Life cycle assessment of a wastewater hybrid system for rural communities, Marcelino Maridueña case of study.

Sara Everhart, J.L. Amaya, J. Hidalgo-Crespo, F.X. Jervis, M.L. Mendoza, C. Moreira

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 116 (2023) 678–683

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference.

Life cycle assessment of a wastewater hybrid system for rural communities, Marcelino Maridueña case of study.

Sara Everhart[a], J.L. Amaya[b], J. Hidalgo-Crespo[c,d], F.X. Jervis[b], M.L. Mendoza[b], C. Moreira[b]*

[a]*University of Colorado, Boulder,* Mortenson Center in Global Engineering & Resilience*, 4001 Discovery Drive, UCB 608 Boulder, CO 80303*

[b]*Facultad en Ingenieria Mecánica y Ciencias de la Producción, Escuela Superior Politécnica del Litoral, ESPOL, Km. 30.5 vía Perimetral, Guayaquil, Ecuador*

[c] *Universidad de Guayaquil, Facultad de Ingeniería Industrial, Av. Dr. Jiménez Lince y Av. Juan Tanca Marengo, 090501 Guayaquil, Ecuador*

[d] *Univ. Grenoble Alpes, CNRS, Grenoble INP, G-Scop, 46 Avenue Felix Viallet, 38000 Grenoble, France*

* Corresponding author. *E-mail address: cemoreir@espol.edu.ec*

Abstract

Wastewater management (WWM) is an issue in low and middle-income countries' rural areas; the lack of technology and funding have been identified as the most critical. Marcelino Maridueña (MM) is a rural village in Ecuador that uses an oxidation pond to treat its household wastewater. As a result, the organic load in the effluent varies depending on the season and the volume treated. Also, it may generate emissions that could harm the environment. Therefore, a hybrid system, i.e., activated sludge (conventional) coupled with an algal photobioreactor system (APS), was developed at a laboratory scale. This study's target was to assess the environmental impact of the developed hybrid system, i.e., the impact of the hybrid system versus a solely a conventional system. Notably, the ecological footprint of the APS alternative may vary depending on the climate. In this study, the APS was fixed for a tropical region with warm temperatures ranging from 25 to 45 °C and plenty of solar light. The environmental impact categories were identified in literature and then analyzed through a Life Cycle Assessment (LCA) methodology. The model demonstrates a percent reduction in most impact categories from switching to the proposed hybrid wastewater system. The percent reductions modeled were as follows: Freshwater Eutrophication would be reduced by 98.09%, Marine Eutrophication would be reduced by 98.61%, and Human Non-carcinogenic Toxicity would be reduced by 98.45% between the proposed and the current system of wastewater treatment.

Keywords: Wastewater Biological Treatment; Effluent; Algal growth; Rural Communities; Life Cycle Assessment

1. Introduction

Ecuador is a unique example of a nation that has enshrined sustainability and equality into their constitution. The Ecuadorian government has established the Andean concept of Sumak Kawsay, harmony between nature and human development, into the 2008 constitution, providing innate rights to nature. Therefore, Ecuador established water and sanitation as a basic human right for all its citizens and created a legal framework to put policies into place to address the dearth of access for its people. As of 2020 90.7% of Ecuadorians have access to safe sanitation facilities, which include septic systems, sewage, and blind tanks; however, there are inequalities in coverage i.e., 97% in urban areas and 78.9% in rural areas. Additionally, only about 23.3% of total wastewater (WW) effluent piped through sewage lines is treated, and the rest is discharged into local bodies of water [1].

Untreated or undertreated WW may contain an excess of nutrients, i.e., ammonia (NH_4^+), phosphorus (P), and nitrogen(N) which severely impacts the ecology of the

2212-8271
10.1016/j.procir.2023.02.114

receiving water body, leading to eutrophication and anoxic water bodies. As a result, they cannot support aquatic organisms; ultimately making the water unsuitable for human use. People interacting with these receiving water bodies will be negatively impacted by a loss of fish species, unusable water sources, and pathogens [2]. Quito, the largest city in Ecuador located in the mountainous region near the top of the watershed, treats less than 10% of its municipal wastewater; untreated sewage is discharged through four rivers that cross the city [1].

