Design and modeling of an on-site grey water treatment plant for a hotel building

Abstract

As the United States is making a significant move towards rejoining the Paris Agreement on climate change, there is a high demand for sustainable solutions across various industries, including construction and hospitality sectors. The aim of this project was to design and model an on-site greywater treatment system for a hotel building for the effective reuse of sewage water. The study considered Los Angeles, California, as a case study location and referred to respective climate conditions and construction standards. This study considered various options of greywater treatment plants such as Membrane Bioreactor (MBR), Sequencing Batch Reactor (SBR), and Reverse Osmosis with Upflow Anaerobic Sludge Blanket (RO with UASB) which were carefully reviewed and modeled through the GPS-X software. The design and modeling results were verified by hand calculations and were followed by the estimation of capital and operational expenses required for the implementation of the plants. Having relatively low capital and operational expenditure requirements as well as superior technical performance, the MBR plant proved to be the most effective solution for the considered location and standards and was recommended for use in hotel buildings.

1. Introduction

Globally, tourism is regarded as a crucial sector of economy and in some cases, even considered as a primary source of income. According to the United Nations World Tourism Organisation (2021), as of 2020, the United States has been a leading country in terms of income from international tourism and the Los Angeles area made a significant contribution as one of the most attractive tourist destinations. While there is no doubt in economic impact of tourism and hospitality industry, their detrimental effects on the environment tend to be underestimated by the tourists and the public. However, there are various environmental policies and norms at governmental and organizational levels which have to be followed by the industry if it is to remain a substantial economic activity (Styles, Schönberger, and Martos 2013). Ecorys (2009), for example, highlights that considering the reliance of the tourism industry on the natural resources, further development of the businesses in an eco-friendly and sustainable manner is essential to ensure competitiveness. Similar principles are widely reflected in various governmental policies, such as “Agenda for a sustainable and competitive European tourism” in the case of the European Union. Styles, Schönberger and Martos (2013) emphasize the role of the following areas which directly or indirectly spawn various environmental pressures on the sector: energy use; water use; land use and landscaping; guest behavior; material use; various emissions into the air; discharge of effluents; detriment to natural biodiversity of the ecosystem; odor and noise pollution; waste disposal. These aspects tend to create various environmental issues both at local and global levels. While the importance of addressing each of these cannot be neglected, for the proposed hotel project (Hotel) only a design of a wastewater reuse system is considered, specifically looking at, “water use” and “discharge of effluents” aspects.

Such a specific focus of the study is formed based on the fact that Los Angeles area constantly faces water shortage issues during summer months and due to the lack of adequate irrigation and sewage systems. Similar to many cities around the world, the city of Los Angeles, particularly, and the California state, in general, face a significant water scarcity problems during dry seasons (or years) (Edry, n.d.). Partially, this, is the result of advancing climate change causing California state to observe higher autumn and winter temperatures with less precipitation (USC Viterbi n.d.). Over the last several years, the amount of precipitation in the state has been 5% below the normal levels. Even with normal precipitation levels, there is often no adequate way to capture rainwater and an infrastructure to reuse it. Historically, the Los Angeles River was well used as a main source of drinkable water until 1940, however, due to concerns around flooding, the river was reengineered to serve as a drainage pathway for excess waters. This resulted in losing the major source of potable water in the area (USC Viterbi, n.d.). At the present, the city has three main sources of water, each representing about a one third of the water supply: the Colorado and Northern California River, the Owens River, and groundwaters. Considering that more than 85% of water in Los Angeles is imported from remote locations, the city’s Water Supply Action Plan, which recommends using new technologies for recycling and reuse of water, is critical (Edry, n.d.).

Besides addressing the issues of water shortage and lack of adequate irrigation and sewage systems, implementing a wastewater reuse system in hotels has a few other benefits as shown in Figure 1 (Styles, Schönberger, and Martos 2013).

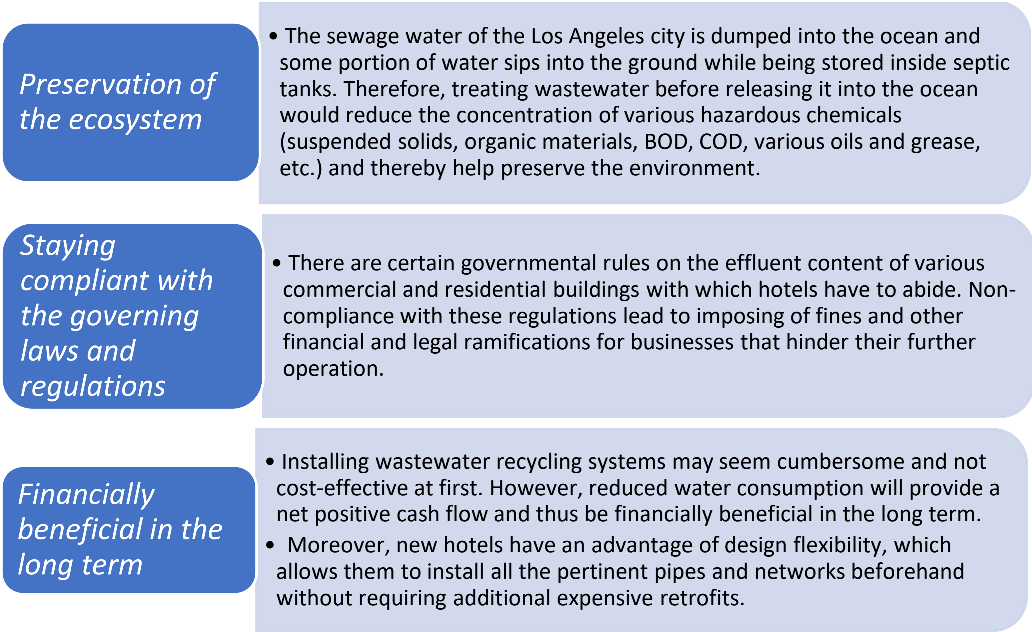

Figure 1. Benefits of implementing a wastewater reuse system in hotels

2. Literature review

2.1. Effluent grey water characteristics

According to Thomas (2020), hotels consume on average about 503.38 L per occupied room on a daily basis. If the annual occupancy rate of 400 rooms in the Hotel is approximately 80%, i.e., the same as the average occupancy rate of Los Angeles hotels, and that the share of grey water is nearly 65%, the daily amount of grey water produced by the Hotel can be calculated as follows:

$$
\begin{aligned}
&Daily\ volume\ of\ grey\ water \\
&\qquad = daily\ water\ use\ per\ occupied\ room\ \times number\ of\ rooms \\
&\qquad \times average\ occupancy\ rate\ in\ LA \\
&\qquad \times average\ portion\ of\ grey\ water \\
&\qquad = 503.38\ L/day/occupied\ room \times 400\ rooms \times 0.80 \times 0.65 \\
&\qquad = \ 104.4\, m^3/day \approx 110\, m^3/day
\end{aligned}
$$

Since data on typical grey water content of hotels does not exist in open sources, the average hotel grey water content was used for the design of the Hotel has been compiled from multiple sources (Atanasova *et al.*, 2017; Jefferson *et al.*, 2004; Li, Wichmann and Otterpohl, 2009) and the end result is summarized in Table 1.

Table 1. The average water content of grey waters in hotels.

	High season	Max
Chemical oxygen demand (COD) [mg/L]	145.1 ± 88.4	535.1
20-day biochemical oxygen demand (BOD_{20}) [mg/L]	161.9 ± 105.5	360
5-day biochemical oxygen demand (BOD_5) [mg/L]	145.4 ± 70.3	295
Total organic carbon (TOC) [mg/L]	42.2 ± 26.5	160.4
Alkalinity [mg/L ($CaCO_3$)]]	168.6 ± 15.8	227.4
Conductivity, µs/cm	767.4 ± 35.8	971.3
pH	6.9 ± 0.6	7.0
Total suspended solids (TSS) [mg/L]	43.4 ± 32.5	195.4
Volatile suspended solids (VSS) [mg/L]	38.5 ± 10.9	149.8
Total nitrogen (TN) [mg/L]	9.2 ± 4.7	25.5
Total Kjeldahl nitrogen (TKN) [mg/L]	9.2 ± 4.1	25.1
$N\text{-}NH_4^+$ [mg/L]	5.9 ± 3.2	14.4
$P\text{-}PO_4^{3-}$ [mg/L]	0.79.2 ± 4.71.4	6.7
Total pathogen count [CFU/100 mL]	1.5×10^7	4.1×10^7
Total coliform count [CFU/100 mL]	1.4×10^6	4.1×10^6
E. coli [CFU/100 mL]	0	1.1×10^6

For the design of grey water treatment systems, either average or maximum values were used specifically with the aim of creating the most adverse operating conditions for the gray ware system. The concentration of other chemicals that needed to be specified within the software were set to remain as default values for common wastewaters.

2.2. EPA standards for reclaimed water

Various standards exist for controlling the amount of different chemicals in effluent and reclaimed waters. Li, Wichmann and Otterpohl (2009), for example, reviewed the wastewater reuse standards for Germany, China, USA, Japan, and Australia. Yoonus and Al-Ghamdi (2020), on the other hand, presented the corresponding wastewater reuse standards for Jordan, Tunisia, Bangladesh, Qatar, USA, and Japan. These standards are quite similar in essence and restrictions that they impose are based on the purpose of reuse. Mostly, these standards set limits on such parameters as BOD, COD, total suspended solids (TSS), pH, NO_3, TN, turbidity, fecal coliforms, etc. For the purposes of the Hotel design, the reclaimed water quality standards set forth by the U.S. Environmental Protection Agency (2012) were used. Namely, the standard for agricultural irrigation and urban reuse of grey water were adopted. The treatment goals required by this standard are provided in a tabulated form in

Table 2 below.

