Preliminary analysis of pollutants removal efficiency of a rural wastewater treatment system based on anaerobic processes coupled with a constructed wetland

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Resumen

La sobreexplotación de las aguas subterráneas y la contaminación gradual de las aguas superficiales ha generado baja disponibilidad del recurso "agua". Los humedales construidos son sistemas de tratamiento de aguas residuales; considerados de bajo costo y mantenimiento, y que permiten una alta remoción de contaminantes en combinación con reactores anaerobios para considerar el posterior reúso del agua tratada. La planta de tratamiento de aguas residuales (PTAR) Atequizayán, localizada en el municipio de Zapotlán el Grande, Jalisco, cuenta con un tanque séptico (TS), un filtro anaerobio de flujo ascendente (FAFA) y un humedal horizontal de flujo subsuperficial (HHFSS). El objetivo del presente proyecto es evaluar la eficiencia de remoción de contaminantes de la PTAR Atequizayán, así como verificar la posibilidad de reusar el agua tratada para riego de zonas de cultivo. Las mejores tasas de remoción obtenidas durante las campañas de monitoreo fueron de 99.99% de Escherichia coli, 99% de sólidos suspendidos totales (SST), 96% de grasas y aceites, 90% de demanda biológica de oxígeno (DBO), 89% de demanda química de oxígeno (DQO) y 38% de nitrógeno total Kjeldahl (NTK). En el caso de fósforo total (PT) se alcanzó un nivel máximo de remoción de 87%. Las mejores tasas de remoción de contaminantes para los reactores anaerobios, TS+FAFA previos al HHFSS, fue de 98% de SST, 84% de DBO y 86% de DQO. Las altas eficiencias en remoción de contaminantes, así como los bajos costos de operación y mantenimiento, de este tipo de PTAR, hace que sean una opción viable para el tratamiento en comunidades rurales de México. Además de la posibilidad del reúso del agua tratada por su calidad satisfactoria.

Palabras clave—Humedales construidos, eficiencia remoción de contaminantes, reactores anaerobios, reúso de agua tratada, tratamiento de aguas residuales.

Abstract

The overexploitation of groundwater and the gradual contamination of surface water have generated low availability of the resource "water". Constructed wetlands are wastewater treatment systems; considered low cost and maintenance, and that allow a high removal of contaminants in combination with anaerobic reactors to consider the subsequent reuse of treated water. The Atequizayán wastewater treatment plant (WWTP), located in the municipality of Zapotlán el Grande, Jalisco, has a septic tank (ST), an upflow anaerobic filter (UAF) and a horizontal subsurface flow constructed wetland (HSSF). The objective of this project is to evaluate the pollutants removal efficiency of the Atequizayan WWTP, and verify, possible use of treated water in irrigation of cultivation areas. The best removal rates during the monitoring campaigns were 99.99% Escherichia coli, 99% total suspended solids (TSS), 96% fats and oils, 90% biological oxygen demand (BOD), 89% chemical oxygen demand (COD) and 38% total Kjeldahl nitrogen (TKN). In the case of total phosphorus (TP), a maximum removal level of 87% was achieved. The best contaminant removal rates for anaerobic reactors, ST+UAF prior to the HSSF, were 98% TSS, 84% BOD and 86% COD. The high efficiencies in pollutant removal, as well as the low operation and maintenance costs, of this type of WWTP´s, make them a viable option for rural communities in Mexico, that normally do not have wastewater sanitation system. In addition, there is the possibility of reusing the treated water.

Keywords*— Anaerobic reactors, constructed wetlands, pollutants removal efficiency, treated water reuse, wastewater treatment.*

1. INTRODUCTION

The pressure that has been exerted on water resources in recent years is well known worldwide. In Mexico only 68% of the aquifers are in availability conditions, which mean the groundwater that can be concessioned to be withdrawn from a hydrogeological unit or aquifer for several uses, in addition to the extraction already under concession and the compromised natural discharge, without endangering the balance of ecosystems [1], revealing the worrying overexploitation state of groundwater resources in the country. In the case of rivers, lakes, and dams, the level of contamination is generating, low availability of water and a decrease in the environmental services that they provide.

There is a lag in wastewater sanitation at national level (67.2% of wastewater is formally treated) [2]. In Mexico, many sanitation facilities have been abandoned or are out of operation mainly due to high operation (predominantly electricity), and maintenance costs that cannot be covered by low-income communities and municipalities aggravated by limited tax collection causing release of untreated water and contamination of water bodies nationwide [3].