Lately, attempts to increase WW treatment plants (WWTP) have been rising nationwide. Indeed, one of the largest projects in Latin America, the Vindabona WWTP is in the planning process [3]. However, fewer projects are proposed in rural areas due to financial and technological restrictions. Most funding for wastewater treatment comes from the public sector; however, funding for large projects is supplemented by the private sector, namely international banks. For example, the Vindabona plant is partially funded through the Inter-American Development Bank (IADB) [4]. Rural projects are mostly funded by local governance or federal public funds [3]. Thus, more research is needed into cheaper low-technology options to retrofit existing treatment plants in rural settings to obtain better removal rates. Options that are considered low-cost are typically decentralized. Centralized wastewater systems are public sewer systems that treat all wastewater at a single site; this type of wastewater treatment is ideal for larger communities but tends to cost more. Decentralized options treat wastewater near where it is generated. These solutions are more affordable and better suited to smaller communities. Several technologies are available, but the optimal solution depends on the local context [5].

This study follows the municipal WWTP in a small rural community on the coast of Ecuador called Marcelino Maridueña (MM). Small communities have fewer than 10,000 members using the system and less than one million gallons of daily wastewater flow [5]. This community uses a single oxidative pond to treat household wastewater [6]. Other studies have examined oxidative pond treatment in tropical and rural regions and have shown promising removal rates for relevant parameters along with optimal design criteria. [7-9]. The purpose of this study is to build on current knowledge of rural low-cost treatment options by conducting a place-based investigation of available solutions. This study proposes using two biological treatment options: activated sludge (AS) and microalgae growth (MG). Previous studies in the WW of MM determined the suitability of a conventional AS due to the WW characteristics [6]. It was found that MM WW is characterized by high chemical oxygen demand (COD), possibly attributed to people's diet, and higher folic acid content, both of which favor biodegradation. To improve resource usage, the system was coupled with algal photobioreactors, where the available nutrients of the AS effluent were used as a growth medium. After algae harvesting, the spent growth medium would be deactivated and released into the environment. Meanwhile, the harvested algae, rich in lipids and proteins, could be used to manufacture animal feedstock. This would utilize a biorefinery to prevent waste from the system from entering the landfill and to provide a potential funding stream.

This study utilizes Life Cycle Assessment (LCA) software, specifically Simapro, to compare the environmental impacts of the two treatment scenarios proposed. A third scenario will also be presented: releasing the WW without treatment. This assessment quantifies improvements in the removal and models impacts from each treatment scenario. This tool can help municipalities decide the best options for each situation and may help municipalities beyond MM make choices when considering their environmental impact.

2. Materials and Methods

This LCA is carried out following ISO 14040 and ISO 14044. The environmental impact categories chosen to evaluate are the most cited in the literature regarding nutrient loading from wastewater effluent [10]. These indicators are climate change, stratospheric ozone, ionizing radiation, ozone formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic, human non-carcinogenic, land use, mineral scarcity, fossil resource scarcity, and water consumption. The key indicators considered are global warming, eutrophication, and ecotoxicity. These key indicators are also metrics chosen for national testing in the US. Furthermore, these indicators are recommended for wastewater systems as they can connect to current monitoring and dynamic modeling. The decision to limit the number of key indicators was meant to simplify the decision-making process for the municipal operators. A midpoint method was chosen to provide a more accurate and clear analysis of the indicators chosen. The methodology chosen is ReCiPe which was used by most of the recent wastewater assessment literature [10]. The scope of the LCA for these processes will be gate-to-gate which will begin with the oxidation pond for the current system and the aeration pond for the proposed scenario and end with emission to air and water ecosystems.