Table 2. US EPA Standards for reclaimed grey waters for restricted and unrestricted reuse.

Category	Treatment Requirement	Applications after the treatment
Unrestricted reuses	BOD_5: max. 10 mg/l	

	Faecal coliforms: max. 10/ml Turbidity: max. 2 NTU pH: 6-9 Residual chlorine: max. 1 mg/l Total coliforms: max. 100/ml	Toilet flushing, landscape irrigation, laundry, fire extinguishing, irrigation of crops, fruits and vegetables, street washing.
Restricted reuses	BOD_5: max. 30 mg/l Detergent (anionic): max. 1 mg/l Faecal coliforms: max. 10/ml pH: 6-9 Residual chlorine: max. 1 mg/l Total coliforms: max. 100/ml TSS: max. 30 mg/l	Limited irrigation of landscape, subsurface irrigation of non-edible and edible crops, fruits and vegetables.

Since reclaimed grey water from the Hotel was used for both restricted and unrestricted uses, the standard for the latter was used since it sets more stringent requirements and demands the grey water to be treated until higher levels of purity.

3. Design of a grey water treatment system

3.1. Review of available grey water treatment technologies and reasoning for shortlisting

Similar to potable water treatment, there are generally three main classifications of grey water treatment technologies — biological, chemical, and physical treatment technologies (Yoonus and Al-Ghamdi 2020). In all these cases, the treatment must be preceded by a pre-treatment step which separates solids from the liquid and must be followed by a post-treatment step which disinfects the water before releasing from the plant.

Physical treatment technologies include primarily those which include adsorption by granular activated carbon, coarse filtration by sands and soils as well as fine filtration by membranes. Generally, this type of treatment clarifies the water from solids and reduces the content of organic pollutants (Yoonus and Al-Ghamdi 2020). This is achieved by three ways: (1) physical separation of particles by filters, (2) chemical removal of contaminants by adsorption to the solid particles of sand, and (3) consumption of nutrients in grey water by microbial organisms. According to Al-Mughalles *et al.* (2012), physical treatment by sand filters and granular activated carbon (GAC) are able to achieve more than 65% COD removal rate. However, the most effective physical grey water treatment technologies are those that use pressure-driven membrane filtration techniques, namely micro-, ultra-, nano-filtration and also the Reverse Osmosis (RO). These technologies have limitations, such as high energy consumption and high fouling rate, i.e., membranes must be replaced with a high frequency.

Moreover, according to Li, Wichmann and Otterpohl (2009), physical treatment technologies have to be combined with other proper technologies to yield adequate removal of surfactants, organic matter, and nutrients.

Yet another category of technologies for grey water recycling is chemical treatment, which includes techniques, such as coagulation, flocculation, photocatalytic oxidation, ion exchange, and many others (Yoonus and Al-Ghamdi 2020). In fact, it is relatively rare that chemical processes are reported to be effective in grey water treatment (Li, Wichmann, and Otterpohl 2009). Pidou *et al.* (2008) experimentally investigated the effectiveness of chemical grey water treatment technologies and concluded that the efficiency of organic removal is not sufficiently high to satisfy reclaimed water quality standards of all the countries. Li, Wichmann and Otterpohl (2009) further corroborates this statement by arguing that chemical treatment technologies are only effective for the treatment of low-strength grey waters.

Lastly, a group of technologies that is considered the most effective against medium and high strength grey waters are the biological treatment technologies. This group includes technologies, such as sequencing batch reactor (SBR), membrane bioreactor (MBR), rotating biological reactor (RBC), up-flow anaerobic sludge blanket (UASB), continuous flow sequencing reactor (CFSR), and others (Yoonus and Al-Ghamdi 2020). A common feature of all these technologies is that they employ microorganisms for removal of organic matter. Generally, biological treatment technologies are often found to provide superior performance in terms of the treatment of grey waters. Lamine, Bousselmi and Ghrabi (2007), for example, reports that SBR plant was able to achieve a 90% COD removal. However, among all the biological treatment technologies, the one that is thoroughly investigated and the most frequently cited by the scientific community is Membrane Bioreactor (MBR). Bérubé (2010) argues that the global market for this technology has already been above 1.3 billion US dollars in 2010 with a 10% annual growth rate and is stated to be an ideal technology for applications involving wastewater reuse.

The primary criterion for shortlisting technologies for further design in the GPS-X software was the technical performance, i.e., the capacity of a technology, as reported in review papers, to reduce the content of chemicals to the levels required by the standards. With this logic, chemical treatment technologies were not considered as they are only effective against low-strength grey waters. According to Yoonus and Al-Ghamdi (2020), among the physical treatment technologies the most promising ones are nanofiltration and reverse osmosis. However, they need to be coupled with a biological treatment technology as they are not good at removing COD content (Li, Wichmann, and Otterpohl 2009). As per biological treatment technologies, studies report that SBR and MBR are very attractive options due to their high efficiency against medium and high strength grey waters (Li, Wichmann, and Otterpohl 2009). The latter is also reported to be particularly cost effective solution for collective use by more than 500 residents (Li, Wichmann, and Otterpohl 2009). Considering all of these, the design was performed on MBR, SBR, and RO technologies. The latter in particular was coupled with a biological treatment technology, as recommended by the literature (Li, Wichmann, and Otterpohl 2009; Yoonus and Al-Ghamdi 2020).

3.2. Membrane Bioreactor (MBR)

Membrane Bioreactor is one of the most widely used grey water treatment technologies. It consists of very simple components and, in fact, it is derived from the conventional activated sludge (CAS) system (Bérubé 2010). Similar to CAS, it uses microorganism and other biomasses to remove contaminants from the wastewater. The main difference in their physical processes is that the former uses the secondary clarifiers and granular filters to retain the biomass, whereas the latter filters them using membranes. At early stages of development of MBR, membranes were mostly external and standalone. At present, almost all MBR systems use submerged membranes since it (a) simplifies the process and (b) reduces the required capital and operational expenses, while yielding the same treatment performance as the MBR with standalone membrane (Bérubé 2010). Figure 2 below illustrates the process schematics of submerged MBR and CAS plants.

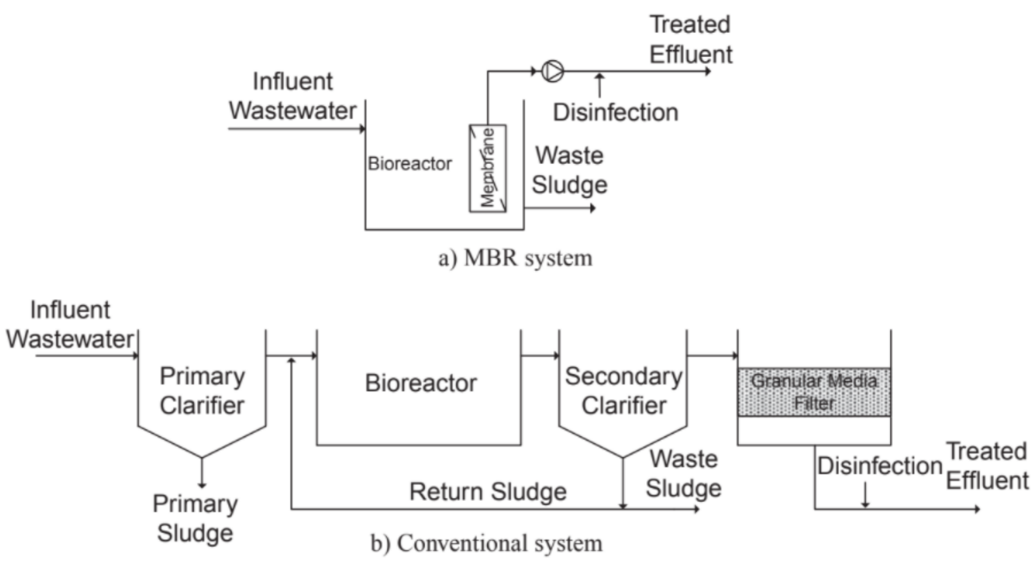

Figure 2. Process schematics of (a) submerged MBR system and (b) conventional activated sludge (CAS) system

The advantage of the MBR system is that it has small footprint area, which is very much critical in the case of the hotel in Los Angeles, and consistently good effluent quality (Atanasova et al. 2017). The system is also quite robust to changes in the grey water quality (Bis et al. 2019; Bérubé 2010). Although it is reported to have a relatively high cost, for multistory buildings, it is economically viable to implement the system with approximately 15 years of payback period (Jabornig 2014).

3.2.1. Design of MBR plant by GPS-X software

For the design of plants, the GPS-X software developed by Hydromantis Inc. was used. GPS-X (Hydromantis Inc. 2021) is the leading and the most advanced software for design, modeling, and optimization of wastewater treatment plants. Generally, the process of designing gray water treatment systems consisted of constructing a layout of each respective grey water treatment plant, identification of the most significant and sensitive design parameters by optimization of these parameters to achieve satisfactory effluent quality at a minimum cost and space.

Figure 3 below demonstrates the layout of the MBR plant, which was modeled through the GPS-X software.

