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Domestic wastewater treatment in the Santiaguito neighborhood wetland, Texcoco de Mora, Mexico

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Abstract

Physical, chemical or biological methods can be used for wastewater treatment. Artificial wetlands are systems specifically constructed for wastewater treatment, creating functions similar to those of natural wetlands, optimizing the processes for pollutant removal. The objective of this work was to determine the efficiency of the Santiaguito neighborhood wetland in Texcoco de Mora, Mexico, as well as the quality of the treated wastewater according to the indicators established by NOM-001-SEMARNAT-2021 and NOM-003-SEMARNAT-1997, with the aim of proposing measures to improve treatment processes. Removal efficiencies were obtained of 100 % for total (TC) and fecal coliforms (FC), 57.7 % for Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD_5), 98.47 % for settleable solids (SS), and 60.25 % for total nitrogen, but only 22.92 % for total suspended solids (TSS). Therefore, it was concluded that there are restrictions on the use of this treated wastewater due to its TSS level. The treatment process can be improved by reducing the number of plant species present and pruning them periodically, by cleaning or changing the filtering substrate and by monitoring the efficiency of the wastewater treatment through sampling at different times and seasons of the year.

Keywords: Fecal coliforms, constructed wetlands, Chemical Oxygen Demand, pollutants, water quality.

Introduction

According to CONAGUA (2022), in 2021, 215.4 $m^3 \cdot s^{-1}$ of domestic wastewater were collected but only 145.3 $m^3 \cdot s^{-1}$ received treatment in 2 872 plants, which means that only 67 % receives some treatment before being discharged into rivers, seas and soil. According to Arellano-García (2022), Mexico generates 312 000 $L \cdot s^{-1}$ or 312 $m^3 \cdot s^{-1}$ of wastewater, which is composed of 99.9 % water and 0.1 % solids, representing 31.2 $m^3 \cdot s^{-1}$ of solids with polluting potential. Hence, wastewater treatment is based on the reduction of organic and mineral materials, either dissolved or in suspension. Treatment processes are classified into three levels: 1) primary, to eliminate particles that due to their size (larger than 0.1 mm) can obstruct subsequent processes; 2) secondary, to reduce impurities of much smaller size (colloidal and dissolved organic materials) with combined mechanical and biological methods; 3) tertiary, to remove dissolved materials such as gases, natural and synthetic organic substances, ions, bacteria and viruses, through the combination of biological, physical and chemical processes (Bucio, Pérez and Cervantes, 2018).

Most treatment plants have high costs, both for construction and operation and maintenance, in addition to requiring high energy consumption; therefore, in small or rural com-

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munities, wastewater is discharged in an open-air manner or into lakes, lagoons, rivers, or the sea (Vidal-Álvarez, 2018). A wetland is a permanent or temporary shallow body of water (Richardson et al., 2022). Wetlands occur due to the presence of stagnant or very slowly flowing water. The shallow depth enables the development of vegetation, either hydrophytic or phreatophytic, even during periods of prolonged drought (Rodrigues et al., 2021). Wetlands are often referred to as the kidneys of the Earth and maintain functions such as sustaining ecological balance, maintaining biodiversity, conserving water, preventing drought, regulating climate and degrading pollution (Zhu et al., 2023).

A constructed wetland is an organic wastewater treatment system that mimics and enhances the effectiveness of processes that help purify water similar to natural wetlands. The system uses aquatic plants, natural microorganisms, and a filter bed (Hota et al., 2023; Kharwade et al., 2021). The use of artificial wetlands can be broad and includes the removal of any waste that is discharged into aquatic ecosystems (Maldonado and Balagurusamy, 2022; Zhang et al., 2023). These systems do not require electrical power or expensive equipment for their operation and, because they are natural systems, their maintenance costs (Salah et al., 2023) are lower than those of any conventional system, making them an option for small communities and rural areas (Hota et al., 2023).

