity occurs in

Table 3. The results of concentrations of NH_4^+-N parameter expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system

NH_4^+-N								
Data	INF	Lagoon #1		Lagoon #2		Lagoon #3		system
		EFF	R%	EFF	R%	EFF	R%	R%
3/08/2022	38.60	21.93	43.19	20.32	7.34	9.54	53.05	75.29
9/08/2022	29.87	19.88	33.44	14.12	28.97	10.65	24.58	64.35
15/08/2022	48.9	21.11	56.83	13.23	37.33	8.22	37.87	83.19
21/08/2022	41.23	23.1	43.97	17.41	24.63	9.45	45.72	77.08
27/08/2022	33.46	19.7	41.12	13.61	30.91	8.34	38.72	75.07
2/09/2022	36.85	18.5	49.80	12.42	32.86	8.56	31.08	76.77
8/09/2022	41.7	26.1	37.41	14	46.36	9.04	35.43	78.32
14/09/2022	31.44	21.7	30.98	11.46	47.19	6.88	39.97	78.12
20/09/2022	37.67	24.61	34.67	21.23	13.73	9.1	57.14	75.84
26/09/2022	42.89	23	46.37	11.11	51.70	8	27.99	81.35
NH4+, average, mg/L	38.26	21.96	41.78	14.89	32.10	8.78	39.15	76.54
Standard deviation, SD	5.75	2.33	7.99	3.56	14.38	1.03	10.43	5.01

Note: INF – total influent, EFF – effluent, R – removal efficiency.

the facultative lagoon #1 under high-temperature conditions, coinciding with the series responsible for the most effective removal of NH_4^+-N, as previously mentioned, highlighting the relationship between the efficiency of ammonium removal based on the presence of algae.

Therefore, increased algae production directly contributes to ammonium consumption in conditions of high photosynthetic rate. As can be seen from the considerations made previously and the values obtained for the removal of ammonium, it is assumed that the three removal mechanisms were covered in this work; however, the volatilization mechanism seemed to be the primary means of removing this form of nitrogen and being influenced by high pH values.

Removal of total nitrogen

Table 4 summarizes the results of concentrations of TN parameters expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system. At the same time, Figure 9 presents variation in the TN concentration for raw

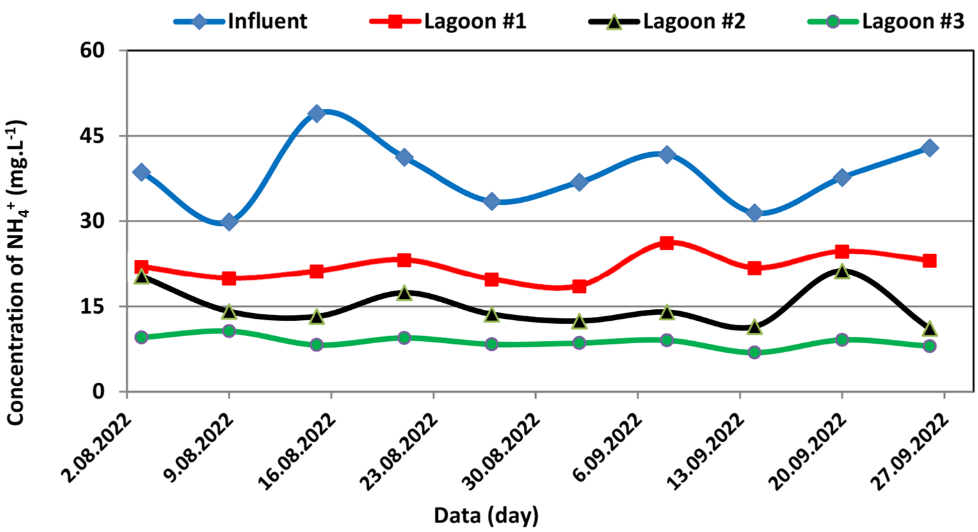

Figure 8. The NH_4^+ -N concentration for raw wastewater and outflows from each lagoon throughout an analysis period

sewage and effluents from lagoons #1, #2 and #3. The average concentrations of total nitrogen in the system's raw sewage (mean 42.42 mg·L^{-1}) (SD= 5.62) were close to the typical range for domestic sewage cited by von Sperling (2005), of 35 to 60 mg·L^{-1} (typical 45 mg·L^{-1}), but still lower than the averages reported in research by Oliveira (2006), 66 mg·L^{-1}, and Destro et al. (2007), 80 mg·L^{-1}. In the classification by Jordão and Pessôa in 2011, the total nitrogen concentration is between that typical of "medium sewage" (40 mg·L^{-1}) and "strong sewage" (85 mg·L^{-1}), closer to the first. Table 4 shows the efficiency of the facultative lagoon and the system as a whole-observing a sequential decrease in TN concentrations throughout the treatment. Where total nitrogen concentrations in the effluents from the lagoons varied from minimum and maximum values of 28.70 to 40.40 mg·L^{-1} for lagoon #1, 23.95 to 35.95 mg·L^{-1} for lagoon #2, and 21.70 to 32.80 mg/L for the lagoon #3. In general, for a large part of the study period, the first lagoon operated under conditions that favored photosynthetic activity (proven by the high levels of DO and pH values), in addition to high temperatures, and consequently, the removal of nitrogen by absorption via microalgae and, or by