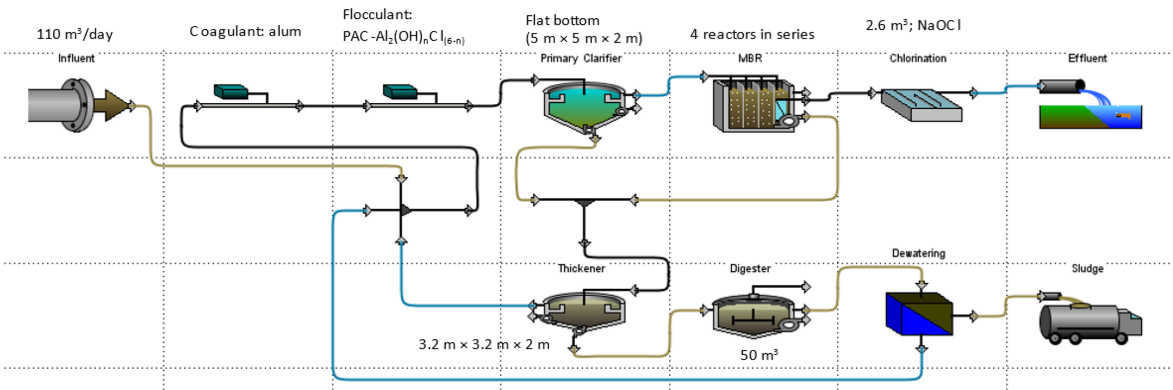

Figure 3. Layout of the MBR plant as modeled in the GPS-X software.

As can be seen from this schematic diagram, first, 110 m^3/day of water enters through an influent pipe and passes through coagulation and flocculation steps. For coagulation and flocculation, alum, $Al(SO_4)_2 \cdot 12H_2O$, and PACl solution, PAC-$Al_2(OH)_nCl_{(6-n)}$, were used, respectively. In these two stages, suspended solids and colloidal particles get enlarged in size by adhering to each other and eventually settle. Upon passing through the primary clarifier, this water passes through the MBR tank with four reactors in it connected in series. This is followed by disinfection through chlorination and, eventually, transmitting clean water through the effluent pipe. There is also a secondary cycle for the flow of sludge: it passes through the thickener (makes the sludge denser by removing excess water), digester (breaks down organic matter inside the sludge into carbon dioxide and methane gases), and dewatering tank (converts slurry sludge into a solid by removing liquid contained in it). Throughout this process, the water removed from the sludge is redirected to the primary cycle of grey water treatment and the final sludge that undergoes through thickener, digester, and dewatering tank is disposed through special transport to sludge gallery. The Sankey diagram shown in Figure 4 illustrates how the total flow rate of influent grey water gets distributed through the plant at various stages.

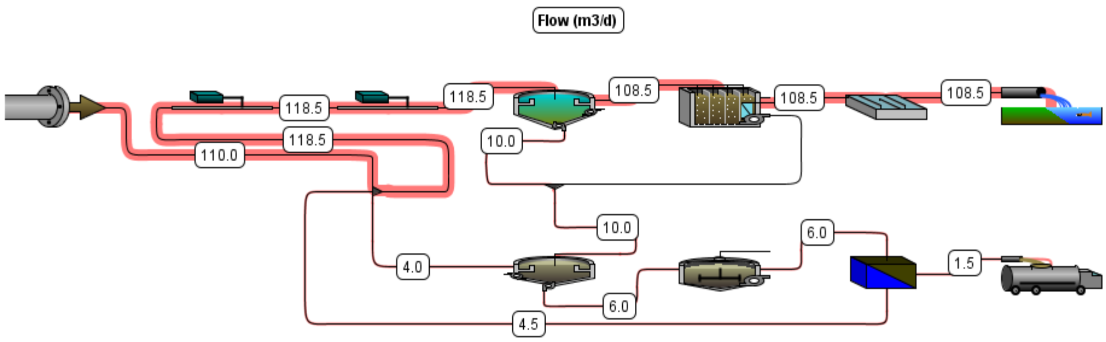

Figure 4. Sankey diagram showing the distribution of flow rate of grey water throughout the plant.

After manual sensitivity analysis, it was determined that the most influential parameters in the case of the MBR plant shown in Figure 3 were the chlorination dosage, volume of chlorination tank, dosage of alum in the coagulation stage, dosage of PACl solution in the flocculation stage, dissolved oxygen (DO) setpoints in each of the four MBR reactors as well as volumes of these reactors, and, lastly, solids capture rate of MBR tank, which has to deal with the characteristics of membrane, its pore size, operational pressures, etc. Table summarizes the list of these parameters, search ranges used for the optimization process, and the final optimum values obtain thereafter.

Table 3. Parameters used for optimization of the MBR plant’s operation, search ranges, and final optimum values.

Parameter	Optimum	Units	Search Range
Cl_2	5.7	mg/L	2.0-9.0
$V_{chlorification\ tank}$	2.6	m^3	1.0-8.0
Alum	4.3	mg(Al)/L	0.0-15.0

PAC-$Al_2(OH)_nCl_{(6-n)}$	3.6	mg(Al)/L	0.0-15.0
$DO_{setpoint, 1}$	1.9	$mg(O_2)/L$	0.0-10.0
$DO_{setpoint, 2}$	1.9	$mg(O_2)/L$	0.0-10.0
$DO_{setpoint, 3}$	1.9	$mg(O_2)/L$	0.0-10.0
$DO_{setpoint, 4}$	1.9	$mg(O_2)/L$	0.0-10.0
V_{MBR}	2.1	m^3	0.0-10.0
(Solids capture rate) $_{MBR}$	0.999	-	0.99-0.9999

After undergoing the treatment process, the content of BOD_5, TSS, residual Cl_2, total coliform count, and pH have changed as shown in Figure 5.

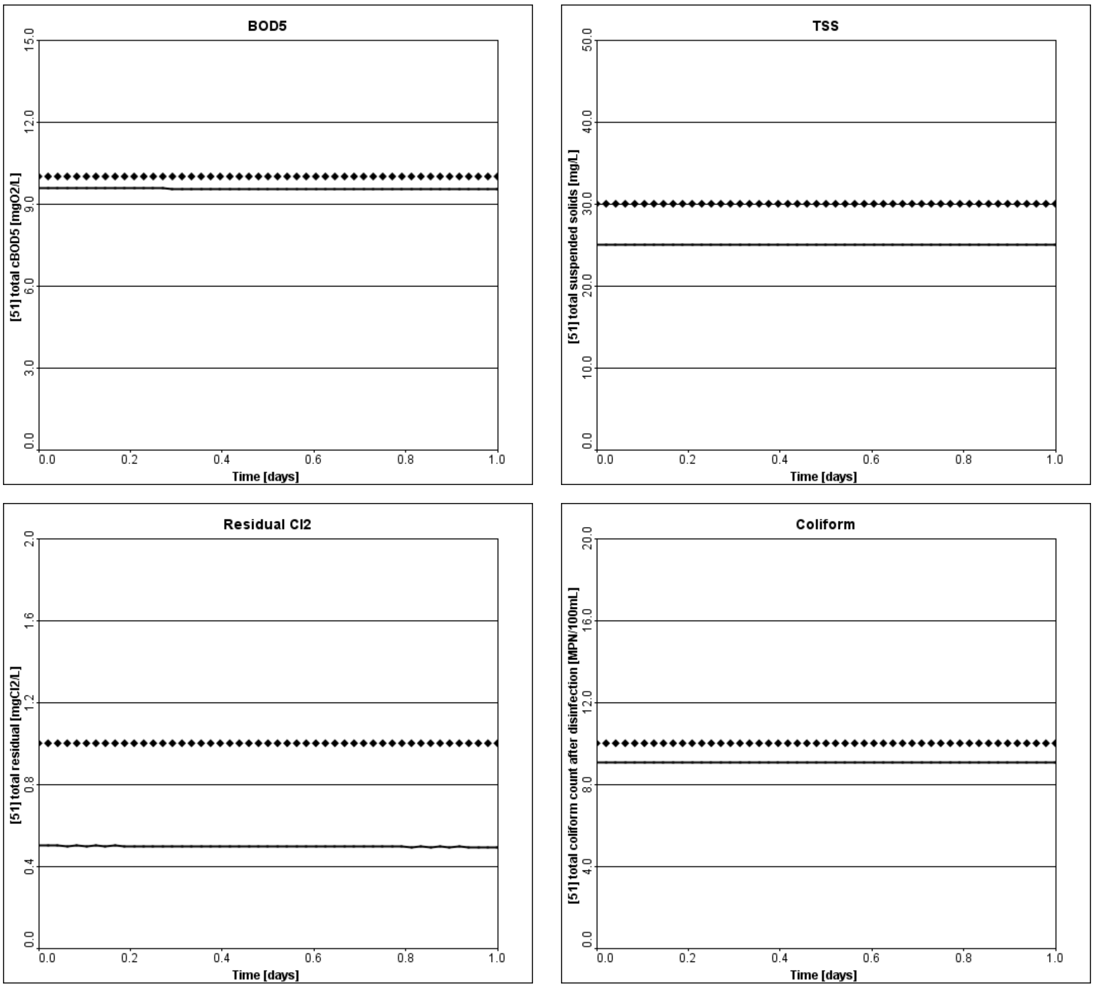

Figure 5. The limits set by EPA standards and the content of BOD_5, TSS, residual Cl_2, and total coliform count within the grey water after the treatment with MBR.