Constructed wetlands have become important for waste treatment, as they are designed to utilize natural processes involving vegetation, soils, and their associated microbial assemblages to achieve pollutant removal (Salah et al., 2023). According to Hota et al. (2023), in a constructed wetland, the combination of substrates, microbes and plants occurs so that the system functions as a filter and purifier. To achieve sedimentation of solids, wastewater flux is slowed down as it enters the wetland. Plant roots and wetland substrate filter out the larger wastewater particles as the water moves over them. Subsequently, bacteria and plants naturally break down and absorb pollutants and nutrients present in the wastewater, removing them. Pathogens present in the wastewater are also removed by ultraviolet radiation, antibiotics secreted by plants and bacteria, and the duration of retention in the wetland, which varies depending on the design and desired level of quality. The water can be safely discharged into surface waterways or used for a variety of purposes after being treated. Constructed wetlands remove some antibiotics such as triclosan (100 %), enrofloxacin (99.8 %), metronidazole (99 %), tetracycline (98.8 %), chlortetracycline (98.4 %), levofloxacin (96.69 %), and sulfamethoxazole (91.9 %), among others, according to Ohore et al. (2022).

This work was focused on the treatment of domestic wastewater generated by the Santiaguito neighborhood in Texcoco de Mora, Mexico. Wastewater has been the result of a combination of various human activities such as kitchen water and sewage, with a highly variable composition. This neighborhood, located in the municipality of Texcoco de Mora, Mexico, with a population of 1,200 inhabitants and an area of 139 ha, faced the problem of wastewater generation. This highlighted the need to treat wastewater, with the aim of producing clean, reusable water and reducing the damage that was being caused to the health of the population. The reuse of wastewater from the Santiaguito neighborhood allowed the creation of green areas in the community, as well as conduction to the water collection channels. This work aimed to determine the quality of the wastewater at the inlet and outlet of the wetland, in order to evaluate the efficiency of pollutant removal and propose measures to improve the treatment system.

Materials and Methods

Study area

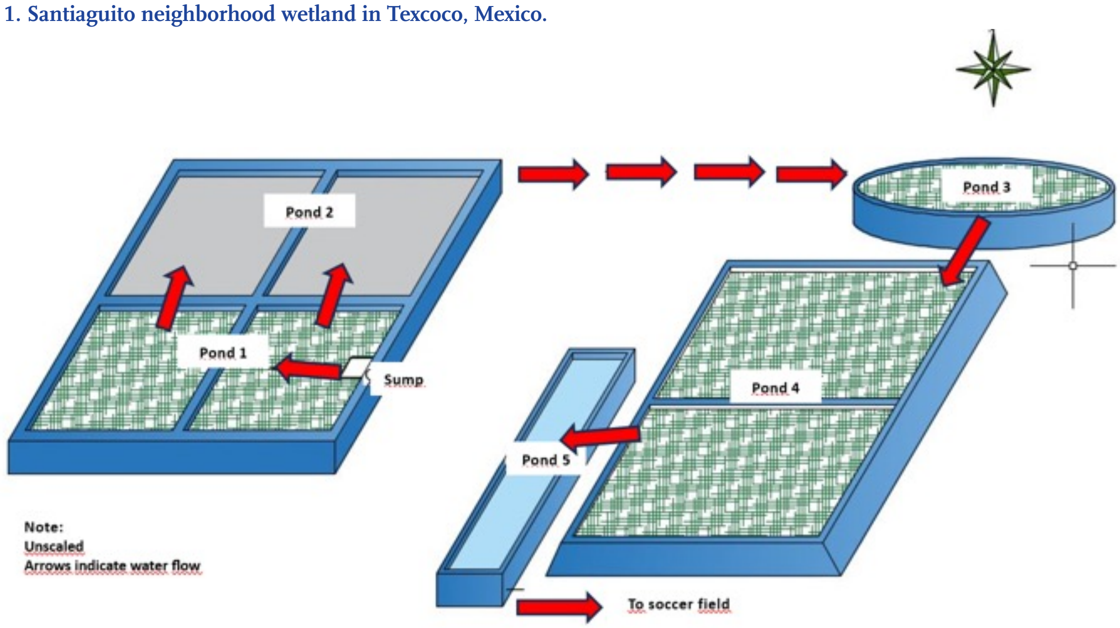
The Santiaguito neighborhood is located within the municipality of Texcoco de Mora, State of Mexico, at coordinates 19° 31´ 25.88” N and 98° 52´ 17.29” W. To the north it borders the community of San Simón, to the south Alameda Texcoco, to the west the community of Tulantongo, and to the east the community of La Resurrección, at an elevation of 2,258 meters above sea level.

