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Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town

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Abstract

This paper consists on a global environmental analysis of a waste water treatment (Conventional Activate Sludge System, CAS, designed for 13,200 population equivalent) and some possible additional tertiary treatments allowing water reuse to that purified waters (UF and immersed and external Membrane Biological Reactors, MBR). The environmental assessment of these water treatment technologies has been realized by means of the Life Cycle Assessment (LCA) technique, in order to establish with a broad perspective and in a rigorous and objective way the technology that provokes the lowest environmental load. The software SimaPro 5.1, developed by Dutch PRé Consultants, has been used as the LCA analysis tool, and three different evaluation methods—CML 2 baseline 2000, Eco-Points 97 and Eco-Indicator 99—have been applied. The results show that tertiary treatment does not increase significantly the environmental loads but provide new uses for that purified water, thus justifying the intensive use of water reuse techniques in water scarce areas.

Keywords: Life cycle assessment; Wastewater treatment; Water-reuse; Conventional activate sludge system; Membrane biological reactor

1. Introduction

In Europe the last two decades have witnessed growing water stresses, both in terms of water scarcity and quality deterioration, which has prompted many municipalities to look for a more efficient use of water

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resources, including a more widespread acceptance of water reuse practices [1]. The use of treated wastewater with high level of quality that, nowadays, are discharged to environment after their treatment in municipal sewage plants, needs a special attention as a new water resource. However, water reuse should not be viewed as simply as reclamation and reuse of wastewater effluents. Rather, a broader definition, encompassing the recovery and reuse of brackish ground waters, water harvesting and agriculture drainage flows, combined with seawater desalination, should be embraced [2].

First, it is important to distinguish between direct and indirect water reuse [3]. In inland catchments, wastewater with more or less treatment is discharged and dissolved in river beds or reservoirs that downstream can be indirectly reused again. It is not the same in coastal zones where wastewater is evacuated to sea by means of emissaries or river beds or aquifers, without any possibility of new uses. Consequently, it is in those coastal zones and inland areas with water scarcity where the implementation of the direct reuse and management of treated wastewater, by means of their collection, treatment and transport to the new use points and without pre-dilution in natural courses of water, is totally feasible.

Regarding water reuse techniques, water reuse has been developed from the most basic method of disposing wastewater without any treatment to often highly-engineered techniques of wastewater upgrading. In any case, water reuse already represents an important water supply in many areas of the world. For instance, nowadays it represents about 17% of the total purified wastewater in Spain: 408 hm^3/y are reused from 2400 hm^3/y discharged from sewage plants, and projections are limited to 1200 hm^3/y due to technical constraints [4].

The main objective of this study is to estimate or predict the environmental aspects and potential impacts associated to some water treatment technologies (wastewater and reuse) as a whole view of the technology less aggressive and harmful for the environment. First, the descriptions of the analyzed water treatment technologies are briefly presented. Then, the main results corresponding to the environmental loads of those technologies as well as a comparative analysis are presented. Finally, the main conclusions achieved are briefly commented.

2. Description of water treatment technologies

The great majority of sewage plants in Spain work with a conventional system of activated sludge. Thus, quality of purified water only fulfils the European Directive 91/271/CEE regarding the quality of secondary treatment discharges, and consequently it is not yet suitable for recycling. Thus, in order to be reused it is necessary to apply complementary (tertiary) treatments. The addition of UF membranes is a possible treatment; this technique has advanced so much that it has emerged a new concept of biological treatment of wastewater: Membrane Bioreactor (MBR) [5]. This new technology offers some advantages versus conventional processes used until now, including, reliability, compactness, and above all, the excellent quality of treated water.

The mission of a sewage plant is to reduce water pollution, that is:

- To eliminate wastes, oils, fatties, sands.
- To eliminate decantable organic and inorganic matter.
- To eliminate ammoniacal compounds containing phosphorous (particularly in vulnerable areas).
- To transform return wastes to stable sludge and to manage it adequately.

According to the population to serve, complexity grade and technology used differs from one sewage plant to other, so we have:

- Conventional treatments. They are used in big population nucleus where an important effect is downstream produced. They use technologies consuming rather electricity and require specialized labour.
- Treatments for small towns (soft treatments and conventional ones adapted). They are used in isolated buildings of drainage grids. Their principal premise is to have low maintenance costs and no-qualified labour. Their technology grade is very low, not needing much or null power consumption.