The content of all the chemicals is below the limits set forth by EPA. The graph for pH level is not shown, but it does not change during the treatment by this plant, i.e., it stays constant at 7.0 as it was initially. Other than these, the magnitude of some important parameters is presented in Table so that changes occurring during the treatment can be better observed.

Table 4. The magnitude of some important parameters before and after the treatment with MBR plant.

	Before	After
BOD_5 [mg/L]	295	4.77
pH	7.0	7.0
TSS [mg/L]	195.4	7.37
Residual chloride [mg/L]	-	0.956
Total coliform [CFU/100 mL]	4.1×10^6	9.061
Total COD [mg/L]	535.1	39.1
Alkalinity [mg/L ($CaCO_3$)]	227.4	14.73
VSS/TSS	0.767	0.775
TKN [mg/L]	25.1	5.58
$N\text{-}NH_4^+$ [mg/L]	14.4	3.29
$P\text{-}PO_4^{3-}$ [mg/L]	6.7	1.82

To further illustrate the dynamics of changes in the plant, two more Sankey diagrams are presented in Figure 6 and Figure 7, which display respectively the spatial distribution of TSS and COD in the plant:

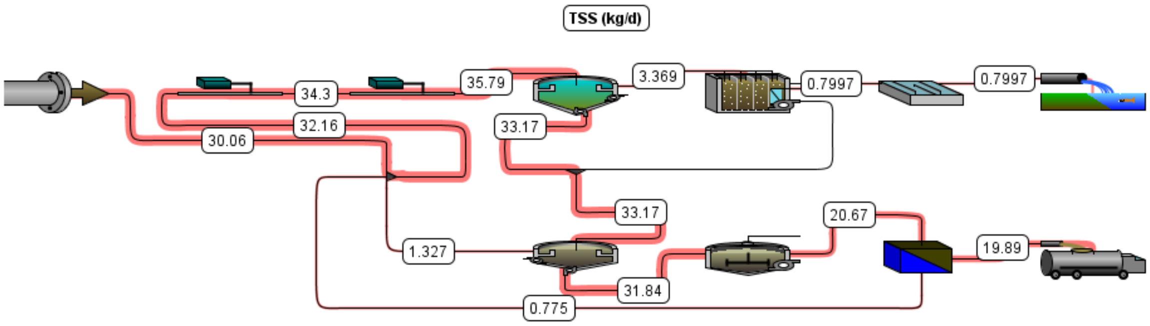

Figure 6. Sankey diagram showing the distribution of the amount of TSS in the water throughout the plant.

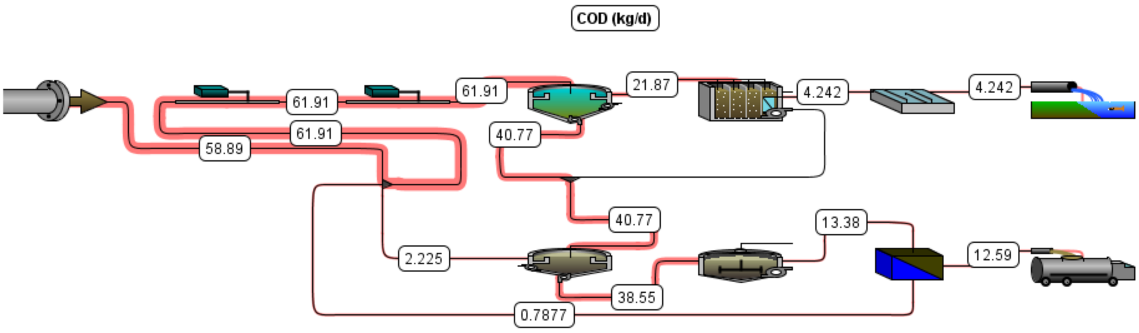

Figure 7. Sankey diagram showing the distribution of the COD levels in the water throughout the plant.

As can be observed from Figures 6-7, most of the TSS and COD are removed during the primary clarification stage.

3.2.2. Verification by hand calculation

This section presents the hand calculations used to verify the validity of software modeling results. It is important to emphasize that not all the calculations can be done by hand since (a) the plant consists of multitude of sub-elements in each of which the content of chemicals undergo some changes and (b) software design was conducted through dynamic simulations meaning that there is no steady state condition and the concentration of chemicals in each successive time period is directly or indirectly influenced by conditions in the previous timestep. Thus, calculations presented below are completely in line with the software results. First, coliform count was calculated as follows (Hydromantis 2019):

$$log\ inactivation = \frac{(chlorine\ dose)(V_{tank}/Q)(t_{10,ratio})}{(0.2828)(pH^{2.69})(chlorine\ dose^{0.15})(0.933^{T-5})}$$

$$= \frac{(5.7\ \ g/m^3)(2.6\ m^3/108.5\ \ m^3/day)(0.7)}{(0.2828)(7.0^{2.69})((5.7\ \ g/m^3)^{0.15})(0.933^{20-5})} = 5.656$$

$$coliform\ count = \frac{initial\ coliform\ count}{10^{log\ inactivation}} = \frac{4.1e6}{10^{5.656}} = \boxed{9.05}$$

Similarly, to understand why pH level does not change, the reaction of the alum dissolving in the grey water can be shown as:

$$\mathrm{Al_2(SO_4)_3 \cdot 14H_2O\ +\ 6HCO_3^- \leftrightarrow\ 2Al(OH)_3 \cdot 3H_2O\ +\ 6CO_2\ +\ 8H_2O\ +\ 3SO_4^{2-}}$$

Since there is a non-zero alkalinity, according to the chemical reaction above, pH level of the water does not change.

The concentration of residual chlorine, $C_{available}$, after a part of chlorine is lost to satisfy some portion of the instantaneous demand can be estimated through the formula below:

$$C_{available} = \frac{C_{dose}}{1 + k_{inact} \cdot t} = \frac{5.7\ g/m^3}{1 + 10 \cdot \frac{34.51\ min}{60\ min/hour}} = \boxed{0.844\ g/m^3}$$

Now, the instantaneous chlorine demand, C_{inst}, for chlorine-ammonia reaction and by-product formation can be calculated through this formula:

$$C_{inst} = \exp\left[-A_{1,inst} + A_{2,inst} \cdot \log\left(\frac{C_{dose}}{TOC}\right) + A_{3,inst} \cdot \log(UV_{254}) + A_{4,inst} \cdot \log(sTOC)\right]$$

$$= \exp\left[-0.62 + 0.522 \cdot \log\left(\frac{5.7\ g/m^3}{171.3\ g/m^3}\right) + 0.302 \cdot \log(0.001\ cm^{-1}) + 0.842 \cdot \log(55.7)\right] = \boxed{0.437\ mg/L}$$

3.2.3. Operational costs of MBR

To calculate the operational costs of the MBR plant, CapdetWorks™ tool was employed with unit costs based on US EPA Computer Assisted Procedure for Design and Evaluation of Treatment Systems (Hydromantis 2018). The following unit costs were assigned to the processes involved in MBR plant:

- Energy Price: 0.1 USD/kWh
- Alum (16% purity): 0.32 USD/kg
- PAC-$Al_2(OH)_nCl_{(6-n)}$: 0.50 USD/kg
- Clarifier: 0.35 kW
- MBR: 3.0 W/m^3
- NaOCl (70% purity): 1.1 USD/kg
- Thickener: 2.2 kW
- Digester: 3.0 W/m^3
- Dewatering: 2.2 kW
- Sludge disposal cost: 80.0 USD/tonnes

Based on these unit costs, the operational expenditures of the plant were estimated to be 24.99 USD/day (Figure 8).

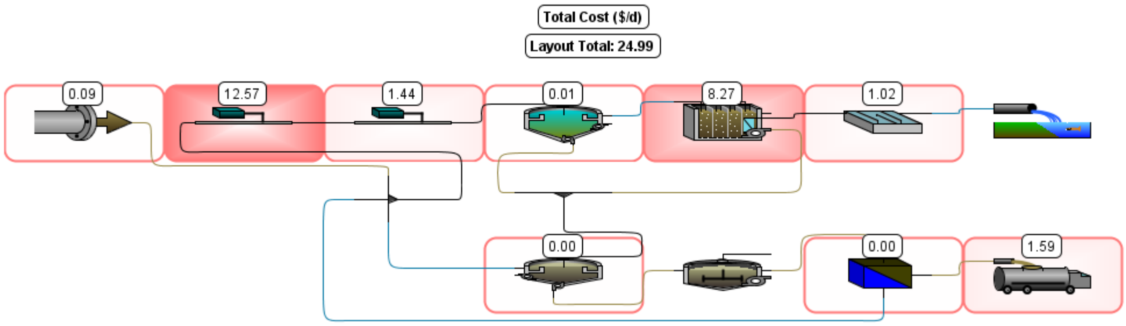

Figure 8. Operational cost of the MBR plant at various stages.

As can be seen from Figure 8, most of the daily expenses are concentrated at coagulation tank and MBR reactors. Figure 9 shows the breakdown of daily expenses by various categories of costs.