The wetland consists of five interconnected ponds, so that water flows by gravity in a single direction (Figure 1) Each pond has two compartments, one with coarse filter material and a second with filter material of smaller granulometry, so that the movement of water from one pond to another is horizontal and at a surface level, while from one compartment to another it is subsurface and vertical. Wastewater from the homes and businesses of the Santiaguito neighborhood is concentrated in a sump and, through a water filter grid that acts as a solid retainer, flows into Pond 1, which functions as an anaerobic biodigester with *Eichhornia crassipes* aquatic plants. From there, it flows into Pond 2, whose two compartments, filled with tezontle of different granulometries, are separated by a wall with lower holes that allow the upward movement of the water. The water then flows into Pond 3, planted with *Zantedeschia aethiopica* L., *Scirpus holoschoenus* and *Typha latifolia*. In the first compartment, the water is filtered through large tezontle (8-10 mm) and in the second compartment, with finer tezontle (2-4 mm). From Pond 3 it passes to Pond 4, which functions as a biofilter, since its two compartments have river sand (8 mm) and *Zantedeschia aethiopica* L. plants. Finally, the water reaches Pond 5, with a capacity of 120,000 L, where the treated water is collected and chlorinated.

Sample collection and preservation

The collection of samples from the constructed Santiaguito neighborhood wetland was carried out in triplicate, at four sites. Site 1 was located in the influent of the sump, i.e., in

Figure 1. Santiaguito neighborhood wetland in Texcoco, Mexico.



Source: Self-made based on a visit to the wetland

the receiving area of the domestic wastewater. Site 2 corresponded to Pond 2, where the wastewater will have been pre-treated (no coarse solids, reduction of pollutants). Site 3 was located in Pond 4, where the water went through all the treatment processes based on the functions of the phytodepurative species. Site 4 was located in Pond 5, which operates as a collector for the treated water (Figure 1).

Parameters analyzed and methods used

The determinations made on the wastewater samples before and after treatment in the wetland, as well as the methodology employed, are shown in Table 1.

Quality for use as treated wastewater or in discharges

To establish quality, we analyzed whether the value of each measured parameter was within the permissible limits for treated wastewater established in NOM-003-SEMARNAT-1997 (DOF, 1998).

Pollutant removal efficiency

To calculate the removal efficiency as a percentage of each of the parameters evaluated, Equation (1) was used, where *A* is the value of the parameter in the influent and *B* is the value in the effluent (Singh et al., 2023):

$$\textit{Removal}\ (\%) = \frac{A - B}{A} * 100 \qquad (1)$$

Statistical analysis

An analysis of variance (ANOVA) with a significance level of 0.05 and Tukey's multiple comparison test were applied to the results obtained from the samples collected at the different wastewater processing stages to measure spatial variation, using InfoStat 2020e software (Di Rienzo et al., 2008).

Results and discussion

Table 2 shows the physical, chemical and biological characteristics of the wastewater collected in the Santiaguito neighborhood wetland, Texcoco, as well as the removal efficiency for each parameter evaluated. Table 3 shows the concentration of heavy metals. It is worth mentioning that, since they were not found in the influent, the effluent was not analyzed in order to optimize economic resources.

Temperature and pH

The average temperature of the wastewater was found to be around 20 °C, with no significant statistical differences in the four wetland sampling sites. The pH remained slightly alkaline, with statistically significant differences. It was higher at the end of the purification process in the wetland (effluent) than at the beginning (influent). The influent had a pH of 7.55 and the effluent 8.06. Similar pH values in constructed wetlands planted with *Sagittaria latifolia* and *Sagittaria lancifolia* for domestic wastewater treatment are reported by Gallegos-Rodríguez et al. (2018), who obtained pH values of 7.7±0.1 and 7.5±0.1, respectively. Modini et al. (2023) also found similar pH values (7.6 to 7.8), with no statistically significant difference between influent and effluent. In terms of quality, the values found for both parameters are within the regulations established by NOM-001-SEMARNAT-2021 (DOF 2022), which establishes temperature limits at 35 °C and pH between 6 and 9 units. Despite the statistically significant differences, the removal efficiency is minimal.