2.1. Conventional activate sludge system (CAS)

The processes (and sizes) included in the conventional activated sludge treatment of our study are the next:

- Pre-treatment:
    - Rough filtering: consists on the separation of solids, in two phases, thick and thin solids, by means of grilles (or sieves). On the separation of thick solids, the wastewaters arrive to an extractable grille. The separation among crosspieces is about 75 mm and the grille has an automatic cleaning system by means of a comb. Thin solids separation is obtained with a grille with crosspieces separation of 10 mm and an auto-cleaning sieve of 3 mm. Solids evacuation is made by an endless screw that collects solids to a container of 5 m^3.
    - Desanded-desoiled: elimination of sand, gravel, oil and fatty is produced in longitudinal aerated channels of 10 m, with a reassuring zone for the fatty separation. Centrifugal pumps perform sand extraction, and a second separation with a sand classifier-washer, are gathered in a closer container with a capacity of 1,000 l. Fatty is gathered by a scraper and is sent to a container of 1,000 l by means of an endless screw.
- Biological treatment of activate sludge:

The procedure of activate sludge consists on making, in a reactor or aeration tank, an intimate mixture between wastewater, bacteriologically active sludge and oxygen necessary for the aerobic fauna maintenance. This mixture is obtained by blowing air or mechanic agitation.

- Secondary decantation:

A time later, the mixture is taken to a secondary tank, where decants since the floccules are separated to depurated wastewater. Some part of activated sludge is returned to the biological reactor for keeping adequate microorganisms concentration in the reactor, meanwhile the other part is drained from the system. Biological treatment is completed in two biological reactors with a capacity of 596 m^3. Each reactor has two immersed agitators and three aeration grates with 125 diffusers per unit.

Summarizing, second decanter has two functions: to clarify the discharge and to thicken sludge. In this case, thickener has 6.50 m of diameter and plastic roof. Sludge is settled and compacted, then thicker sludge is extracted by the lower part of the tank. Then, thicken sludge is pumped out to the dehydration equipment. Two centrifugal pumps dehydrate the sludge to 18–20% of humidity after adding polyelectrolyte.

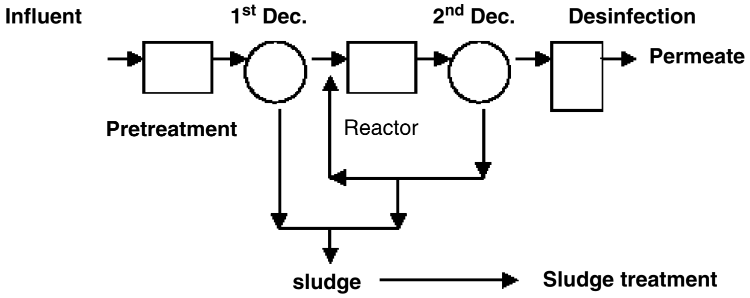

Fig. 1. CAS system.

2.2. Conventional activate sludge system with filtration treatment (CAS-TF)

The system CAS-TF is a conventional system of activated sludge including a tertiary treatment (UF membranes). Wastewater comes from the secondary decantation, passes by a 1 mm diameter sieve and then is pumped to two tanks of 55 m^3, with 6 cassettes of 22 UF elements or modules (ZeeWeed 1000 membranes).

A ZeeWeed 1000 module is a 36 m^2 membrane mounted on two vertical collectors. The cassettes are built coupling the elements in vertical and horizontal. In vertical, the standard structure has three elements, but tanks are not so deep and then one or two elements structures could be easily adjusted.

2.3. Immersed membrane biological reactor

The system has the same pretreatment phase as CAS. Then, wastewater passes to the biological treatment that has two membrane bioreactors of 225 m^3 of capacity. Each bioreactor has 6 cassettes of 22 elements per unit of ZeeWeed 500 (UF) membranes. The sludge is purged to the bioreactor, but differs from the CAS system in the sense that secondary tank is not required; then is pumped to a thickener and a dehydration treatment.