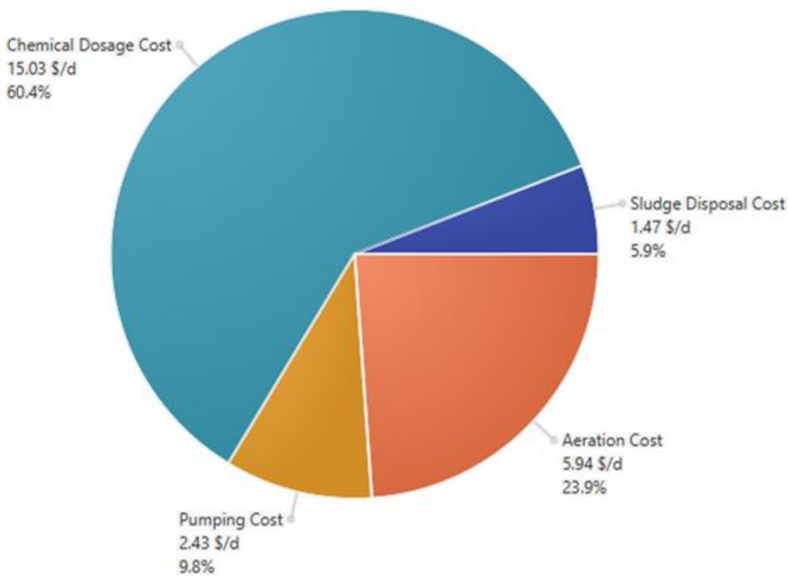

Figure 9. Costs of various types of consumables.

The pie chart in Figure 9 shows that cost of chemical consumables makes up more than half of all the daily expenses, followed by aeration costs, pumping costs, and sludge disposal costs.

3.3. Sequencing Batch Reactor (SBR)

SBR is essentially a tank with activated sludge system, in which all kinds of treatment processes, including COD/BOD removal, oxidation, settling, nitrification and denitrification, take place (Savage and Diaz 2006; Ergas and Aponte-Morales 2014). A constant air supply is provided into the tank by pumping to ensure that there is always a sufficient amount of oxygen available within the system for aerobic biodegradation to take place. The treatment process consists of at least six stages, all occurring inside a single fill-and-draw type reactor (Ergas and Aponte-Morales 2014). First, a new batch of grey water is supplied into the chamber with nitrified mixed liquor suspended solids remaining from preceding cycles. Then, the grey water is mixed anoxically to denitrify the grey water. The next stage is aeration, in which BOD within the grey water is oxidized and the Total Kjeldahl Nitrogen (TKN) is nitrified. Afterwards, aeration and mixing of the wastewater is stopped and the sludge can settle. This is followed by decanting, i.e., gradually pouring the liquid at the higher levels to another container without disturbing sediments at the bottom of the tank. Lastly, all these stages are concluded by an 'idle' stage, which is aimed at obtaining some variability in the flow rate. These six stages are graphically summarized in Figure 10.

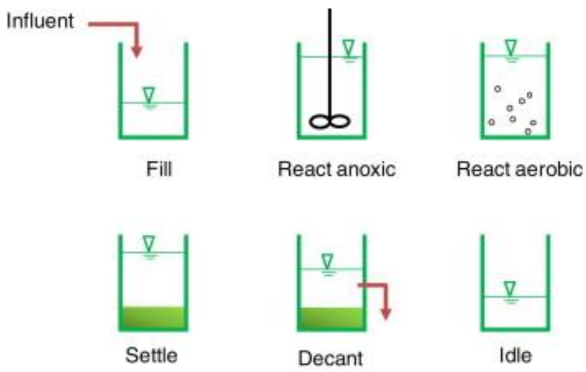

Figure 10. Six stages of Sequencing Batch Reactor (SBR).

The advantages of the SBR technology are related to the high treatment efficiency which allow a broad flexibility level in operational conditions. However, the technology is limited in the sense that it cannot remove pathogens effectively and requires high capital expenditures (CAPEX) and operating expenses (OPEX) as well as stringent maintenance requirements. For disinfection of the grey water, a conventional chlorination tank was included into the plant.

3.3.1. Design of SBR plant by GPS-X software

Figure 11 displays the layout of the SBR plant which was modeled in the GPS-X software.

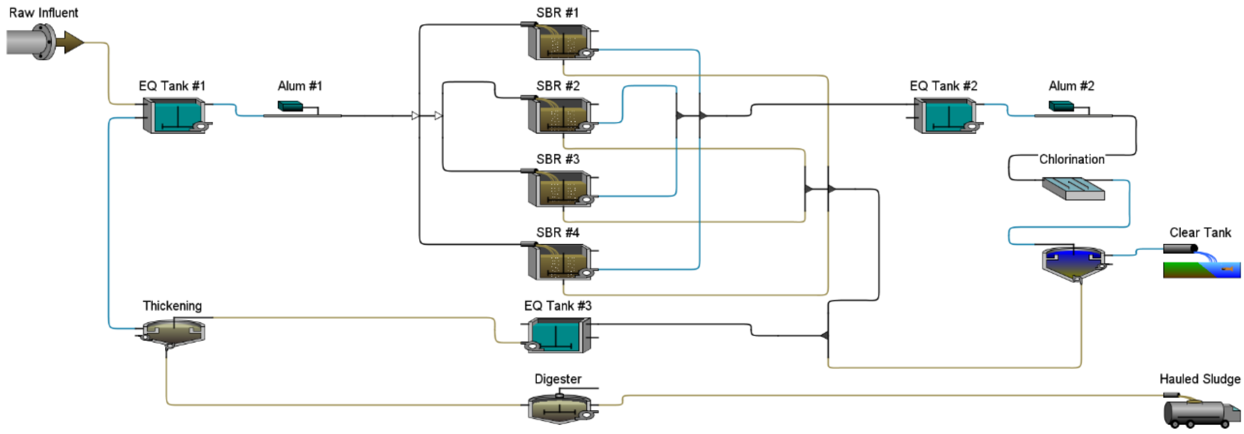

Figure 11. Layout of the SBR plant as modeled in the GPS-X software.

As in the case of MBR plant, several parameters that have the greatest influence on the objective functions were identified by manually adjusting the process controls. By varying these parameters within a reasonable range, their magnitude was optimized. The results are summarized in Table .

Table 5. Parameters used for optimization of the SBR plant's operation, search ranges, and final optimum values.

Parameter	Optimum	Units	Search Range
$DO_{setpoint, 1}$ of equalization (EQ) Tank	2.0	mgO2/L	0.0-10.0
$V_{alum\ tank\ \#1}$	100	m^3	0.0-500.0
$V_{alum\ tank\ \#2}$	50	m^3	0.0-200.0
$V_{alum\ tank\ \#3}$	10	m^3	0.0-20.0
Surface Area of SBR Tanks	330	m^2	0.0-500.0
$DO_{setpoint\ of\ aeration\ phases}$	2.0	$mg(O_2)/L$	0.0-10.0
Alum	0.83	mg/L	0.0-10.0
NaOCl	9.9	mg/L	0.0-50.0
$V_{chlorination\ tank}$	120	m^3	0.0-10.0

Here it should be emphasized that the surface area of the SBR tank was left to be large because otherwise the performance of the plant, especially the COD and BOD removal efficiencies were significantly reduced. With the optimum values shown in Table , the SBR plant was able to keep the control variables below the limits set by US EPA (Figure 2).

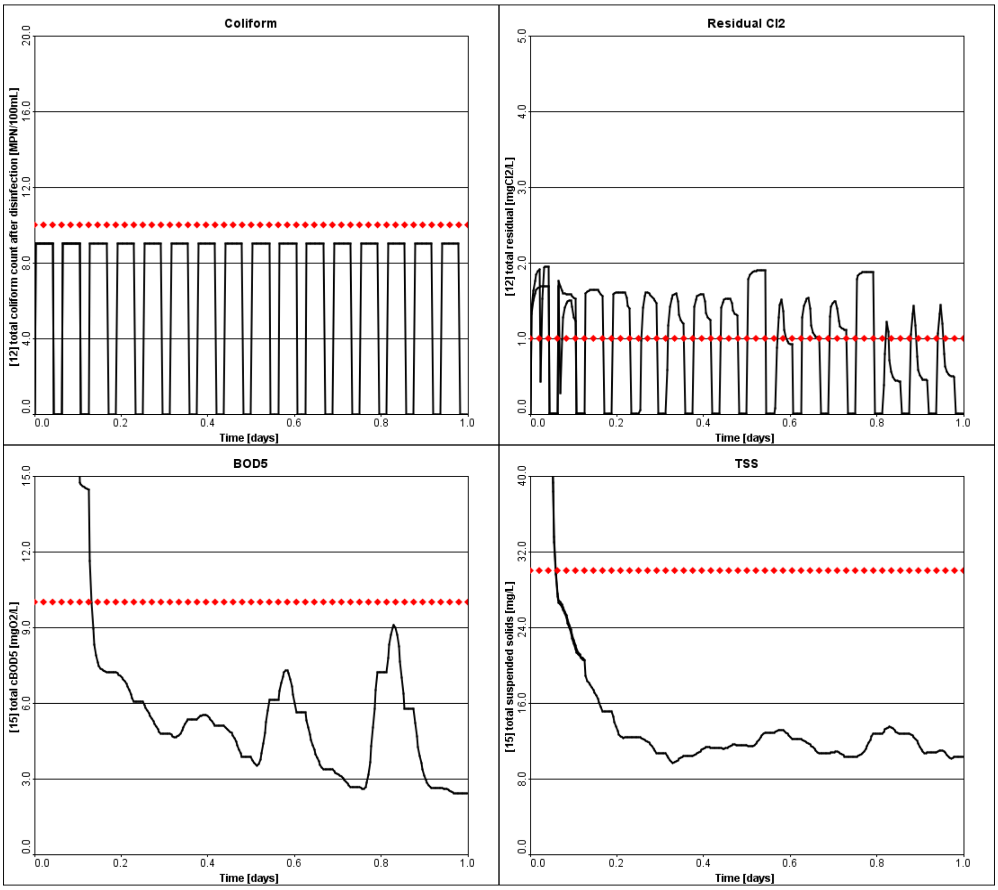

Figure 12. The limits set by EPA standards and the content of BOD_5, TSS, residual Cl_2, and total coliform count within the grey water after the treatment with SBR.