Several studies have shown that combining anaerobic reactors and constructed wetlands perform a satisfactory treatment of domestic sewage. Chernicharo [4] mentioned removal efficiencies of 75-85% of organic matter as BOD in anaerobic systems integrated by a ST followed by an anaerobic filter, treating domestic sewage. Merino-Solís et al. [5] reported for a system integrated by UAF and a HSSF, removal efficiencies of 80-90% of BOD, 80-86% of COD, 33% of total nitrogen (TN) and 24% to 44% of TP. These authors reported the preferential removal of 80% of organic matter in the UAF, with a hydraulic retention time (HRT) of 18 hours, while the removal of nutrients was favored in the constructed wetland eliminating 30% of TN with a HRT of 3 days. De Anda et al. [6], reported removal efficiencies of 98.2% of BOD, 97.2% of COD, 95.6% of TSS, 48.9% of TN, 48.6% of TP and 99.96% of total coliforms in a ST, UAF and HSSF treatment system. Saeed et al. [7] reported 99% BOD removal, 99% of COD, 92% of TSS, 95% of TN, 97% of ammoniacal nitrogen (NH_4^+-N), 100% of TP and 99.9% of Escherichia coli. Fernández del Castillo et al. [8], summarized average removal of 95.2% of BOD, 91.3% of COD, 92.8% of TSS, 69.8% of TN, and 61.75% of TP from reports of UAF and HSSF systems. In these literature reports, the effluent quality complied with the Mexican regulation for reuse of treated wastewater, demonstrating the potential to reduce the pressure on water resources [9] and attenuate the environmental impact by anaerobic reactors coupled to constructed wetlands.

It has been demonstrated that wastewater treatment systems based on anaerobic processes coupled with constructed wetlands release satisfactory quality treated water. Some advantages of integrated constructed wetlands are: they produce a minimal amount of sludge and the energy consumption is minimal compared with conventional wastewater treatment such as activated sludge, besides wetlands also generate important environmental services, such as habitats for various animal species, as well as recreational benefits [6] [9] [10].

Therefore, it is relevant to continue evaluating UAF-HSSF systems treating domestic sewage, particularly in real suburban or rural application, to better characterize the efficiency and specific characteristics in real applications.

The aim of this study was to evaluate the evolution of domestic sewage treatment in a rural location in Jalisco, Mexico from start-up, comparing the quality of treated wastewater with the Mexican regulation for reuse in agricultural irrigation. According to our knowledge this is one of the first evaluations of the efficiency of wastewater treatment, based on anaerobic processes and artificial wetlands at a community scale, which will provide useful data to analyze the convenience of promoting this technology in Mexico.

2. CONTENT

2.1. MATERIALS AND METHODS

The system evaluated in this project was built to treat municipal wastewater from Atequizayán, municipality of Zapotlán el Grande, Jalisco Mexico (Figures 1, 2). This system is based on the technology called “System and modular process for the passive treatment of domestic wastewater” patent MX 342095 B [11]. The rural WWTP, was designed to provide sanitation services to a population of 800 inhabitants, considering an average potable consumption of 200 l/person/day, which represents a wastewater flow of 1.85 l/s and 586 PE (PE=population equivalent=60 g BOD/d) [12].

Figure 1. Aerial view of Atequizayán WWTP.

Figure 2. Lateral view of horizontal subsurface flow constructed wetland (HSSF).

The treatment system has seven operational units; receiving tank, sump pump, septic tank, upflow anaerobic filter, constructed wetland, level tank and disinfection chamber -with a 136 Watts ultraviolet lamp- (Figure 3). Three monitoring campaigns were carried out on June 9 (M1), August 18 (M2) and September 22 (M3) 2022, all of them taken in rainy season.

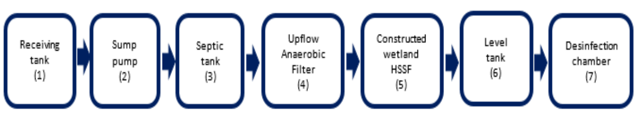

Figure 3. Operational units Atequizayán WWTP.

The sampling was made at the receiving tank (ATE-TR), and at the inlet and outlet of the constructed wetland (ATE-WLE, ATE WLS) (Figure 4). The samples were analyzed according to the Mexican regulation NOM-001-SEMARNAT-2021 (NOM-001) [13]. The samples were maintained at 4 ºC before its use.