The membrane bioreactor volume is lower than the biological reactor volume of a CAS system since it does not depend on decantation and therefore its concentration could reach to higher values: this point out the benefits of better

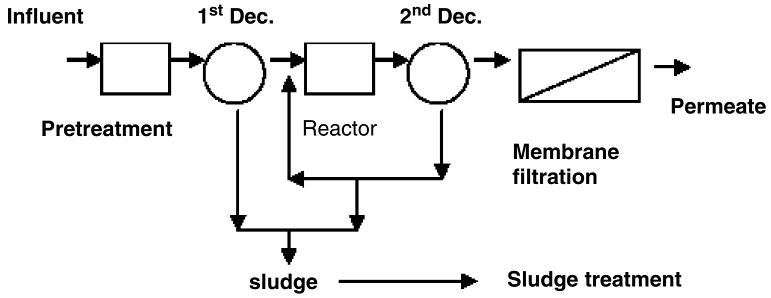

Fig. 2. CAS-TF system.

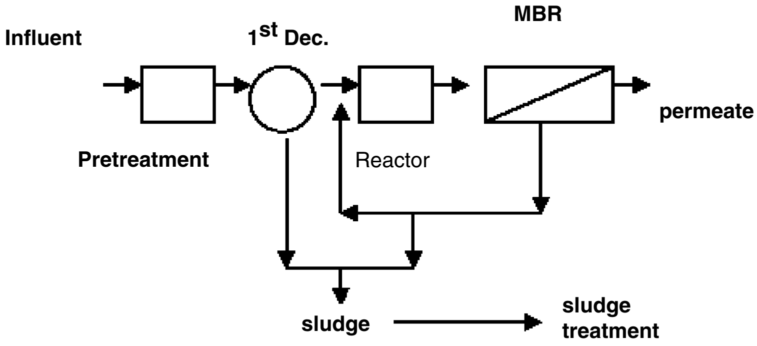

Fig. 3. CAS-immersed MBR system.

purification efficiency [6]. The studied immersed MBR system had 1.8 hours of hydraulic hold time, a sludge age of 24 days and 15,000 mg/l of solids concentration in the reactor.

2.3. External membrane biological reactor

This new arrangement has two trains of ZeeWeed 500 membranes. Each train contains 6 cassettes of 22 elements per cassette. They are nearby to the biological reactor, in fact this forces to install pumps to drive the mixture liquor to membranes tanks [7,8]. The sludge purge is performed directly from biological reactor. Permeate pumps, aeration blower and storage, chemical dosing and washing systems are installed in a container next to the membranes tank.

External MBR system works under similar conditions of MLSS (Mixed Liquor Suspended Solids) and sludge age than immersed MBR system.

ZeeWeed 500 and 1000 are Zenon hollow fibre membranes, with chlorine and oxidants-resistant hydrophilic polymer (PVDF). Filtration configuration is from inside to outside and under a soft suction. ZeeWeed 500 model is built with internal reinforcement (higher hollow fibre diameter).

CAS-TF and immersed or external MBR provide effluents with higher quality than CAS systems, allowing their reuse in many applications (irrigation, groundwater recharge, households, and industrial processes). Some other advantages of those systems compared to conventional CAS are:

- When UF is used, retention of bacteria and virus is achieved forming a sterile flow, thus avoiding the need of rambling

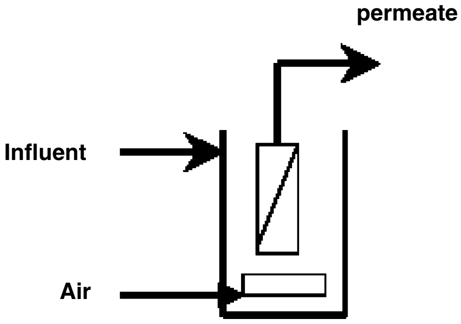

Fig. 4. Immersed MBR membranes.