Table 4. The results of concentrations of total nitrogen parameter expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system

Total nitrogen								
Data	INF.	Lagoon #1		Lagoon #2		Lagoon #3		System
		EFF.	R. %	EFF.	R. %	EFF.	R. %	R. %
3/08/2022	39.39	30.6	22.32	26.10	14.69	24.6	5.76	37.55
9/08/2022	43.54	33.8	22.37	29.96	11.35	26.8	10.56	38.45
15/08/2022	51.60	40.2	22.09	35.95	10.57	32.8	8.77	36.43
21/08/2022	39.89	31.4	21.28	27.34	12.93	25.4	7.09	36.32
27/08/2022	46.60	35.8	23.18	32.16	10.15	29.8	7.35	36.05
2/09/2022	36.10	29.6	18.01	25.87	12.60	24.6	4.91	31.86
8/09/2022	35.38	28.7	18.88	23.95	16.56	21.7	9.38	38.67
14/09/2022	39.90	33.6	15.79	30.71	8.59	28.6	6.88	28.32
20/09/2022	41.10	33.1	19.46	28.03	15.32	25.1	10.45	38.93
26/09/2022	50.70	40.4	20.32	33.56	16.94	31.4	6.43	38.07
TN, average, mg/L	42.42	33.72	20.37	29.36	12.97	27.08	7.76	36.06
Standard deviation, SD	5.62	4.06	2.33	3.79	2.84	3.48	1.94	3.41

Note: INF – total influent, EFF – effluent, R – removal efficiency.

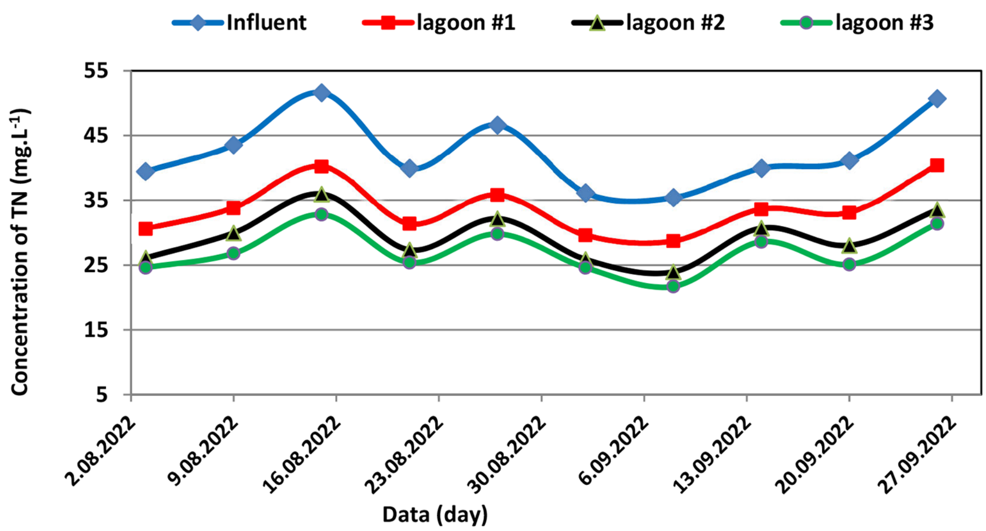

Figure 9. The TN concentration for raw wastewater and outflows from each lagoon throughout an analysis period

volatilization. Removal is less in the next two lagoons, possibly due to the lower concentrations flowing into the unit. In terms of removal for the system, the lagoon systems showed an overall efficiency of 36.06 mg/L (SD = 3.41) of TN removal, with its reduction in the lagoon series – lagoon #1 with 20.37% (SD = 2.33), followed by 12.70% (SD = 2.84) and 7.76% (SD = 1.94) for the lagoon #2 and lagoon #3 series, respectively.

Removal of total phosphorus

In treatment lagoon systems, the main mechanisms involve the removal of organic phosphorus by assimilation into the biomass of algae and bacterial cells(which exit with the final wastewater) and phosphate precipitation when the pH value is high. (von Sperling, 2002; Torres, 2014). Table 5 summarizes the results of concentrations of the TP parameter expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system. At the same time, Figure 10 presents variation in the TP concentration for raw sewage and effluents from lagoons #1, #2 and # 3. From Figure 10 and Table 5, it can be observed that the average concentrations of total phosphorus in the influent raw sewage are a mean of 6.56 mg/L

Table 5. The results of concentrations of TP parameter expressed as the mean, standard deviation, and efficiency obtained in each lagoon at the system