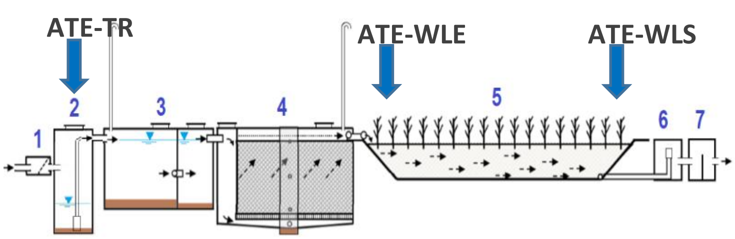

Figure 4. Atequizayán WWTP diagram, the sampling points are marked with blue arrows. Adapted from Mijangos et al. (2020) [14].

The removal percentage was calculated from the inlet and outlet concentration of each parameter. The results of treated water quality in the effluent of Atequizayán WWTP were compared with the Mexican norm NOM-001-SEMARNAT-2021 [13] which establishes the permissible limits of pollutants in wastewater discharges in receiving bodies owned by the nation. In this project we considered the standard indicated by NOM-001 for treated water quality for discharges to the ground, including reuse for agriculture irrigation, through the measured instantaneous values (I.V.). The parameters TN and TP does not apply for discharge to soil -infiltration and other risk- however TKN and TP were included [13]. The analytical methods were: Temperature (NMX-AA-007-SCFI-2013), pH (NMX-AA-029-SCFI-2011), TSS (NMX-AA-034-SCFI-2015), fats and oils (NMX-AA-005-SCFI-2013), COD (NMX-AA-030/1-SCFI-2012), Escherichia coli (NOM-210-SSA1-2014 appendix H), helminth eggs (NMX-AA-003-1980), TKN (NMX-AA-026-SCFI-2010) and TP (NMX-AA-029-SCFI-2001).

Temperature, pH, and electrical conductivity were measured on site by triplicate utilizing a multiparametric probe (YSI Multiparameter Water Quality Sonde -6600 V2).

2.2. RESULTS AND DISCUSSIONS

The measurements of electrical conductivity and monitored parameters during campaigns M1, M2 and M3 are shown on Tables 1 and 2.

Table 1. Conductivity at ATE-WLS in M1, M2 and M3

Parameter	Unit	M1	M2	M3
		ATE-WLS1	ATE-WLS2	ATE-WLS3
		Average and SD		
Electric conductivity	dS m^{-1}	1.36 ± 0.001	0.67 ± 0.049	1 ± 0.003

SD: Standard deviation.

Table 2. Quality of wastewater by monitored stage, removal and compliance with NOM-001-SEMARNAT-2021.

WWTP ATEQUIZAYAN		M1 June 2022				M2 August 2022				M3 September 2022				Normative compliance	
Parameter	Unit	ATE-TR1	ATE-WLE1	ATE-WLS1	Pollutans removal %	ATE-TR2	ATE-WLE2	ATE-WLS2	Pollutans removal %	ATE-TR3	ATE-WLE3	ATE-WLS3	Pollutans removal %	Soil (Infiltration and others) I.V.	Compliance level
pH	-	6.7	6.7	7.4	NA	6.2	6.9	7.2	NA	6.8	6.8	7.1	NA	6.0 - 9.0	√
Temperature	°C	24.4	24.2	22.2	NA	23.1	23.7	24.3	NA	21.9	22	20.1	NA	35	√
Settleable Solids*	ml l^{-1}	5	<0.5	<0.5	90%	35	<0.5	<0.5	99%	3	<0.5	<0.5	83%	140	√
Total Suspended Solids	mg l^{-1}	323.6	52.5	10.6	97%	1750	26.2	10	99%	347.5	42.3	10.2	97%	140	√
Fats and oils	mg l^{-1}	11.4	4.1	6.4	44%	207.2	10.8	9	96%	70	15	4.8	93%	21	√
Biological Oxygen Demand*	mg l^{-1}	18.2	24.3	12.1	33%	158	24.3	16.2	90%	60.7	15.2	9.1	85%	NA	NA
Chemical Oxygen Demand	mg l^{-1}	39.6	43.7	28.7	28%	311.6	41.9	33.5	89%	117	31.2	18.7	84%	210	√
Amoniacal Nitrogen*	mg l^{-1}	9	11.3	11.6	-29%	86.9	66.8	58.2	33%	61.2	54.1	47	23%	NA	NA
Total Nitrogen Kjendahl	mg l^{-1}	10.1	13.1	13.6	-34%	226	142.1	139.4	38%	158	138.8	105	34%	NA	NA
Total Phosphorus	mg l^{-1}	7.5	1.5	<1	87%	<1	<1	<1	NR	7.5	2.1	1.6	78%	NA	NA
Fecal Coliforms*	MPN/100ml	$92x10^6$	$33x10^5$	$13x10^5$	99%	$92x10^7$	$54x10^3$	$23x10^4$	99.98%	$17x10^6$	$24x10^6$	$54x10^4$	96.8%	NA	NA
Escherichia coli	MPN/100ml	-	-	-	-	$92x10^7$	$1,5x10^2$	$45x10^3$	99.99%	$17x10^6$	$24x10^6$	$54x10^4$	96.8%	600	●
Helminth Eggs	e/l	-	-	-	-	<1	-	<1	NR	-	-	-	-	1	√

