

## Life Cycle Assessment of a Municipal Wastewater Treatment Plant using SimaPro 9 software tool - Preliminary Results

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Wastewater treatment plants are powerful tools not only to protect human health and the environment from diseases, but they can also produce effluents that can be released in superficial/groundwater aquifers or reused for different purposes (civil, industrial, agricultural). If properly designed and managed, these plants can contribute to mitigating the effects of global warming, which is the principal cause of water scarcity. This problem is affecting more and more countries, as the CO<sub>2</sub> emissions in the atmosphere are still increasing significantly. On the other side, care must be paid to evaluate the environmental impact of these plants. They need energy to correctly work and chemical additives to favour the precipitation of some pollutant species; furthermore, they produce solid waste, the sludge, which must be properly disposed of, without forgetting the emissions that, in some cases, must be treated before being released into the atmosphere.

The challenge is to achieve high-quality water but, in the meantime, to perform a process that is not high-energy and high-chemical consuming.

Life Cycle Assessment (LCA) is a formidable approach that permits the evaluation of the environmental impact of whatever industrial process, service, or agricultural practice. This tool can be successfully applied to wastewater treatment plants, too. In particular, in this paper, the commercial software SimaPro 9 will be used, together with the CML-IA method and Ecoinvent database (updated to the 3.10 version), to evaluate the LCA of a wastewater treatment plant, which produces an effluent to be reused for irrigation. The leading environmental indicators for global warming, eutrophication, and acidification will be computed for this case study.

### Introduction

The need for effective and ecologically responsible wastewater management techniques has been underlined by the rising demand for water resources worldwide and growing worries about environmental sustainability. Wastewater treatment plants (WWTPs) are vital components of a closed-loop water cycle approach (Prisciandaro et al., 2016) and are necessary infrastructures for protecting public health and preventing water pollution (Tsangas et al., 2023). However, there are also significant energy and environmental costs related to their operation (Opher and Friedler, 2016).

A popular and useful technique for estimating the environmental effects of a process or product over its whole life cycle, from the procurement of raw materials to end-of-life care, is life cycle assessment (LCA) (Negi and Chandel, 2024a). LCA can be performed to evaluate the environmental costs of building, running, and decommissioning WWTPs in the context of wastewater treatment. It can also reveal the trade-offs and hotspots of various treatment technologies and management scenarios (Tsangas et al., 2023).

WWTPs have a variety of effects on the environment (Xue et al., 2019). These are a few of the most important, beginning with greenhouse gas emissions and energy consumption: Significant energy inputs are needed for WWTP operation, mostly for pumping, aeration, and other treatment procedures (Opher and Friedler, 2016). Greenhouse gas (GHG) emissions are frequently caused by this energy use, especially when fossil fuels are

used to generate electricity (Kamble et al., 2019). Biological processes in wastewater treatment and sludge handling can result in direct greenhouse gas emissions, including nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>), in addition to indirect emissions from energy use (Tarpani et al., 2021). A WWTP's environmental effects can be significantly impacted by the electricity mix selection (Xue et al., 2019).

Another significant environmental impact is Water Quality Degradation: while the primary purpose of WWTPs is to remove pollutants from wastewater, they can also contribute to water quality degradation if not properly managed. For example, the discharge of treated effluent can lead to eutrophication due to the presence of nutrients such as nitrogen and phosphorus, which are among the most impactful categories (Opher and Friedler, 2016). Moreover, the release of partially treated wastewater or sludge can contaminate water bodies with pathogens, heavy metals, and other harmful substances (Negi and Chandel, 2024a).

Finally, Resource Depletion is an environmental impact linked to the construction and operation of WWTPs. Both require significant amounts of materials, such as concrete, steel, and plastics, contributing to the depletion of natural resources (Xue et al., 2019). In addition, WWTPs often rely on chemicals for disinfection and other treatment processes, leading to further resource consumption (Negi and Chandel, 2024 a). Specifically, the infrastructure requirements can significantly affect the metal depletion category (Xue et al., 2019).

This study focuses on the environmental impacts of a specific wastewater treatment plant designed for water reuse and irrigation purposes. The selected case study is based on a combination of information derived from part of the simulated plant published elsewhere (Cecchini et al., 2024), thus offering a realistic example of a plant aimed at wastewater treatment and water reclamation for non-potable uses. The main objective is to identify and quantify the significant environmental impact categories associated with the plant during its operational phases, allowing a more detailed understanding of the system's environmental performance and potential areas for improvement.