2.1 A Systematic Approach for the Production Engineering Industry

Wastewater treatment can be thought of as a product-service relationship. The effluent corresponds to the product and the treatment of wastewater to the service. LCA provides a systematic approach to developing knowledge regarding efficiencies and system improvements [11]. In this study, the municipality of MM is the client seeking advice on improving the cost and sustainability of their service (wastewater treatment) and the quality of their product (the effluent). The quality of the product (effluent) is crucial and can have social and economic impacts [12]. The manufacturing industry can benefit twofold from the knowledge generated in this study. Firstly, wastewater treatment is a manufacturing process in and of itself, and this framework can be applied more broadly and relate to any product service relationship. Secondly, wastewater is produced in most manufacturing processes, and these methods can help reduce costs and improve removal efficiencies in these sectors.

2.2 Goal Definition

The goal of this LCA is to compare the environmental impacts of the current WWTP in MM to a two-step process created as a pilot system in the lab involving an aerobic treatment followed by an algal pond and deactivation [6]. The aim is to quantify which treatment option removes nutrients more effectively and to determine if the additional inputs outweigh any potential benefits of additional removal. These results will also be compared to a third scenario: releasing the WW without treatment.

2.2.1 Objective of the Study

Currently, Ecuador experiences surface water contamination due to a lack of wastewater treatment [1]. Improved treatment is expensive and not feasible for small municipalities such as MM. This LCA will help to determine the environmental impact of retrofitting the existing municipal wastewater treatment system.

2.3 Scope Definition

2.3.1. Description of the two wastewater treatment scenarios

The current wastewater treatment train used in MM is an oxidation pond followed by discharge. The proposed treatment trains begin with an aeration-activated sludge pond followed by an algal pond treatment with deactivation succeeded by discharge to the environment. Domestic wastewater influent is piped through the local sewerage system to the treatment plant. Gravity is used to transfer water to each treatment system.

Oxidation ponds are also called lagoons or stabilization ponds. Microorganisms such as bacteria and algae break down chemicals and consume nutrients in the wastewater. Treatment efficiencies depend on the microbial community and require sunlight and oxygen to perform effectively. When microbial communities are well balanced and parameters such as sunlight, oxygen, nutrients, and temperature are adequate, oxidation ponds can be considered self-sufficient treatment options that offer good removal efficiencies for low labor costs. Oxidation ponds are considered methane emitters because they are not fully oxygenated and possess sections that become anaerobic; the microorganisms produce methane as a byproduct in these conditions [13]. The current treatment plant in Marcelino Maridueña utilizes one oxidation pond before discharging to the environment.

Activated sludge is a two-step process involving an aeration chamber and a settling chamber. During the first stage, wastewater is introduced into the aeration chamber, which contains a microbial population. Then the air is either diffused using compressed air or introduced through surface agitation. Aeration through compressed air requires electricity inputs but is recommended to prevent anaerobic regions which produce methane. Aeration has two functions: to provide oxygen for the aerobic microbial communities and to provide continued stirring, ensuring microbes are exposed to a steady source of sustenance from the wastewater. Microbes utilize nutrients such as P, N, and NH_4^+ as food, thus removing these harmful parameters from the effluent. The wastewater is then passed to the settling chamber, where the biosolids settle, leaving the effluent mostly free of solids. Activated sludge is made up of these biosolids that are reintroduced from the bottom of the settling tank to continually update the microbial population to ensure proper treatment [14]. These solids must be dredged from the bottom of the settling tank at regular time intervals to prevent overfilling. Activated sludge processes are common in much of the world and are highly effective in tropical regions such as MM.

Microalgal growth is a treatment process that utilizes microbial photosynthetic organisms to convert nutrients, water, and carbon dioxide into biomass while reducing harmful parameters from the effluent. Algae biomass can be utilized as feedstock for producing biodiesel, bio-oil, fertilizer, bioplastic, and biogas. Microalgae need well-controlled inputs such as temperature and light [15]. This can be a good option in tropical regions with more consistent light and dark periods and warm temperatures. Both options can be retrofitted to the existing treatment train and have products that can be sold to offset costs and provide significant additional removal of key nutrient parameters [14]. The proposed option utilizes these recommendations and optimizes the process by using native algae strains selected based on their ability to consume nutrients and fast growth rates [6].