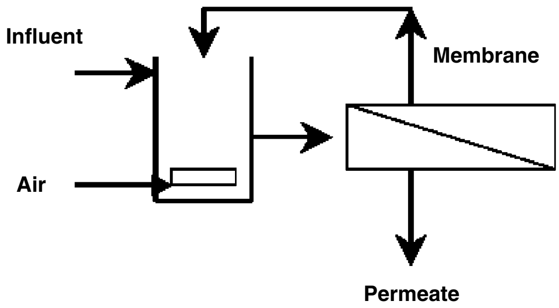

Fig. 5. External MBR membranes.

disinfection processes and also eliminating the hazardous disinfection subproducts [7].
- The lack of secondary decanter, which is also a natural selector of bacteria population, makes possible the development of slow-growth bacteria with persistence in the reactor even for low solid hold times [9].
- Compactness, since MBR technology could operate under concentrations of 15–30 g MLSS/l. At maximum concentration of MLSS, plant surface could be reduced to 50% or even more. Furthermore, sludge age is higher than conventional systems (the majority of MBR plants operate with sludge ages of 40 days or more), and therefore sludge production could be reduced up to 40% with the consequent reduction in operating costs.

The main disadvantages of MBR systems are:

- Higher investment cost derived from UF membranes.
- Elevated energy consumption provoked by an increase of endogen respiration in the reactor, the decrease of oxygen transfer as consequence of a higher concentration of suspended solids in the mixture liquor, and the aeration and recirculation required for membranes.
- Operational problems associated to looking for the adequate cleaning sequence in membranes [10].

3. LCA of water treatment technologies

The scope of the considered water treatment technologies is contributing to improve the quality of waste waters. The quality obtained by the analyzed technologies is shown in the Table 1.

The functional unit considered for the analysis is the production on average of 3000 m^3/day of water during 25 years, taking into account that the membrane replacement will be made every 7 years. The unitary energy consumption considered for each treatment was: 0.5 kWh/m^3 for CAS, 1.2 kWh/m^3 for CAS-TF, 0.8 kWh/m^3 for immersed MBR plants and 1 kWh/m^3 for external MBR plants.

In the LCA of the analyzed systems the next aspects have been considered:

- The constructive data have been taken from an existing wastewater plant in operation in Tauste (Spain) [11] with a capacity of 3000 m^3/day and 13,200 population equivalent: i.e. the pieces of equipment of the plant, and materials involved in the construction of the plant components (including their transport) and their

Table 1
Input and output parameters of treated water

Parameter	Input	Output CAS	Output UF membranes
DQO (mg/l)	560	125	35
DBO_5 (mg/l)	225	25	5
SST (mg/l)	230	35	5
Nt (mg/l)	52	10	9
Pt (mg/l)	10	2	0.1

manufacturing processes. The rest of materials of the other additional treatments are also based in this plant size as well as compiled data from different bibliography [12,13].
- Operation and maintenance of the aforementioned wastewater treatment plant.
- Dismantle and final disposal (without considering any recycling) of the whole plant.

It has been neglected the effects provoked by later uses of waters purified by tertiary treatments (CAS-TF and external and immersed MBR), underlying that quality of the recycled waters is similar for the three applications.

The detailed inventory tables including all input and output substances (raw material, airborne, water and soil emissions and wastes) of all considered systems can be found in [14].

4. Results

The main waterborne emissions associated to the technologies are shown in the Table 1. Next tables show the evolution of main airborne emissions and overall scores for the analyzed wastewater treatments (Table 2 and Table 3, respectivetely). Power consumed in the analyzed sewage plants is considered that it has been produced accordingly to the average European electricity production model [15] in which 43.3% is produced in thermal power plants, 40.3% in nuclear power plants and 16.4% in hydroelectric systems.

The CAS-TF technology presents the highest emissions to the atmosphere; the external MBR is the second one. These are the systems with higher energy consumption in the operational phase.

As the airborne emissions, CAS-TF technology provokes the higher environmental impact, next is the external MBR.

The operation and assembly phases in the CAS system have a similar importance in respect to the impacts, whereas in the rest of systems, the operation is the most impactant one. CAS-TF technology is the highest power consumer, and for this reason is the system with highest scores in operating phase. For all systems and methods, the impact of final disposal is negligible.

With respect to UF membranes, their impact is higher in MBR technologies than CAS-TF. This is because of membrane model in CAS-TF (ZeeWeed 500) has a higher diameter than membrane model in MBR (ZeeWeed 1000), due to its internal reinforcement.