Some more numerical results that show how the chemical content of the grey water has changed after the treatment is shown in Table .

Table 6. The magnitude of some important parameters before and after the treatment with SBR plant.

	Before	After
BOD_5 [mg/L]	295	4.42
pH	7.0	7.0
TSS [mg/L]	195.4	15.81
Residual chloride [mg/L]	-	0.0
Total coliform [CFU/100 mL]	4.1×10^6	9.018
Total COD [mg/L]	535.1	45.03
Alkalinity [mg/L ($CaCO_3$)]	227.4	14.73
VSS/TSS	0.767	0.4584

TKN [mg/L]	25.1	3.624
$N\text{-}NH_4^+$ [mg/L]	14.4	0.2866
$P\text{-}PO_4^{3-}$ [mg/L]	6.7	0.9974

3.3.2. Verification by hand calculation

The total coliform count was calculated as follows:

$$log\ inactivation = \frac{(chlorine\ dose)(V_{tank}/Q)(t_{10,ratio})}{(0.2828)(pH^{2.69})(chlorine\ dose^{0.15})(0.933^{T-5})}$$

$$= \frac{(9.9\ g/m^3)(120\ m^3/4941\ m^3/day)(0.7)}{(0.2828)(7.0^{2.69})((9.9\ g/m^3)^{0.15})(0.933^{20-5})} = 9.164$$

$$coliform\ count = \frac{initial\ coliform\ count}{10^{log\ inactivation}} = \frac{4.1e6}{10^{9.164}} = \boxed{0.01}$$

As in the case of the MBR plant, the level of pH does not change, and no chemical is added that consumes alkalinity during the process:

$$\mathrm{Al_2(SO_4)_3 \cdot 14H_2O\ +\ 6HCO_3^- \leftrightarrow\ 2Al(OH)_3 \cdot 3H_2O\ +\ 6CO_2\ +\ 8H_2O\ +\ 3SO_4^{2-}}$$

Therefore, based in the same chemical reaction shown above, the level of pH within the grey water does not change in the case of SBR plant.

The available chlorine before the instantaneous chlorine demand is consumed is as shown below:

$$C_{available} = \frac{C_{dose}}{1 + k_{inact} \cdot t} = \frac{9.9\ g/m^3}{1 + 10 \cdot \frac{34.97\ min}{60\ min/hour}} = \boxed{1.450\ g/m^3}$$

Finally, the instantaneous chlorine demand itself can be estimated using the following relation:

$$C_{inst} = \exp\left[-A_{1,inst} + A_{2,inst} \cdot \log\left(\frac{C_{dose}}{TOC}\right) + A_{3,inst} \cdot \log(UV_{254}) + A_{4,inst} \cdot \log(sTOC)\right]$$

$$= \exp\left[-0.62 + 0.522 \cdot \log\left(\frac{9.9\ g/m^3}{171.3\ g/m^3}\right) + 0.302 \cdot \log(0.001\ cm^{-1}) + 0.842 \cdot \log(55.7)\right] = \boxed{0.495\ mg/L}$$

3.3.3. Operational costs of SBR

The following unit costs from the CapdetWorks database will be used to estimate the daily operational expenses of the SBR plant:

- Energy Price: 0.1 USD/kWh
- Alum (16% purity): 0.32 USD/kg

- PAC-$Al_2(OH)_nCl_{(6-n)}$: 0.50 USD/kg
- Clarifier: 0.35 kW
- SBR Mixing Energy Usage: 3.0 W/m^3
- NaOCl (70% purity): 1.1 USD/kg
- Thickener: 2.2 kW
- Digester: 3.0 W/m^3
- Sludge disposal cost: 80.0 USD/tonne

The resultant operational cost is 116.29 USD per day and as can be seen from the Sankey diagram in Figure 13, chlorination tank is responsible for a major part of this cost.

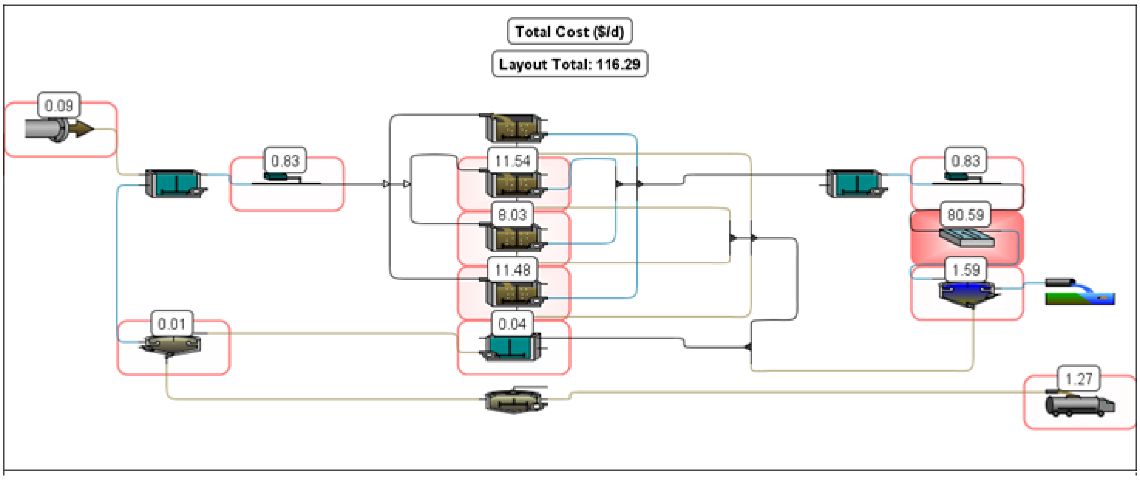

Figure 13. Breakdown of operational costs of the SBR plant.

This is partially due to the fact that SBR technology is ineffective against pathogens, therefore, to keep the number of coliforms below the limit, the chlorination tank consumes vast amounts of NaOCl solution on a daily basis.

3.4. Reverse Osmosis with the Upflow Anaerobic Sludge Blanket (RO with UASB)

The last, third technology to be designed for the Hotel is the reverse osmosis, which purifies the water by pushing the grey water through membranes with pores in with a diameter in the order of nanometers under high pressures. The reverse osmosis is quite conventional technology for the treatment of potable waters; however, it is not quite effective in terms of removal of chemical and biological oxygen demand. Elmitwalli et al. (2007) recommended combining aerobic and anaerobic treatment technologies to leverage advantages of both technologies to achieve more superior grey water treatment performance and suggested to place anaerobic treatment at early stages before the physical treatment. However, the obtained results with RO and UASB showed that this is not the case and, in this case, UASB does not address limitations of RO in terms of COD/BOD removal. Therefore, against this recommendation, the UASB plant was placed at later stages, just before the RO step (refer to Figure 14).

3.4.1. Design of RO with UASB by GPS-X software

The layout of the RO with UASB plant modeled through the GPS-X software is shown in Figure 14.

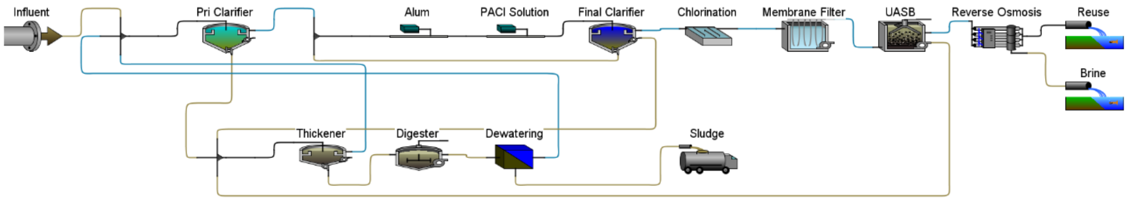

Figure 14. Layout of the RO with UASB plant as modeled in the GPS-X software.

After optimizing volumes of various tanks, dosages of chemical consumables, pore sizes of membranes, and temperature within the UASB reactor, pipe diameter and number of vessels inside the RO reactor, the magnitudes of BOD_5, pH, total coliform count, and TSS to the levels were reduced to the levels shown in Figure 5.