2.3.2 Functional Unit

The functional unit for the LCA analysis will be 1 liter of influent untreated WW, chosen because the bench test of the proposed treatment options operated with three-liter batch reactors for the incoming untreated wastewater for the algal treatment [6].

2.3.3 System Boundary

For this LCA a gate-to- gate approach was followed. This study will provide inputs and outputs only for the treatment processes identified in figure 1. We will not include household management or sewage collection, pipe construction or pumping processes required during treatment. Figure 1 includes the whole wastewater system from generation to discharge for the current and proposed treatment train. The third scenario to be compared: releasing the WW without any treatment, is not shown as a figure.

The proposed scenario was bench tested in the lab by using native algal strains found in Guayaquil, Ecuador. A bench test was chosen as a preliminary step in the development of these novel methods to keep costs down and to determine if scaling up to a pilot plant would be appropriate in the future. The municipality of MM has neither the technology nor the equipment necessary for a pilot plant development. During this case study, the MM WW was transported in a 500 liter container every two weeks and delivered to ESPOL. The removal rates for P, N, and NH_4^+ for these systems were collected and used in the LCA model. The studied parameters are key to determine the effectiveness and suitability of AS systems. Initial and final COD data measure the amount of

organic matter that has been biodegraded. Total ammonia nitrogen (NH_4^+-N + NH_3-N) measures the extent to which organic N has been transformed and oxidized. Total Kjeldahl nitrogen (organic, NH_3 and NH_4^+ nitrogen) assesses the contribution of reduced nitrogen (organic) transformation into NH_4+, nitrate, and NO_3^-. The assessment of these parameters allow to identify the origin of other and external nitrogen sources other than those of sewage nitrogen in effluents, which are already studied and tabulated [16-18]. P is present in treated sewage as $PO4^{3-}$, which together with ammonium and nitrate, in its ionic form, provokes eutrophication of water [19, 20].

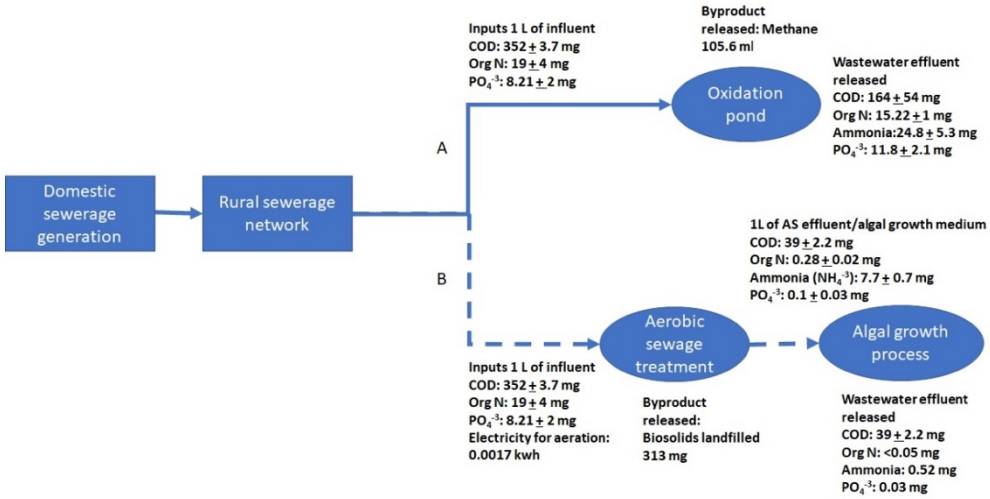

Figure 1. A) Marcelino Maridueña Current Treatment Train B) Proposed Treatment Train

2.3.4 Data Sources

The data collected for the proposed treatment train was collected through a bench-scale laboratory setup [6]. The wastewater influent data reported, which was used for both the proposed treatment train and the current treatment process, is the average the plant registered over five days [6]. The data for the Oxidative Pond treatment was taken from published sources with similar oxidative ponds in tropical regions [21-26]. Two to three primary data sources were used for each of the four parameters tracked through both treatment trains. The removal efficiencies were averaged together to estimate better removal efficiencies for the oxidation pond used by Marcelino Maridueña. Effluent data was not available from the treatment plant in Marcelino Maridueña. Ecuadorian electricity is 79.41% hydropower, 13.13% oil, and the rest is a mixture of gas and renewables [27]. The data is detailed in figure 1 for the current oxidative pond treatment and the proposed treatment train.