NA: Not apply or it is not regulated, NR: No removal reported, -: There is no data, √: Compliance, ●: No compliance, I.V.: Instantaneous value, °C: Celsius degrees, mg l^{-1}: milligram per liter, ml l^{-1}: milliliter per liter, MPN/100 ml: Most probable number per 100 milliliters, el: eggs per liter. *: These parameters are not included in NOM-001-SEMARNAT-2021.

According to CONAGUA, the typical BOD content in domestic sewage is 400, 220 and 110 mg l^{-1}, for water with high, medium, and low concentration of organic matter, respectively [15]. In this study, the influent BOD in M1 was 18.2 mg l^{-1}, which is an atypical value that was attributed to the dilution effect of sewage in the rain season.

In addition, we can observe that the TKN values, in M2 and M3 of 226 and 158 mg l^{-1}, respectively, are also comparatively atypical to what is indicated by CONAGUA [15], which establishes as typical values for water with high, medium and low concentrations 85, 40 and 20 mg l^{-1} of TN. If we obtained the TN corresponding to TKN of M2 and M3, these values are expected to be even higher, because the fraction of nitrites and nitrates must be added, so it can be stated that the TKN values of M2 and M3 are atypical. This suggests that due to the dilution effect of rains, evident from the low BOD values in M2 (158 mg l^{-1}) and M3 (60.7 mg l^{-1}), the same runoff of rainwater passed from crop fields close to the WWTP, and carries excess of fertilizers which caused the high level of TKN in M2 and M3.

In the first sampling (M1), removal percentages were settleable solids (SS) 90%, TSS 97%, fats and oil 44%, BOD 33%, COD 28%, TP 87%, and fecal coliforms 99%. However, ammoniacal nitrogen, increased by 29% going from 9 to 11.6 mg l^{-1}, at the effluent and also TKN increased by 34% from 10.1 to 13.6 mg l^{-1}. The satisfactory removal of SS, SST and fecal coliforms, are similar to the results obtained by de Anda et al., [6] in treatment systems with similar characteristics. Nonetheless, the comparatively lower removal of BOD, COD, fats and oils, and NH_4^+-N and TKN increase were related to the performance settling of the Atequizayán WWTP just 12 months after start-up. In the case of TP, a greater removal was obtained in M1 compared with the removal registered by de Anda et al. [6] (87% vs. 48.6%).

The results of the removal contaminants in M2 improved considerably with respect to M1, and removal close to 100% were obtained for fecal coliforms and Escherichia coli (99.98 and 99.99 respectively), while SS and SST were both removed by 99%, reduction of 96% of fats and oils, 90% BOD, 89% COD, 33% NH_4^+-N, and 38% for TKN were also achieved. These results are in accordance with the removal efficiencies reported by Merino et al. [5] and de Anda et al. [6]. For M3 monitoring, some contaminants removals were lower compared with M2 monitoring, getting 96.8% removal of fecal coliforms 96.8% Escherichia coli, 97% SST, 83% SS, 93% fats and oils, 85% BOD, 84% COD, 23% NH_4^+-N, 34% TKN and TP 78.02% removal.

The low BOD and COD removals in M1 can be attributed to the low amount of organic matter in the influent and the high phosphorus removal in M1 and M3 can be attributed to the good adsorption capacity of the UAF and HSSF packing material (volcanic rocks) [12] [16], given that the system is still in its stabilization phase after having started its operation, a year ago.

The increase in TKN through the TS+UAF in sampling M1, from 10.1 to 13.1 mg l^{-1}, was probably obtained due to the ammonification taking place in anaerobic reactors, where nitrogenous organic molecules such as proteins are reduced to ammonium. This behavior was also reported by Caixeta et al. [17] and Fernández del Castillo et al. [8].