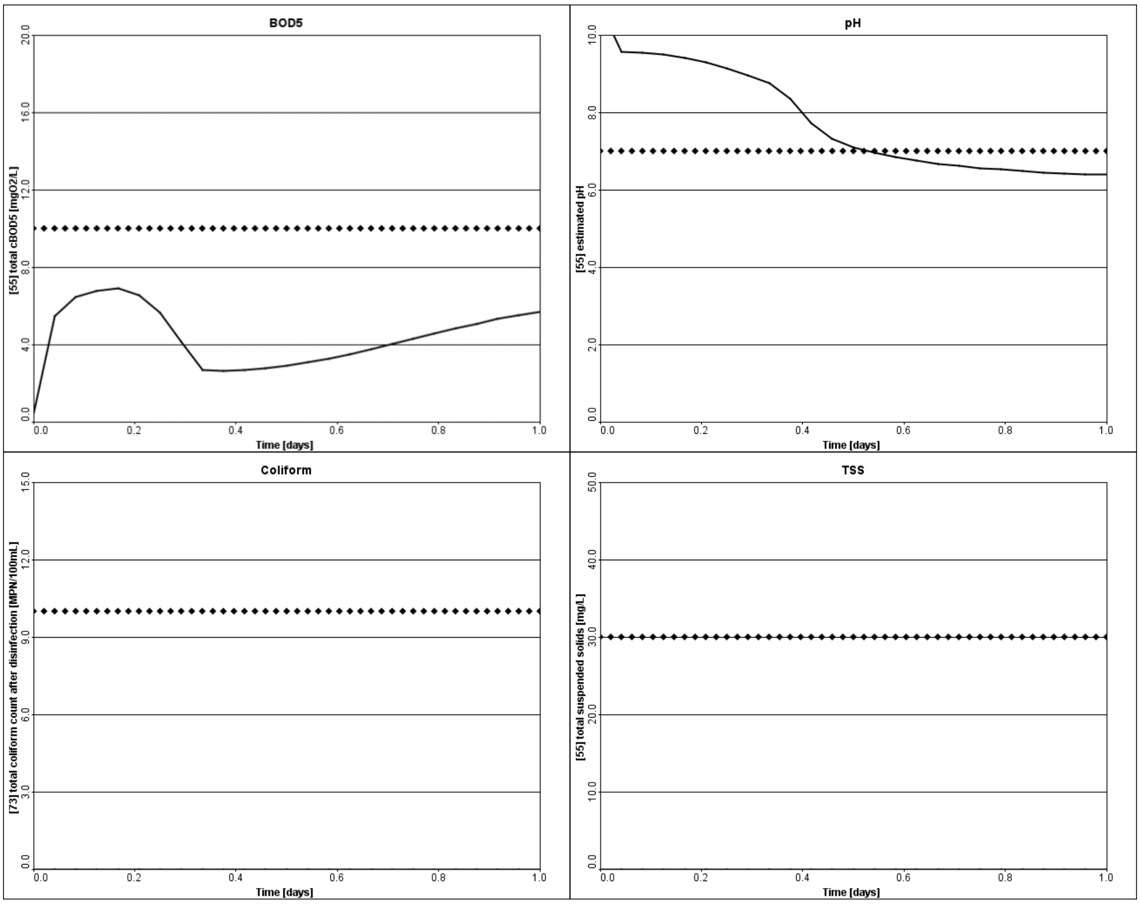

Figure 25. The limits set by EPA standards and the content of BOD_5, TSS, residual Cl_2, and total coliform count within the grey water after the treatment with RO with UASB.

More quantitative results comparing the grey water quality before and after the treatment can be found in Table .

Table 7. The magnitude of some important parameters before and after the treatment with RO with UASB.

	Before	After
BOD_5 [mg/L]	295	5.698
pH	7.0	6.386
TSS [mg/L]	195.4	0.0
Residual chloride [mg/L]	-	0.0
Total coliform [CFU/100 mL]	4.1×10^6	0.0
Total COD [mg/L]	535.1	97.85
Alkalinity [mg/L ($CaCO_3$)]	227.4	14.73
VSS/TSS	0.767	0.0
TKN [mg/L]	25.1	25.86
$N\text{-}NH_4^+$ [mg/L]	14.4	19.39
$P\text{-}PO_4^{3-}$ [mg/L]	6.7	0.4039

3.4.2. Verification by hand calculation

First of all, the number of total coliforms is calculated as follows:

$$log\ inactivation = \frac{(chlorine\ dose)(V_{tank}/Q)(t_{10,ratio})}{(0.2828)(pH^{2.69})(chlorine\ dose^{0.15})(0.933^{T-5})}$$

$$= \frac{(12.0\ \ g/m^3)(30\ m^3/108.5\ \ m^3/day)(0.7)}{(0.2828)(7.0^{2.69})((12.0\ \ g/m^3)^{0.15})(0.933^{20-5})} = 122.9$$

$$coliform\ count = \frac{initial\ coliform\ count}{10^{log\ inactivation}} = \frac{4.1e6}{10^{122.9}} = \boxed{0.00}$$

In this case, due to high retention time, the number of coliforms is reduced to practically zero. The available chlorine before exhausting the instantaneous chlorine demand is as shown below:

$$C_{available} = \frac{C_{dose}}{1 + k_{inact} \cdot t} = \frac{12.0\ \ g/m^3}{1 + 10 \cdot \frac{398.16\ min}{60\ \ min/hour}} = \boxed{0.178\ g/m^3}$$

The last calculation is for the instantaneous chlorine demand:

$$C_{inst} = exp\left[-A_{1,inst} + A_{2,inst} \cdot log\left(\frac{C_{dose}}{TOC}\right) + A_{3,inst} \cdot log(UV_{254}) + A_{4,inst} \cdot log(sTOC)\right]$$

$$= exp\left[-0.62 + 0.522 \cdot log\left(\frac{12.0\ \ g/m^3}{171.3\ \ g/m^3}\right) + 0.302 \cdot log(0.001\ cm^{-1}) + 0.842 \cdot log(55.7)\right] = \boxed{0.518\ mg/L}$$

3.4.3. Operational costs of RO with UASB

Unit costs were again obtained from the CapdetWorks database and are practically the same as the ones presented in sections 3.2.3 and 3.3.3. The only new cost item may be that UASB plant 20.0 kW of power which is estimated at 0.1 USD/kWh. Overall, the estimates show that the plant will consume about 10.01 USD per day not including the cost of membranes in RO which have to be replaced periodically (Figure 16). Most of the daily operational expenses are constituted by chemical consumables.

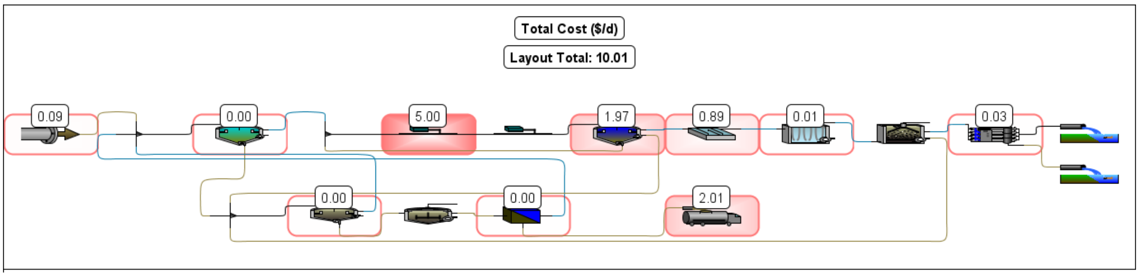

Figure 16. Operational costs of RO with UASB

4. Overall Cost Analysis and Technology Selection

To develop an optimal solution selection, it is necessary to calculate the capital and operational expenditures, and, if applicable, a life cycle cost or net present value need to be estimated. It is recommended to conduct a detailed cost estimation for each individual plant, considering the construction costs, maintenance needs, replacement of various supplementary for each component of plants. However, data availability is an issue, especially for SBR and RO with UASB. In the present report, CAPEX, OPEX, and net present value (also called as life cycle cost) were calculated using relations proposed in scientific publications based on statistical analysis of industry data or regression analysis. For MBR, Lo, McAdam and Judd (2015) suggest to use the following relations for estimation of CAPEX, OPEX, and NPV:

$$\mathrm{CAPEX} = 1060 \cdot \mathrm{Q}^{0.872} = 1060 \cdot 108.5^{0.872} = 63{,}124\ \mathrm{USD}$$

$$\begin{aligned}\mathrm{OPEX} &= (-0.0509 \cdot \ln\mathrm{Q} + 0.664) \cdot \mathrm{Q} = (-0.0509 \cdot \ln 108.5 + 0.664) \cdot 108.5 \\ &= 97.9\ \mathrm{USD/day} = 35{,}743\ \mathrm{USD/year}\end{aligned}$$

$$\mathrm{Consumables} = 25.0\ \mathrm{USD/day} = 9{,}125\ \mathrm{USD/year}$$

$$\begin{aligned}\mathrm{NPV} &= 1265 \cdot \mathrm{t}^{0.44} \cdot \mathrm{Q}^{-0.00385 \cdot \ln t + 0.868} = 1265 \cdot 20^{0.44} \cdot 108.5^{-0.00385 \cdot \ln 20 + 0.868} \\ &= 261{,}710\ \mathrm{USD}\end{aligned}$$

Similarly, based on statistical data from US EPA (United States Environmental Protection Agency, n. d.) and Advisian (Advisian, n. d.), the CAPEX and OPEX of SBR and RO with UASB plants were calculated as shown in Table 8.

Table 8. CAPEX and OPEX of SBR and RO with UASB.

	CAPEX	OPEX
SBR	139,900 USD	42,340 USD/year
RO with UASB	226,000 USD	23,650 USD/year

All these cost analysis results are presented in Figure 17.