2.3.5 Life Cycle Inventory

Table 1. Influent Data for both scenarios

Marcelino Maridueña Influent	Amount (mg)
COD	352+/- 32
Organic Nitrogen	19 +/- 4
Ammonia (TAN)	32+/- 3.7
Phosphorus	8.21+/2

Table 2. Inventory for Marcelino Maridueña Current Situation

Oxidation Pond	Removal % [21]	Removal % [22]	Removal % [23]	Removal % [24]	Removal % [25]	Average Removal Rates %	Output Amount (mg)
COD	67.20	63.16			63.2	64.52	124.89
Organic Nitrogen				7	33.82	20.41	15.22
Ammonia (TAN)	33.69			48	-6.02	25.22	23.93
Phosphorus	41.58		43		-33.4	17.06	6.81
Methane [26]							105.06

This study tracks four parameters across both treatment trains: COD, Organic Nitrogen, NH_4^+, and P; adequate parameters when determining ecotoxicity and eutrophication of receiving bodies of water.

These parameters are also easily and affordably tested for in the effluent and can be potentially used by other municipalities. in the future. Tables 1, 2, and 3 show the inventory of the tracked parameters in each scenario.

3. Results and Discussion

The results from the LCA quantify the impacts on the environment due to each input and output. These quantities are then displayed in graphs to compare the two scenarios.

Figure 2A shows the characterization of each impact indicator, comparing the scenarios to each other in terms of a percentage of impact. It is important because each impact

category is measured using a different unit which would make direct comparison irrelevant. Figure 2B is a normalization of this data, showing the relative impact of each category compared to the scenarios.

The characterization results suggest that the current treatment train has a larger impact on global warming, stratospheric ozone, freshwater eutrophication, marine eutrophication, and human non-carcinogenic indicators. Other indicators were more impacted by the proposed treatment train.

The normalization results show that two categories were impacted most: stratospheric ozone and global warming, and that these impacts are caused by the currently operated treatment plant.

These indicators are most impacted due to the methane released from the oxidation pond. Electricity used to operate the aerators on the proposed treatment train is responsible for that scenario's wide range of impact categories [28].

Table 3. Inventory for proposed bench scale scenario [6]

Aeration process Outputs	Amount (mg)	Percent Removal (%)	Algal process Outputs	Amount (mg)	Percent Removal (%)
COD	39+/-2.2	89	COD	39+/-2.2	X
Organic Nitrogen	0.28+/-0.02	98	Organic Nitrogen	<0.05	99.59
Ammonia (TAN)	7.7+/-0.7	76	Ammonia (TAN)	0.52	98.38
Phosphorus	0.1+/-0.03	99	Phosphorus	0.03	99.63
Electricity (output)	0.0017 kwh				