TP								
Data	INF.	Lagoon #1		Lagoon #2		Lagoon #3		system
		EFF.	R. %	EFF.	R. %	EFF.	R. %	R. %
3/08/2022	7.74	6.04	21.96	5.12	15.23	4.67	8.79	39.66
9/08/2022	7.89	5.96	24.46	5.13	13.93	4.76	7.21	39.67
15/08/2022	4.35	3.58	17.70	3.29	8.10	3	8.81	31.03
21/08/2022	6.94	5.87	15.42	4.63	21.12	4.11	11.23	40.78
27/08/2022	5.77	4.11	28.77	3.51	14.60	3.28	6.55	43.15
2/09/2022	5.84	4.32	26.03	3.81	11.81	3.51	7.87	39.90
8/09/2022	7.97	5.92	25.72	5.57	5.91	5.11	8.26	35.88
14/09/2022	5.69	4	29.70	3.68	8	3.51	4.62	38.31
20/09/2022	5.55	4.08	26.49	3.74	8.33	3.47	7.22	37.48
26/09/2022	7.89	6.15	22.05	5.18	15.77	4.96	4.25	37.14
TP, Average, mg/L	6.56	5	23.83	4.37	12.28	4.04	7.48	38.30
Standard deviation, SD	1.29	1.06	4.59	0.84	4.71	0.78	2.05	3.28

Note: INF – total influent, EFF – effluent, R – removal efficiency.

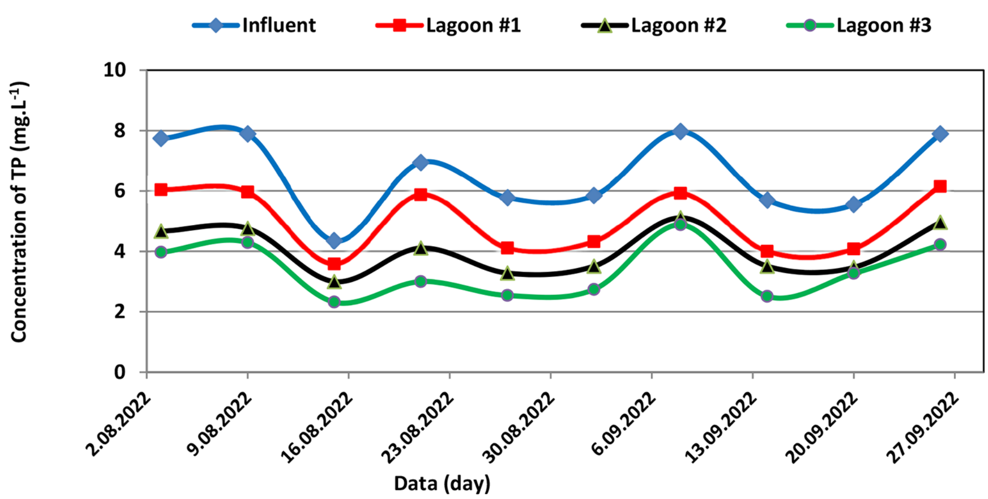

Figure 10. The TP concentration for raw wastewater and outflows from each lagoon throughout an analysis period

(SD = 1.29), were close to the typical domestic sewage ranges cited by von Sperling, 2005 and Metcalf and Eddy, 2003, 4 to 15 mg/L (typical seven mg/L) and 4 to 16 mg/L, respectively. The results in Table 5 indicate good removal of total phosphorus in each lagoon and system, where a reasonable efficiency can be seen in the facultative lagoon, with an average efficiency of 23.83% (SD = 4.59) and lower efficiency in cells #2 and #3, an average of 12.28% (SD = 4.71) and 7.48% (SD = 2.05), respectively, but still contributing to removal, resulting in a good efficiency of the lagoon system as a whole an average of 38.30% (SD = 3.28). According to von Sperling (2002) and Jordão and Pessôa (2011), removal is usually less than 35% in facultative lagoons. Based on these references, the facultative lagoon can be considered to be functioning well in terms of phosphorus removal. It must be regarded that the greater removal in the facultative lagoon may reflect the lower percentages of reduction in the two other lagoons. The system presented an average efficiency (38.30%) as expected or better.

CONCLUSIONS

It is a truism that transferring from a level of knowledge to a full-scale operation is often difficult. Hence, considerations regarding startup times and methodologies become more relevant when implementing lagoon treatment systems in wastewater treatment processes. This work presented the startup operation for the stabilization lagoons system, which consisted of three lagoons in a series. The system successfully treated influent municipal sewage for the laboratory-scale plant, which was collected immediately after the preliminary stage of the Al Rumaitha sewage treatment Plant. Using batch and continuous feed procedures during the startup period facilitated an efficient startup process and promoted better acclimatization of microorganisms within the lagoons. During batch mode, steady-state conditions were achieved within seven days, during which the system effectively eliminated 68.71% and 23.55% of COD and NH_4^+-N, respectively. After that, once the hydraulic retention time was determined, the second phase of the startup experiments began, which was carried out for 60 days. It is intended to help in the continuous performance assessment of these facilities by providing basic information about the treatment processes occurring in three lagoons, depending on the site-specific conditions, and summarizing performance expectations until a steady state is achieved. The biological process stabilized and treated all pollutants, mainly COD, NH_4^+-N, TN, and TP. The system removed 73.34%, 76.54%, 36.06 %, and 38.30%, respectively. Therefore, it is recommended that this lagoon procedure system be applied in a full-scale wastewater treatment plant for future research plants.

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