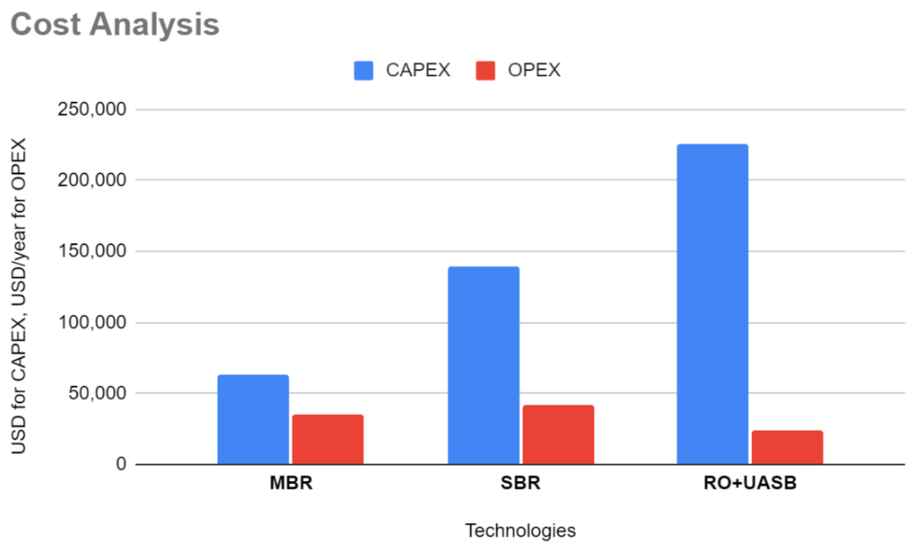

Figure 17. CAPEX and OPEX of MBR, SBR, and RO with UASB.

Despite difficulties estimating the net present value of SBR and RO with UASB, it is evident that MBR is the optimal choice based on the economic feasibility criterion. There are other non-financial factors that must be considered to make the final decision, such as space requirements, robustness of performance of these technologies, capacity to consistently yield an effluent quality compliant with the EPA Standards, percent recovery, etc. All of these are necessary conditions for the alternative technologies to be considered for further design steps. When compared against these criteria, SBR proved to be unsuitable for use in the Hotel as it requires large land areas and is also inefficient in terms of removal of pathogens. On the other hand, for RO with UASB, the main challenge is low BOD and COD removal rate and low recovery level, just above 50% (in contrast to 98.6% for MBR plant). As per MBR, its main limitation is the relatively high cost, which, however, is significantly lower than that of its competitors. However, studies show that it is financially feasible with an average of 15-year payback period if implemented in a multi-story building. Taking all these factors into account, the membrane bioreactor plant appears to be a clear winner and thus, may be used for further detailed design stages.

5. Conclusions

The challenges associated with the ongoing climate change and energy scarcity demand industries across the globe to adopt new ways of development and operation. The impact of construction and hospitality industries on the resources and the environment are evidently significant. This study aimed at designing and modeling a gray water treatment plant for a newly designed hotel building. The objective was to perform a detailed design, run modeling and optimization of a grey water treatment. The greywater treatment plant aims to address the shortage of potable water and lack of adequate and environmentally friendly sewage systems. In this project, state of the art technologies for treatment of grey waters were reviewed, and thereafter, Membrane Bioreactor, Sequencing Batch Reactor, and Reverse Osmosis with Upflow Anaerobic Sludge Blanket were modeled through the GPS-X software. The results from software were verified through hand calculations and finally, capital and operational expenses required for implementation of each of the plants were calculated. Overall, due to its relatively low CAPEX and OPEX as well superior technical performance, it was decided to implement the MBR plant into the hotel building.

6. References

Advisian. n.d. "The Cost of Desalination." Accessed April 2, 2021. https://www.advisian.com/en/global-perspectives/the-cost-of-desalination.

Al-Mughalles, Mohammed Hasan, Rakmi Abdul Rahman, Fatihah Binti Suja, Mastura Mahmud, and Sharifah Mastura Syed Abdullah. 2012. "Greywater Treatment Using GAC Biofilm Reactor and Sand Filter System." *Australian Journal of Basic and Applied Sciences* 6 (3): 283–92.

Atanasova, Natasa, Montserrat Dalmau, Joaquim Comas, Manel Poch, Ignasi Rodriguez-Roda, and Gianluigi Buttiglieri. 2017. "Optimized MBR for Greywater Reuse Systems in Hotel Facilities." *Journal of Environmental Management* 193 (May): 503–11. https://doi.org/10.1016/j.jenvman.2017.02.041.

Bérubé, Pierre. 2010. "Chapter 9 Membrane Bioreactors: Theory and Applications to Wastewater Reuse." In , 255–92. https://doi.org/10.1016/S1871-2711(09)00209-8.

Bis, Marta, Agnieszka Montusiewicz, Adam Piotrowicz, and Grzegorz Łagód. 2019. "Modeling of Wastewater Treatment Processes in Membrane Bioreactors Compared to Conventional Activated Sludge Systems." *Processes* 7 (5): 285. https://doi.org/10.3390/pr7050285.

Ecorys. 2009. "Study on the Competitiveness of the EU Tourism Industry," no. October: 3–173. https://op.europa.eu/en/publication-detail/-/publication/43457894-3281-4181-80fe-0745b8e2c78f.

Edry, Liron. n.d. "Water Resource Development for Los Angeles County Plan." Accessed March 21, 2021. http://www.csun.edu/~le288758/Water Supply Paper.htm.

Elmitwalli, Tarek A., and Ralf Otterpohl. 2007. "Anaerobic Biodegradability and Treatment of Grey Water in Upflow Anaerobic Sludge Blanket (UASB) Reactor." *Water Research* 41 (6): 1379–87. https://doi.org/10.1016/j.watres.2006.12.016.

Ergas, S.J., and V. Aponte-Morales. 2014. "Biological Nitrogen Removal." In *Comprehensive Water Quality and Purification*, 123–49. Elsevier. https://doi.org/10.1016/B978-0-12-382182-9.00047-5.

Hydromantis. 2018. "CapdetWorks." Hydromantis. https://www.hydromantis.com/CapdetWorks.html.

———. 2019. “GPS-X Technical Reference - v8.0.” https://www.hydromantis.com/help/GPS-X/docs/8.0/Technical/index.html.

Hydromantis Inc. 2021. “GPS-X.” Hydromantis Inc. https://www.hydromantis.com/GPSX.html.

Jabornig, Simon. 2014. “Overview and Feasibility of Advanced Grey Water Treatment Systems for Single Households.” *Urban Water Journal* 11 (5): 361–69. https://doi.org/10.1080/1573062X.2013.783086.

Jefferson, B, A. Palmer, P. Jeffrey, R. Stuetz, and S. Judd. 2004. “Grey Water Characterisation and Its Impact on the Selection and Operation of Technologies for Urban Reuse.” *Water Science and Technology* 50 (2): 157–64. https://doi.org/10.2166/wst.2004.0113.

Lamine, M., L. Bousselmi, and A. Ghrabi. 2007. “Biological Treatment of Grey Water Using Sequencing Batch Reactor.” *Desalination* 215 (1–3): 127–32. https://doi.org/10.1016/j.desal.2006.11.017.

Li, Fangyue, Knut Wichmann, and Ralf Otterpohl. 2009. “Review of the Technological Approaches for Grey Water Treatment and Reuses.” *Science of The Total Environment* 407 (11): 3439–49. https://doi.org/10.1016/j.scitotenv.2009.02.004.

Lo, C. H., E. McAdam, and S. Judd. 2015. “The Cost of a Small Membrane Bioreactor.” *Water Science and Technology* 72 (10): 1739–46. https://doi.org/10.2166/wst.2015.394.

Pidou, Marc, Lisa Avery, Tom Stephenson, Paul Jeffrey, Simon A. Parsons, Shuming Liu, Fayyaz A. Memon, and Bruce Jefferson. 2008. “Chemical Solutions for Greywater Recycling.” *Chemosphere* 71 (1): 147–55. https://doi.org/10.1016/j.chemosphere.2007.10.046.

Savage, G.M., and L.F. Diaz. 2006. “Biological Processes.” In *Waste Management Series*, 171–218. https://doi.org/10.1016/S0713-2743(06)80010-3.

Styles, David, Harald Schönberger, and Jose Luis Galvez Martos. 2013. *Best Environmental Management Practice in the Tourism Sector*. 1st ed. Luxembourg: Joint Research Center. https://doi.org/10.2788/33972.

Thomas, Michelle L. 2020. “Doctor of Philosophy.” *ProQuest LLC*. Walden University. https://doi.org/10.1503/cmaj.180710.

U.S. Environmental Protection Agency. 2012. *2012 Guidelines for Water Reuse*. Edited by Nancy Stoner, Eric Postel, and Lek Kadeli. 2nd ed. Washington, DC: U.S. Agency for International Development. https://www.epa.gov/sites/production/files/2019-08/documents/2012-guidelines-water-reuse.pdf.

United Nations World Tourism Organisation. 2021. *International Tourism Highlights, 2020 Edition*. World Tourism Organization (UNWTO). https://doi.org/10.18111/9789284422456.

United States Environmental Protection Agency. n.d. “Wastewater Technology Fact Sheet: Sequencing Batch Reactors.” Washington, DC. https://www3.epa.gov/npdes/pubs/sbr_new.pdf.

USC Viterbi. n.d. “LOS ANGELES WATER ISSUE: Why It’s Not Just the Drought.” Accessed March 21, 2021. https://viterbi.usc.edu/water/.

Yoonus, Hamad, and Sami G. Al-Ghamdi. 2020. “Environmental Performance of Building Integrated Grey Water Reuse Systems Based on Life-Cycle Assessment: A Systematic and Bibliographic Analysis.” *Science of The Total Environment* 712 (April): 136535.

https://doi.org/10.1016/j.scitotenv.2020.136535.