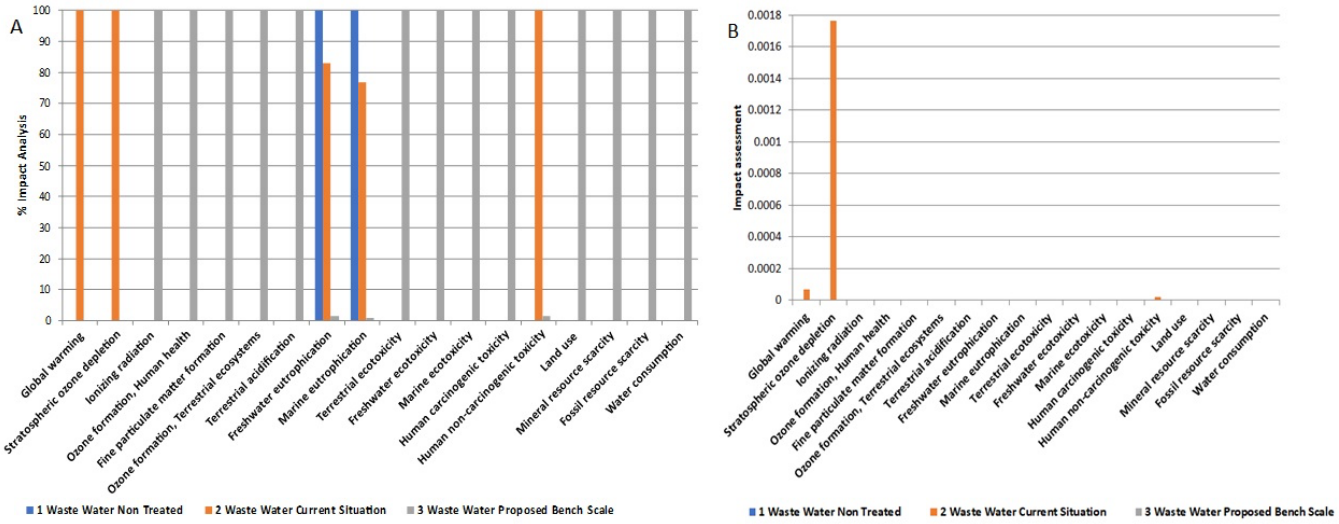

Figure 2. A) Characterization of impact categories comparing 1 kg of: (1) non-treated wastewater, (2) wastewater treated under current system, (3) wastewater treated in the proposed bench scale system. B) Normalization of impact categories comparing 1 kg of: (1) non-treated wastewater, (2) wastewater treated under current system, (3) wastewater treated in the proposed bench scale system.

The normalization graph shows that while the impacts are wide-ranging, they are much smaller in quantity when compared to the impact indicators of methane emissions. The characterization graph shows the relative reduction in nutrients released to the environment by comparing impacts on freshwater and marine eutrophication. in most treatment plants to move water to different systems. Pumping requires electricity but was not included in this study.

Table 4 shows that adopting the hybrid proposed system reduces: Freshwater Eutrophication by 98.09%, Marine Eutrophication by 98.61%, and Human Non-carcinogenic Toxicity by 98.45%.

Results suggest a significant reduction in the ecosystem and human health harm due to adopting the hybrid proposed system. This is especially true when considering the comparison to untreated water. This is due to the decrease in nutrients released to the environment and would help preserve fish populations and improve the livelihoods of people accessing the river resources downstream [2].

Table 4. Total wastewater normalization Impact Categories Comparing Three scenarios.

Impact Category	Non-Treated (NT)	Current Situation (CS)	Proposed Bench Scale (PBS)	(%) Impact Reduction PBS vs. CS / vs NT Wastewater
Global Warming (kg CO2 eq)	X	7.07E-05	2.06E-08	99.97
Stratospheric Ozone Depletion (Kg CFC11 eq)	X	1.76E-03	1.82E-08	99.99
Freshwater Eutrophication (kg P eq)	4.17E-06	3.46E-06	6.60E-08	98.09 / 98.42
Marine Eutrophication (kg N eq)	2.92E-06	2.24E-06	3.12E-08	98.61 / 98.93
Human Non-carcinogenic Toxicity (Kg 1,4-DCB)	X	2.36E-05	3.66E-07	98.45

This study serves as a model for under-resourced municipalities that need a low-cost tool (LCA) to compare emission reductions to diverse types of treatments and determine the most suitable upgrades for each individual case.

4. Conclusions

The results from this study show that improvements in the reduction of nutrients and methane emissions are more beneficial than potential emissions from increased electricity usage in the proposed plant. Furthermore, indicates a net benefit to retrofitting the existing infrastructure to include the proposed treatment plan.

However, it was difficult to find studies analyzing all the relevant parameters included in this study, which novelty lies in that the data included encompasses a broader range of indicators and therefore provides a complete picture of the impacts of each scenario.