## Materials and methods

### Description of WWTP

This paper considers a wastewater treatment plant (WWTP) for simulation. It can elaborate an influent stream of 1000 m<sup>3</sup>/h with the composition shown in Table 1.

*Table 1: Wastewater composition (FSS Fixed Susp. Solids, TSS Total Susp. Solids, COD Chemical Oxygen Demand, BOD Biological Oxygen Demand, TOC Total Organic Carbon, Total Kjeldahl Nitrogen)*

Component	Concentration (mg/l)
NH <sub>3</sub>	19.84
CO <sub>2</sub>	48.2
NO <sub>3</sub>	2.84
Ca <sup>2+</sup>	70.88
Cl <sup>-</sup>	74.65
K <sup>+</sup>	3.78
Mg <sup>2+</sup>	2.84
HCO <sub>3</sub> <sup>-</sup>	104.9
Na <sup>+</sup>	31.19
FSS	57.65
TSS	158.77
TOC	110.66
COD	336.53
BOD5	210.32
TKN	19.15

In Figure 1 a sketch of the WWTP is reported. A rotodrum device with a fine screen is provided to separate the Fixed Suspended Solids (FSS) from liquid wastewater. The influent stream is tangentially introduced into the screen through a special distribution headbox. Solids are captured inside the cylinder, thickened, and continuously discharged to the outlet. A washing system contributes to keep the screen clean.

Then, wastewater enters the biological section, consisting of an anoxic tank for denitrification and an aerated tank for biological oxidation, nitrification, and active biomass decay. During nitrification, ammonia is oxidized to nitrates, so part of the output water is recirculated to the anoxic tank to convert nitrates to nitrogen.

The output stream is sent to a secondary sedimentation basin to separate sludge from clarified liquid. 80% of the sludge is recirculated to the top of the plant, while the remaining part is sent to a sludge treatment section. This section includes an aerobic digestion basin, a thickener, and a belt filter for sludge dewatering.

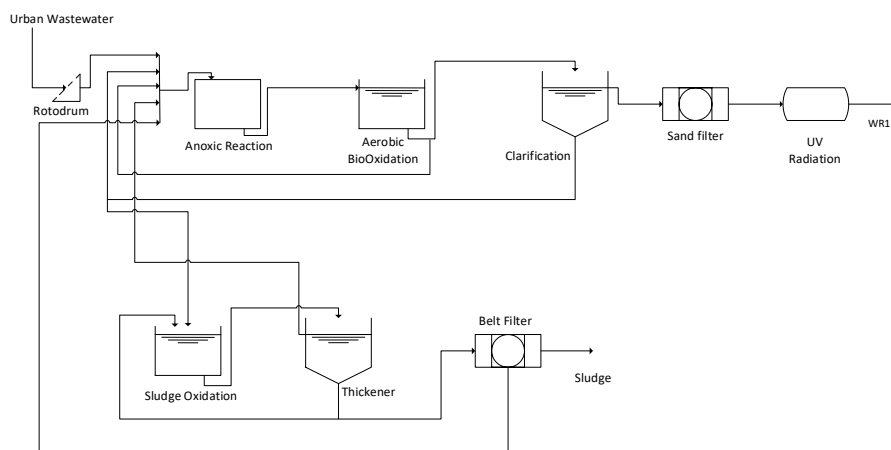


Figure 1: Wastewater treatment plant

After the secondary sedimentation process, the wastewater undergoes a filtration step through a sand filter, which needs washing water to correctly work. Finally, the stream enters a disinfection process, where UV lamps realize wastewater disinfection.

### Life Cycle Assessment (LCA) method

LCA consists of four main steps, according to ISO 14040 (2006) and ISO 14044 (2006): goal and scope definition, inventory analysis, impact assessment, and interpretation of results.

#### Goal and scope

The scope of this study is to evaluate the life cycle of the WWTP reported in Figure 1. Here, a typical approach of cradle-to-gate modeling is used. Still, as this is a preliminary study, the analysis has focused exclusively on the environmental impact of the clean water associated with its production. The environmental impact caused by the overall life cycle (equipment manufacturing, maintenance, and disposal) will be investigated in a subsequent paper, where the use of reusable components that are differently disposed of will also be considered.