Denitrification processes require a suitable source and concentration of organic carbon to supply the denitrifying microorganisms [18] besides anoxic conditions. In the M1 monitoring campaign TKN removal was not achieved, however, in M2 and M3 removal of 38% and 34% was achieved, respectively. Anaerobic reactors as ST and UAF, are efficient in removing organic matter, in addition, HRT greater than 12 hours [19] also generate low rates of denitrification since both factors; high removal of the previous anaerobic reactors and high HRT achieve high removals of organic matter, which lowers the amount of carbon necessary for nitrogen removal to be achieved. In M2 and M3 the sufficient organic matter plus the anaerobic conditions in ST and UAF influenced TKN removals.

The disinfection of the effluent of Atequizayan WWTP, were carried out by means of an ultraviolet lamp (UV lamp), the efficiency of the disinfection was verified in monitoring (M3), since the UV lamp had already been in operation for a year. Pathogens removal was not found, due to the fact that the values for the sampling point at the exit of the wetland (ATE-WLS) was $54x10^4$ MPN/100 ml, same for fecal coliforms and Escherichia coli. These values remained unchanged in the discharge from the WWTP, after passing through the disinfection chamber, thus verifying that the equipment (UV lamp) was not performing its function. Recently it was installed a chlorination system with calcium hypochlorite tables, however it is necessary to verify in further research, if the disinfection is being carried out.

The comparison between the results obtained in the three monitoring campaigns M1, M2 and M3 with NOM-001-SEMARNAT-2021 showed compliance in terms of pH, temperature, TSS, COD, fats and oils and helminth eggs (only monitored in M2), and a suitable quality for soil infiltration and others, with the exception of Escherichia coli. Therefore, the effective disinfection of the treated wastewater must be ensured before its use in crops or orchards irrigation.

The reuse of Atequizayán WWTP treated water in agricultural activities is feasible if microbiologic quality is assured. This is relevant for the point of use due to proximity to cultivated fields, specifically we can find avocado orchards (*Persea americana*) near to the WWTP. Recent studies have found that avocado trees are sensitive to salinity, showing affectations when they are irrigated with treated water with electrical conductivity (EC) of 1.5 dS m^{-1} [20]. Due to the EC range of the treated water of Atequizayán WWTP, ranges from 0.67 to 1.36 dS m^{-1}, the recommendation is to mix water 1:1, well water or first-use water with treated water [21], to avoid affectations to the soil and avocado trees.

3. CONCLUSIONS AND RECOMMENDATIONS

The Atequizayán WWTP showed satisfactory pollutant removal, the system is robust and efficient. The highest level of contaminant removal was obtained during M2 monitoring, which was 99.99% removal of *Escherichia coli*, 99% TSS, 96% fats and oils, 90% BOD, 89% COD and 38% of TKN. In monitoring M3, removal of 87% of TP was achieved. According to data from the second M2 monitoring, it was obtained that ST+UAF achieves removal of 98% of TSS, 84% of BOD and 86% of COD. It is important to mention that the system is still in the stabilization phase, which is evident especially in the first monitoring M1, it is expected that once the process is stabilized, more consistent efficiencies will be obtained on a daily basis.

The treated water form Atequizayán WWTP comply with permissible limits of the parameters pH, temperature, TSS, COD, fats and oils and helminth eggs (this only monitored in M2) indicated in NOM-001-SEMARNAT-2021, for soil infiltration and others (I.V.), except for Escherichia coli. Therefore, the effective disinfection of the treated wastewater must be ensured before the reuse in crops or orchards irrigation.

It is possible to reuse the treated water from Atequizayán WWTP, it is necessary to ensure the disinfection and verify the salinity tolerance of the crop that wanted to be irrigated.

Especially those crops or trees with moderate tolerance to salinity in a range of 0.7 to 3 dS m^{-1}. In the case of avocado orchards (*Persea americana*) as trees are sensitive to salinity (damages at 1.5 dS m^{-1}), it is recommended to irrigate in a 1:1 ratio (fresh water: treated water).

It is possible to integrate constructed wetland as an operational unit in WWTP with anaerobic processes such ST and UAF in order to achieve a suitable quality in the water discharge.

We consider it is necessary to carry out further research regarding the efficiency of contaminant removal that covers a longer sampling time, and that includes all the parameters of NOM-001-SEMARNAT-2021.

3.1. General observations

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