References

[1] Wingfield, S., Martínez-Moscoso, A., Quiroga, D., & Ochoa-Herrera, V. (2021). Challenges to water management in Ecuador: Legal authorization, quality parameters, and socio-political responses. Water, 13(8), 1017. https://doi.org/10.3390/w13081017

[2] Ullah Bhat, S., & Qayoom, U. (2022). Implications of sewage discharge on freshwater ecosystems. Sewage - Recent Advances, New Perspectives and Applications. https://doi.org/10.5772/intechopen.100770

[3] Gómez Ávila, L. A. (2020, November 18). VINDOBONA PROJECT Executive Summary EPMAPS Agua de Quito. agua quito. Retrieved from https://www.aguaquito.gob.ec/wp-content/uploads/2021/01/Executive-Summary-Vindobona-18-11-2020.pdf

[4] Fay , M., Andres, L. A., Fox, C., Narloch, U., Straub , S., & Slawson, M. (2017). (rep.). Rethinking Infrastructure in Latin America and the Caribbean Spending Better to Achieve More. International Bank for Reconstruction and Development / The World Bank. Retrieved 2022, https://documents1.worldbank.org/curated/en/676711491563967405/pdf/114110-REVISED-Rethinking-Infrastructure-Low-Res.pdf.

[5] Environmental Protection Agency. (n.d.). Small and Rural Wastewater Systems. EPA. Retrieved January 22, 2023, https://www.epa.gov/small-and-rural-wastewater-systems

[6] Mendoza, L., Aray-Andrade, M. M., Bermudez, R., Amaya, J., Zhang, L., & Moreira, C. (2019). Influence of volumetric loading rate on aerobic sewage treatment for indigenous algal growth. Water Science & Technology, 80.7. https://doi.org/doi: 10.2166/wst.2019.377

[7] Steinmann, C. R., Weinhart, S., & Melzer, A. (2003). A combined system of lagoon and constructed wetland for an effective wastewater treatment. *Water Research*, *37*(9), 2035–2042.

[8] Barjenbruch, M., & Erler, C. (2005). A performance review of small German wsps identifying improvement options. *Water Science and Technology*, *51*(12), 43–49. https://doi.org/10.2166/wst.2005.0423

[9] Ghazy, M. M., El-Senousy, W. M., Abdel-Aatt, A. M., & Kamel, M. (2008). Performance evaluation of a waste stabilization pond in a rural area in Egypt. *American Journal of Environmental Sciences*, *4*(4), 316–325. https://doi.org/10.3844/ajessp.2008.316.325

[10] Corominas, L., Byrne, D. M., Guest, J. S., Hospido, A., Roux, P., Shaw, A., & Short, M. D. (2020). The application of Life Cycle Assessment (LCA) to wastewater treatment: A best practice guide and critical review. Water Research, 184, 116058.

[11] Sakao, T., Neramballi, A., Matschewsky, J., Carlson, A., Bäck, M., & Tirumalasetty, V. T. (2022). Systemic Improvement of Lifecycle Performance by leveraging product and service interdependencies – a case of a product for wind power generation systems. *CIRP Annals*, *71*(1), 9–12. https://doi.org/10.1016/j.cirp.2022.04.052

[12] Jiang, Y., Dinar, A., & Hellegers, P. (2018). Economics of social trade-off: Balancing wastewater treatment cost and ecosystem damage. *Journal of Environmental Management*, *211*, 42–52. https://doi.org/10.1016/j.jenvman.2018.01.047

[13] Butler, E., Hung, Y.-T., Suleiman Al Ahmad, M., Yeh, R. Y.-L., Liu, R. L.-H., & Fu, Y.-P. (2015). Oxidation pond for municipal wastewater treatment. Applied Water Science, 7(1), 31–51.

[14] Scholz, M. (2016). Activated sludge processes. Wetlands for Water Pollution Control, 91–105.