5.1. LCA of desalination versus different electricity production models

In previous sections it has been proved the importance of energy in wastewater

Table 2
Airborne emissions for wastewater technologies

	CAS	CAS-TF	External MBR	Immersed MBR
kg. CO_2/m^3 produced water	0.39	0.78	0.82	0.77
g. dust/m^3	0.42	0.98	0.87	0.72
g. NO_x/m^3	0.84	1.78	1.65	1.40
g. NMVOC/m^3	0.24	0.49	0.54	0.46
g. SOx/m^3	1.61	3.73	3.36	2.79

Table 3
Percentage rate corresponding to each life cycle phase and total environmental load, for the wastewater technologies

Process	Life cycle phase	Unit	EI 99	Eco 97	CML 2 baseline
CAS	Assembly	%	42.7	44.7	29.4
	Operation	%	57.2	55.2	70.5
	Final disposal	%	0.14	0.13	0.06
Total scores			0.0207 MPoints/hm^3	0.357 GPts/hm^3	$0.0446{\cdot}10^{-5}$/hm^3
CAS-TF	Assembly	%	24.9	27.4	15.4
	Operation	%	74	71.2	83.6
	Membranes	%	1.03	1.35	1.02
	Final disposal	%	0.08	0	0
Total scores			0.0380 MPts/hm^3	0.636 GPts/hm^3	$0.0920{\cdot}10^{-5}$/hm^3
External MBR	Assembly	%	26.1	29	16.7
	Operation	%	69.7	66.7	79.4
	Membranes	%	3.5	4.29	3.83
	Final disposal	%	0.089	0.084	0.044
Total scores			0.0299 MPts/hm^3	0.504 GPts/hm^3	$0.0723{\cdot}10^{-5}$/hm^3
Immersed MBR	Assembly	%	30	31.4	18.1
	Operation	%	65.7	63.4	77.2
	Membranes	%	4.2	5.1	4.70
	Final disposal	%	0.11	0.10	0.05
Total scores			0.0241 MPts/hm^3	0.416 GPts/hm^3	$0.0573{\cdot}10^{-5}$/hm^3

technologies. For this reason in this subsection is studied the evolution of the environmental loads for different electricity production patterns. Four different scenarios, corresponding to existing countries, have been considered [15]:

- European model corresponds to the average power generation in Europe [15] (43.3% thermal, 40.3% nuclear and 16.4% hydroelectric).
- French model is a dominant nuclear production model (11.4% thermal, 72.9% nuclear and 15.7% hydroelectric).
- Electricity in Norway is almost produced by renewable energies (0.5% thermal, 0.3% nuclear and 99.2% hydroelectric).
- Portuguese model is mainly based on fossil fuels (80.8% thermal, 2.6% nuclear and 16.6% hydroelectric).

When comparing the four analyzed water treatment technologies by selecting diverse power generation models, it is shown (Tables 4 and 5) that the progressive substitution of fossil fuels, either by nuclear energy (French model) or by renewable energies (Norwegian model), provokes an important reduction of the environmental load, particularly in the latter.

The figures demonstrate that for all systems and electricity models, CO_2 is always the most important emission, then the SO_x, NO_x, NMVOC, and dust, except for European

Table 4
Airborne emissions depending on the different origins of the electricity consumed by wastewater technologies

	kg. CO_2/m^3 produced water	g. dust/m^3	g. NO_x/m^3	g. NMVOC/m^3	g. SOx/m^3
CAS, EM	0.69	0.77	1.24	0.30	2.81
CAS, FM	0.19	0.11	0.39	0.16	0.50
CAS, NM	0.13	0.03	0.26	0.13	0.24
CAS, PM	0.50	0.43	1.14	0.62	2.99
CAS-TF, EM	0.79	1.34	2.18	0.55	4.93
CAS-TF, FM	0.27	0.25	0.69	0.28	1.04
CAS-TF, NM	0.15	0.07	0.38	0.21	0.42
CAS-TF, PM	1.05	1.03	2.50	1.39	7.05
External MBR, EM	0.82	0.87	1.65	0.54	3.36
External MBR, FM	0.26	0.26	0.74	0.35	1.12
External MBR, NM	0.16	0.10	0.48	0.30	0.61
External MBR, PM	0.90	0.91	2.26	1.27	6.14
Immersed MBR, EM	0.77	0.72	1.40	0.46	2.79
Immersed MBR, FM	0.23	0.23	0.68	0.32	1.00
Immersed MBR, NM	0.14	0.10	0.47	0.28	0.59
Immersed MBR, PM	0.74	0.75	1.89	1.06	5.00

EM: European model; FR: French model; NM: Norwegian model; PM: Portuguese model.

model, where dust emissions are higher than NMVOC.