Table 1. Parameters analyzed in wastewater samples in the Santiaguito neighborhood wetland, Texcoco.

Parameter	Method	Reference
Temperature (°C)	Potentiometer	NMX-AA-007-2013
pH	Potentiometer	NMX-AA-008-2016
Electrical conductivity (EC)	Potentiometer	NMX-AA-093-2018
Total coliform (TC) and fecal coliform (FC) bacteria	Most Probable Number (MPN)	NMX-AA-042- SCFI-2015
Chemical Oxygen Demand (COD)	Sealed reflux (600 nm)	NMX-AA-030/2-SCFI-2011
Biochemical Oxygen Demand (BOD_5)	Iodometric titration	NMX-AA-028-2001
Metals (Cd, Ni, Pb, Cr, Cu and Zn)	Atomic absorption	NMX-AA-051-2016
Total Suspended Solids (TSS)	Gravimetric	NMX-AA-034-2015
Total Nitrogen (total N)	Persulfate digestion	NMX-AA-026-2010
Total phosphorus (total P)	Stannous chloride	NMX-AA-029-2001

Source: Self-made with information from Official Mexican Standard NOM-001-SEMARNAT-2021 (DOF 2022) and Official Mexican Standard NOM-003-SEMARNAT-1997 (DOF 1998).

Electrical conductivity (EC)

NOM-001-SEMARNAT-2021 (DOF 2022) does not establish maximum permissible limits for this parameter. With the exception of Pond 2, the average EC values in the evaluated sites did not have significant statistical differences. Parra (2020) reports values of 1.8 ± 0.9 $mS \cdot cm^{-1}$ in constructed wetlands with *Hydrocotyle bonariensis* Lam. and *Typha latifolia* L. established for lead removal purposes. The salt removal efficiency is minimal (2.4 %), which, according to Teixeira et al. (2020), is attributable to the fact that the evapotranspiration of the plants present in the wetland favors the accumulation of salts in the water. Pérez-Molina et al (2021) reported EC reduction of 22.4 and 15 % in wetlands without and with *Pennisetum* plants, respectively.

Total suspended solids

Solids removal occurs through sedimentation and filtration since the water velocity within the wetland is reduced by the presence of macrophyte roots and filtering material. In this study, total suspended solids (TSS) removal efficiency was 22.9 %, decreasing from 600 $mg \cdot L^{-1}$ in the sump to 462.5 $mg \cdot L^{-1}$ in Pond 5 (Table 2), showing no significant statistical differences ($\alpha = 0.05$). The average value of total suspended solids (TSS) found in the wastewater treated by the wetland (Table 2) does not comply with the regulations established in NOM-001-SEMARNAT-2021 (DOF 2022) and NOM-003-SEMARNAT-1997 (DOF 1998) for discharge into receiving bodies, sewage or reuse, respectively.

Total suspended solids (TSS) removal of only 22.9 % (Table 2) may indicate saturation of the filter material and, therefore, loss of its solid retention capacity. Josimov-Dundjerski et al. (2015) reported 93-96 % efficiency for suspended solids removal and 65 % for TSS, while Hadad et al. (2011) obtained 30 % removal, which was close to that of the Santiaguito wetland.

Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD)

Due to its COD, the effluent from the Santiaguito wetland in Texcoco de Mora, Mexico, is within the permissible limits established in NOM-001-SEMARNAT-2021 (DOF, 2022) and can be discharged into rivers, streams, canals, drains, reservoirs, lakes, lagoons, and Mexican marine areas, or be used to irrigate green areas and any type of soil. However, due to its BOD_5, greater than 20 $mg \cdot L^{-1}$, it cannot be used to fill artificial lakes and canals used for recreational purposes such as boating, rowing, canoeing and waterskiing, nor for ornamental fountains, vehicle washing, irrigation of parks and gardens, including highway medians, avenue medians, and golf courses, fire hydrant supply systems, non-recreational artificial lakes, hydraulic safety barriers or cemeteries, in accordance with NOM-003-SEMARNAT-1997 (DOF, 1998).