#### System boundary

A crucial step in LCA is the exact definition of system boundary: in Figure 2, a sketch is reported.

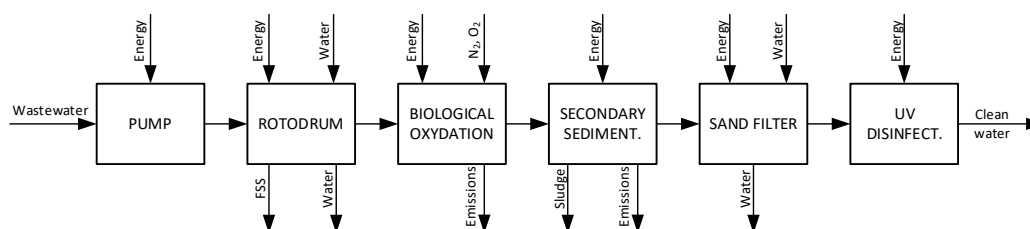


Figure 2: The system boundary for this LCA study

As confirmed by the system boundary in this study, the environmental impact of clean water has been exclusively considered. In addition, the sludge in the original plant (see Figure 1) is partly recycled and partly properly treated into a separated line, which was considered effluent that has to be disposed of.

The mean lifetime of the plant was set at 30 years (Van Haadel and Van Der Lubbe, 2007), while the function unit of this study was 1000 m<sup>3</sup> of wastewater.

#### Inventory analysis

The inventory analysis involves parameters describing resources, materials, and emissions in air and water. The assessment considered in this paper covers the environmental impact caused by the WWTP of Figure 1 to produce a clear effluent, starting from a wastewater stream, whose characteristics have been specified in Table 1.

In addition, Table 2 reports information about the use of water for rotodrum and sand filter, the need for N<sub>2</sub> and O<sub>2</sub> for biological processes, the energy demand for each equipment involved in Figure 2, and finally, the emissions, if any, for each equipment.

*Table 2: Inventory analysis*

Equipment	Mass flow, kg/h	Energy, kWh	Emissions, kg/h
Pumps (total)		32.7	
Rotodrum			
Wash water	4920		
Energy		0.111	
FSS			11.53
Wash water			4920
Biological oxidation			
N <sub>2</sub>	1233		
O <sub>2</sub>	374		
Energy		170	
N <sub>2</sub>			1233
O <sub>2</sub>			331
CO <sub>2</sub>			76
Secondary sedim.			
Energy		1	
NH <sub>3</sub>			16.54
CO <sub>2</sub>			0.75
Sludge			16752
Sand filter			
Wash water	76.1		
Energy		5.81	
Wash water+others			91.33
UV disinfection			
Energy		23.02	

### Impact assessment in SimaPro

SimaPro covers a wide variety of impact assessment methods. They can be classified into two main categories: midpoint and endpoint. The first one includes a lot of environmental impacts like freshwater eutrophication, human toxicity, and global warming. The second converts these midpoint impacts into four damage categories: damage to the ecosystem, damage to human health, damage to resources, and climate change (Ichehboroun et al., 2024).

In the literature, some authors (Ichehboroun et al., 2024) used the CML-IA method that is defined for the midpoint approach, while others (Alanbari et al., 2014) preferred the IMPACT 2002+, available both as midpoint and endpoint damage level.

In this paper, the CML-IA method, the midpoint approach, has been selected by the authors for assessing acidification, eutrophication, and global warming impact categories. For all these, time span is the eternity, and the geographical scale varies between local and global scales.

Acidification is the result of oxidation processes, which generate SO<sub>2</sub> and NO<sub>x</sub> emissions: these substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, and materials (buildings). Acidification potential for emissions to air is expressed as kg SO<sub>2</sub> equivalents/kg emission.

Eutrophication is mainly due to the presence of phosphorus and nitrogen in WWTP. It includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water, and soil. It is expressed as kg PO<sub>4</sub> equivalents per kg emission.

Global warming includes impacts related to a rapid increase in temperature to which humans and species must adapt very quickly. It is expressed in kg CO<sub>2</sub> equivalents per kg emission. Global warming is caused by Greenhouse Gases (GHG), which can be divided into two different categories: direct and indirect. The first consists of gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) emitted during the process treatment as a result of biological activities; the second is associated with power consumption.