[15] Chen, S., Xie, J., & Wen, Z. (2021). Microalgae-based wastewater treatment and utilization of microalgae biomass. Advances in Bioenergy, 165–198. https://doi.org/10.1016/bs.aibe.2021.05.002

[16] Salim Dantas, M., Rodrigues Barroso, G., & Corrêa Oliveira, S. (2021). Performance of sewage treatment plants and impact of effluent discharge on receiving water quality within an urbanized area. *Environmental Monitoring and Assessment*, *193*(5).

[17] Qteishat, O., Myszograj, S., & Suchowska-Kisielewicz, M. (2011). Changes of wastewater characteristic during transport in sewers. *WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT*, *7*(11), 349–358.

[18] Al-Mamun, A., Jafary, T., Baawain, M. S., Rahman, S., Choudhury, M. R., Tabatabaei, M., & Lam, S. S. (2020). Energy recovery and carbon/nitrogen removal from sewage and contaminated groundwater in a coupled hydrolytic-acidogenic sequencing batch reactor and denitrifying biocathode microbial fuel cell. *Environmental Research*, *183*, 109273. https://doi.org/10.1016/j.envres.2020.109273

[19] Yaakob, M. A., Mohamed, R. M., Al-Gheethi, A., Aswathnarayana Gokare, R., & Ambati, R. R. (2021). Influence of nitrogen and phosphorus on microalgal growth, biomass, lipid, and fatty acid production: An overview. *Cells*, *10*(2), 393.

[20] Al-Sahari, M., Al-Gheethi, A., Radin Mohamed, R. M., Noman, E., Naushad, M., Rizuan, M. B., Vo, D.-V. N., & Ismail, N. (2021). Green Approach and strategies for wastewater treatment using BIOELECTROCHEMICAL systems: A critical review of fundamental concepts, applications, mechanism, and future trends. *Chemosphere*, *285*, 131373. https://doi.org/10.1016/j.chemosphere.2021.131373

[21] El Hamouri, B., Rami, A., & Vasel, J.-L. (2003, July 1). The reasons behind the performance superiority of a high rate algal pond over three facultative ponds in series. Water Science and Technology. Retrieved November 17, 2022, from https://doi.org/10.2166/wst.2003.0130

[22] Ali, A. E., Salem, W. M., Younes, S. M., & Kaid, M. (2020). Modeling climatic effect on physiochemical parameters and microorganisms of Stabilization Pond Performance. Heliyon, 6(5).

[23] García, J., Hernández-Mariné, M., & Mujeriego, R. (2004). Analysis of key variables controlling phosphorus removal in high rate oxidation ponds provided with clarifiers. Water SA, 28(1), 55. https://doi.org/10.4314/wsa.v28i1.4868

[24] Yeh, T. Y., Pan, C. T., Ke, T. Y., & Kuo, T. W. (2010). Organic matter and nitrogen removal within field-scale constructed wetlands: Reduction performance and microbial identification studies. Water Environment Research, 82(1), 27–33. https://doi.org/10.2175/106143009x447957

[25] Abdel-Shafy, H. I., & Salem, M. A. (n.d.). Efficiency of oxidation ponds for wastewater treatment in Egypt. Wastewater Reuse–Risk Assessment, Decision-Making and Environmental Security, 175–184.

[26] Paredes, M. G., Güereca, L. P., Molina, L. T., & Noyola, A. (2015). Methane emissions from Stabilization Ponds for municipal wastewater treatment in Mexico. Journal of Integrative Environmental Sciences, 12(sup1), 139–153. https://doi.org/10.1080/1943815x.2015.1110185

[27] Ritchie, H., Roser, M., & Rosado, P. (2022, October 27). Ecuador: Energy country profile. Our World in Data. Retrieved November 12, 2022, from https://ourworldindata.org/energy/country/ecuador

[28] Ramirez, A. D., Boero, A., Rivela, B., Melendres, A. M., Espinoza, S., & Salas, D. A. (2020). Life cycle methods to analyze the environmental sustainability of electricity generation in Ecuador: Is decarbonization the right path? Renewable and Sustainable Energy Reviews, 134, 110373.