Table 2 shows that the Santiaguito wetland has 57.7 % efficiency in chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5) removal. Auguet et al. (2017), in free-flowing wetlands using *T. domingensis*, reported 97.1 % COD and 83.4 % BOD_5 removal, respectively, while Grinberga et al. (2021) reported a reduction of 74 and 80 % for COD and BOD, respectively, even though the studied wetland, due to the prevailing climatic conditions of winter in Poland, from October to March, lacks vegetation.

Total nitrogen

NOM-001-SEMARNAT-2021 (DOF 2022) establishes that there is no restriction if the use is for irrigation of green areas and soil, except for karst. However, it defines 35, 30, 35 and 30 mg of total $N \cdot L^{-1}$ as maximum permissible limits for discharge into rivers, streams, canals, drains, reservoirs, lakes, lagoons, Mexican marine areas and karst soil. Therefore, wastewater from the Santiaguito neighborhood must receive treatment at least up to Pond 4. On the other hand,

Table 2. Physicochemical composition of wastewater sampled at four treatment sites or ponds in the Santiaguito neighborhood wetland, Texcoco, and removal efficiency.

Parameter	Units	Sump	Pond 2	Pond 4	Pond 5	Removal efficiency (%)
Temp.	°C	20.20 ± 0.08 a	20.27 ± 0.08 a	20.23± 0.08 a	20.23 ± 0.08 a	-
pH		7.55 ± 0.04 b	7.07 ± 0.04 c	7.49 ± 0.04 ba	8.06 ± 0.04 a	-
EC[1]	$mS\cdot cm^{-1}$	0.82 ± 0.01 a	0.75 ± 0.01 b	0.80 ± 0.01 a	0.80 ± 0.01 a	2.4
TSS	$mg\cdot L^{-1}$	600.00 ± 41.58 a	415.00 ± 41.58 ab	410.83 ± 41.58 b	462.50 ± 41.58 ab	22.9
COD	$mg\cdot L^{-1}$	169.08 ± 11.50 a	153.90 ± 11.50 a	92.73 ± 11.50 b	71.51±11.50 b	57.7
BOD_5	$mg\cdot L^{-1}$	84.54 ± 5.51 a	76.95 ± 5.51 a	46.36 ± 5.51 b	35.76 ± 5.51 b	57.7
Total N	$mgv\cdot L^{-1}$	48.80 ± 1.14 a	36.40 ± 1.14 b	25.00 ± 1.14 c	19.40 ± 1.14 d	60.2
Total P	$mg\cdot L^{-1}$	5.60 ± 0.23 ab	5.07 ± 0.23 b	5.93 ± 0.23 a	6.20 ± 0.23 a	-
TC	MPN 100 $m\cdot L^{-1}$	2'330,766 ± 160,116 a	1'235,622 ± 160,116 b	519,803 ± 160,116 bc	0 ± 0 c	100.0
FC	MPN100 $m\cdot L^{-1}$	357,496 ± 164,963 a	310,274 ± 164,963 a	312,469 ± 164,963 a	0 ± 0 b	100.0

EC (electrical conductivity), Total Coliforms (TC), Fecal Coliforms (FC), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Total Suspended Solids (TSS), MPN: Most Probable Number. Values indicate means ± Standard Error. Different letters in the lines indicate significant statistical differences with an α=0.05. n = 3).

NOM-003-SEMARNAT-1997 (DOF 1998) does not establish maximum limits for total N in treated wastewater to be used in direct and indirect contact activities. Regarding total nitrogen removal efficiency, the wetland has a low efficiency (60.2 %), since other authors report efficiencies of 80-90 % (Yaragal and Mutnuri, 2023; Pérez-Molina et. al, 2021).

Total phosphorus

Similar to total nitrogen, NOM-001-SEMARNAT-2021 (DOF 2022) establishes that there is no restriction if the use is for irrigation of green areas and soil, except for karst. However, it defines 21, 15, 21 and 15 mg of total $P\cdot L^{-1}$ as maximum permissible limits for discharge into rivers, streams, canals, drains, reservoirs, lakes, lagoons, Mexican marine areas and karst soil. Therefore, the wastewater from the Santiaguito neighborhood in Texcoco does not have any restrictions. It is worth mentioning that an increase in total P was observed at the end of treatment in Pond 5, despite the lily, calla lily, rush, cattail and navelwort plants, with which the wetland is planted. Masharqa et al. (2023) and Tatoulis et al. (2017) report removal efficiencies of 60 and 90 % of total P, respectively.