### 3. Results and discussions

The impact categories investigated by the CML method are eleven (eutrophication, acidification, marine aquatic ecotoxicity, freshwater aquatic ecotoxicity, abiotic depletion, terrestrial ecotoxicity, global warming, human toxicity, abiotic depletion, photochemical oxidation, ozone layer depletion).

Figure 3 reports only three of them and precisely acidification and eutrophication, which result in the highest of all eleven in terms of normalized values, together with global warming. This last shows a much lower contribution if compared with eutrophication and acidification, but it is extremely important in terms of CO<sub>2</sub> emissions in the atmosphere.

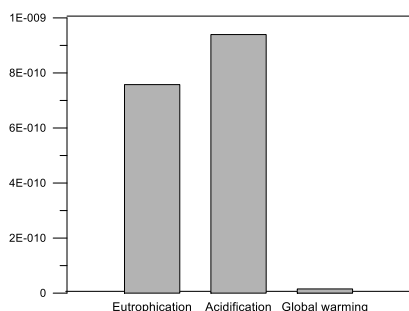


Figure 3: Normalized result of environmental LCA of WWTP with CML method.

As reported in Table 3, the clean water stream shows the highest contribution to acidification impact categories. This behavior is due to the emissions in the air in terms of kg SO<sub>2eq</sub> from the denitrification section of biological treatment, where high concentrations of NO<sub>x</sub> are released in the atmosphere.

Table 3: Contribution to acidification process

Process	kgSO <sub>2eq</sub>
Clean water	26.46
Electricity	0.25
Sludge	0.00754
Wash water	0.00691
FSS	0.00253
Total	26.73

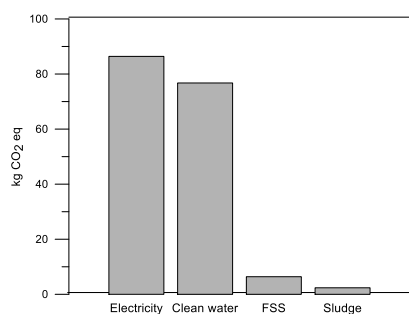


Figure 4: Contribution to global warming process

This result is in good agreement with the LCA analysis performed by other researchers (Piemonte et al., 2017) on a similar WWTP with the same midpoint approach. The environmental impact of this plant can be improved by covering the oxidation tank and by conveying the gas phase to a depuration system properly designed to reduce the acidification potential. Figure 4 shows the contribution to the global warming in terms of kgCO<sub>2</sub> equivalent.

As expected, the highest contribution to global warming is due to electricity: this can be explained by the dataset selected, which describes the electricity available in Italy based on a mix of different sources, prevailing fossil fuels. This contribution can be lowered if an alternative choice is made, for example, considering electricity produced by means of renewable sources or cogeneration.

Figure 4 also shows clean water as another important contribution to the global warming process. This behavior is due, again, to the oxidation process, where biological reactions produce a considerable amount of carbon dioxide, which is realized in the atmosphere. Here, the solution proposed before, which consists of covering the oxidation tank coupled with an advanced system designed to capture and store emitted CO<sub>2</sub>, could be useful to mitigate the emission of greenhouse gases in the air, contributing to further decrease the environmental impact of the WWTP.

## Conclusions

In this paper, an LCA study on a WWTP was performed. The software used is SimaPro 9, which is provided with the database Ecoinvent 3.10. The method selected for impact assessment is CML-IA, defined for the midpoint approach. A typical strategy, cradle-to-gate modeling, has been used; however, the study investigated does not consider, for now, the overall life cycle of the plant, but exclusively the environmental impact of clean water.

Results obtained showed that acidification and eutrophication are the prevalent impact categories, while global warming, despite having a minor effect, has been considered, too, for the strong interest in CO<sub>2</sub> emissions. This study has demonstrated that the oxidation step is crucial for the environmental impact of the WWTP: here, NO<sub>x</sub> emissions are responsible for strong acidification potential, while CO<sub>2</sub> contributes to global warming. Therefore, to mitigate the environmental impact of the plant, it is necessary to cover the oxidation tank and to convey the gas phase to a depuration system, provided with an advanced system designed to capture and store emitted CO<sub>2</sub>.

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