The tertiary treatments, with the Norwegian model, produce similar environmental loads than CAS system. This emphasizes the importance of the adequate integration with the power generation system, obtaining as a result higher water quality (and new feasible uses) with similar environmental loads than in secondary treatment.

7. Conclusions

This paper consists on performing the environmental assessment, by means of the Life Cycle Assessment (LCA) technique, of different water treatment technologies—Conventional Activate Sludge system (CAS) with and without tertiary treatment (immersed and external Membrane Biological Reactors, MBR)—in order to know which technology provokes lower impact to the environment. A well-known LCA software has been used (SimaPro 5.1, developed by Dutch PRé Consultants), and three different evaluation methods have been applied: CML 2 *baseline* 2000, Eco-Points 97 and Eco-Indicator 99 [16,17].

The results show the CAS system with tertiary treatment provokes the highest environmental loads, as expected. The immersed and external MBR have similar environmental impacts, although the external MBR technology is higher, due to its electricity consumption is higher. As all those treatments require energy, the environmental load associated to the operation stage is higher than that one associated to the plant construction, maintenance and final disposal. Using renewable energies (wind and solar) or taking advantage of sludge produced to obtain biogas for power generation in situ, are forms of reducing the environmental load associated to energy consumption.

It is important to note that diverse qualities are obtained in effluents, so allowing analysing the environmental load associated

Table 5
Overall scores for different integration arrangement of wastewater technologies

	EI 99 (MPoints/hm^3)	Eco 97 (GPoints/hm^3)	CML 2 *baseline*/hm^3
CAS, EM	0.0207	0.357	$0.0446\cdot10^{-5}$
CAS, FM	0.0121	0.217	$0.0195\cdot10^{-5}$
CAS, NM	0.0946	0.179	$0.0131\cdot10^{-5}$
CAS, PM	0.0328	0.486	$0.0610\cdot10^{-5}$
CAS-TF, EM	0.0380	0.636	$0.0920\cdot10^{-5}$
CAS-TF, FM	0.0169	0.301	$0.0317\cdot10^{-5}$
CAS-TF, NM	0.0106	0.207	$0.0162\cdot10^{-5}$
CAS-TF, PM	0.0668	0.972	$0.1310\cdot10^{-5}$
External MBR, EM	0.0299	0.504	$0.0723\cdot10^{-5}$
External MBR, FM	0.0161	0.291	$0.0307\cdot10^{-5}$
External MBR, NM	0.0108	0.212	$0.0178\cdot10^{-5}$
External MBR, PM	0.0577	0.825	$0.1140\cdot10^{-5}$
Immersed MBR, EM	0.0241	0.416	$0.0573\cdot10^{-5}$
Immersed MBR, FM	0.0140	0.255	$0.0259\cdot10^{-5}$
Immersed MBR, NM	0.0979	0.193	$0.0155\cdot10^{-5}$
Immersed MBR, PM	0.0471	0.683	$0.0924\cdot10^{-5}$

to its improvement. Regarding the quality of the treated effluents, the MBR meet the most stringent discharge criteria and are often suitable for direct reuse, apart from other additional technical advantages (except their operational and implantation costs, [18]). Again, the results emphasize that appropriate integration with power producers (see Table 5 and for instance the Norwegian model) allow obtaining even similar environmental charges for tertiary (new use is possible) and secondary treatments (discharged to river beds or sea).

Finally, and thinking about the possible extrapolation of the results to other sewage plants and tertiary treatments, the influent quality should be similar that the wastewater collected in Tauste (Spain, 13,200 population equivalent, pe), that quality depends on population customs and agricultural and industrial activities around the village. If some other treatment plant typologies (mainly classified by the number of pe) and plant sizes are studied, a new inventory will be needed for the LCA analysis.

Nomenclature

EI 99 — Eco-indicator 99
LCA — Life cycle assessment
CAS — Conventional activate sludge system
TF — Tertiary treatment
MBR — Membrane biological reactors
MLSS — Mixed liquor suspended solids
NMVOC — Non methane volatile organic compounds
UF — Ultrafiltration membranes
pe — Population equivalent

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