Total and fecal coliforms

NOM-001-SEMARNAT-2021 (DOF, 2022) specifies that if the electrical conductivity is less than 3 500 $\mu S\cdot cm^{-1}$, *E. coli* is analyzed and reported; but if it is greater than or equal to 3 500 $\mu S\cdot cm^{-1}$, fecal enterococci must be analyzed and reported. In this work, the EC value did not exceed 3.5 $mS\cdot cm^{-1}$, so total coliforms (TC) and fecal coliforms (FC) were analyzed as indicators of fecal enterococci. With statistically significant differences, both parameters are reduced as they flow from one pond to another, until they are completely eliminated with the chlorination applied in Pond 5, and their absence in the effluent reveals 100% removal (Table 2). In this regard, Gallegos-Rodríguez et al. (2018) obtained 99.8 % removal for both groups of bacteria in wetlands planted with *Sagittaria latifolia* and *Sagittaria lancifolia*. Sandoval-Herazo et al. (2020) report TC removal in wetlands planted with *Canna hybrids* and *Iris germanica* for treatment of swine industry effluents of 94 and 93 %, respectively. Waly et al. (2022) in a review of constructed wetlands report removal percentages of 93 % and 99 % for TC and FC, respectively. Other reported values are 99 % for TC (Singh et al., 2023). It is worth mentioning that the treatment in the Santiaguito wetland, Texcoco, generates an effluent that complies with the permissible limits established by NOM-003-SEMARNAT-1997 (DOF 1998): 1 000 $MPN\cdot 100\ mL^{-1}$ for agricultural use, and 240 $NMP\cdot 100\ mL^{-1}$ for public service with direct and indirect contact.

Heavy metals

Table 3 shows that the metal content in the wetland sump, which receives the domestic wastewater produced by the Santiaguito neighborhood, Texcoco, is within the limits allowed by NOM-001- SEMARNAT-2021 (DOF 2022).

Table 3. Concentration of heavy metals in wastewater from the Santiaguito neighborhood, Texcoco, before being treated in the local wetland.

Metals	Cd	Ni	Pb	Cr	Cu	Zn
$mg\cdot L^{-1}$	0.00	0.00	0.00	0.08	0.20	0.16

Considering the parameters analyzed, the quality of the wastewater treated by the Santiaguito neighborhood wetland only has limitations in terms of TSS and BOD_5. The low pollutant removal efficiency can be attributed to the clogging of pipes due to the growth of the root system of the installed macrophytes (Masharqa et al., 2023), as well as other species transported by wind and torrential rain, in addition to saturation of the filter material over time (Tatoulis et al., 2017) and poor sedimentation pretreatment (Pérez-Molina et al, 2021; Singh et al, 2023).

Conclusions

Due to its COD and concentration of potentially toxic metals, the effluent from the Santiaguito wetland in Texcoco de Mora, Mexico, is within the permissible limits established in NOM-001-SEMARNAT-2021 (DOF, 2022) and can be discharged into rivers, streams, canals, drains, reservoirs, lakes, lagoons, and Mexican marine areas, or be used to irrigate green areas and any type of soil. However, due to its BOD_5, greater than 20 $mg \cdot L^{-1}$, and TSS, it cannot be used to fill artificial lakes and canals used for recreational purposes such as boating, rowing, canoeing and waterskiing, nor for ornamental fountains, vehicle washing, irrigation of parks and gardens, including highway medians, avenue medians, and golf courses, fire hydrant supply systems, non-recreational artificial lakes, hydraulic safety barriers or cemeteries, in accordance with NOM-003-SEMARNAT-1997 (DOF, 1998). The Santiaguito neighborhood in Texcoco, Mexico, shows efficiency for removing pollutants, such as fecal coliform bacteria, COD, BOD_5 and total N, at 100, 57.7, 57.7 and 60.2 %, respectively, but not for total suspended solids (22.9 %). The measures proposed to improve its efficiency are to change or clean the filtering material and periodically prune the macrophytes' root system, in order to stimulate phytodepuration and reduce clogging and deterioration of the facilities through which the effluent circulates.

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