Environmental performance of a photovoltaic solar electrooxidation (PSEO) process: comparisson with a conventional biological treatment

Rubén, Aldaco [1,*], María Margallo [1], María José Amores [2], Montse Meneses[2], Jorgelina Pasqualino [2], Francesc Castells [2], Ángel Irabien[1]

[1]Departamento de Ingeniería Química y Química Inorgánica, Universidad de Cantabria (UC) Avda. de Los Castros, s.n. 39005 Santander, Spain

[2]AGA, Chemical Engineering Department, Rovira and Virgili University, Avinguda dels Països Catalans 26, 43007 Tarragona, Spain

* e-mail: aldacor@unican.es Tel. +34 942 20 15 86

Abstract. Generally, wastewater treatment is carried out using primary, secondary or tertiary methods, depending of the nature of the pollutant. As far as organic pollutants in wastewaters are concerned, biological abatement may sometimes be impossible, due to the bio-refractory and recalcitrant character of the substances. So, in these cases, the application of electrochemical technologies becomes clear as a versatile and potential cost effective alternative treatment. One of the most remarkable electrochemical techniques is the electro-oxidation (EO) that in the recent years, have been applied in several works to eliminate a wide variety of pollutants present in wastewaters. In this work, the LCA methodology has been applied in order to assess the environmental performance of a conventional biological treatment of a Waste Water Treatment Plant (WWTP) and the electro-oxidation process, comparing both technologies for wastewater treatment.

1 Introduction

Generally, wastewater treatment is carried out using primary, secondary or tertiary methods, depending of the nature of the pollutant. As far as organic pollutants in wastewaters are concerned, biological abatement may sometimes be impossible, due to the bio-refractory and recalcitrant character of the substances. So, in these cases, the application of electrochemical technologies becomes clear as a versatile and potential cost effective alternative treatment [1]. One of the most remarkable electrochemical techniques is the electrochemical oxidation or electro-oxidation (EO). This process is an environmental benign technology based on the application of an electrical current to the electrodes to mineralize completely non-biodegradable organic matter and to eliminate nitrogen species. This technology has been applied to treat effluents from landfill and a wide diversity of industrial effluents including agro-industrial, chemical, textile, tannery and food industry. Some advantages of the electrochemical oxidation are the use of a clean reagent, the electron, little or no need for addition of chemicals, simple equipment, easy operation and brief retention time and finally that neither sludge nor solid waste are generated [2].

On the other hand, this process entails higher costs as compared to biological treatment, due to an intensive use of energy. In order to overcome this problem, the substitution of electricity by solar energy, have been proposed as a suitable strategy [3]. Likewise, other disadvantage of the electrochemical oxidation is that is a novel technology that only has been applied in a pilot plant scale. So it is necessary to assess the environmental performance of the electrochemical oxidation in order to evaluate the advantages and disadvantages of this technology and to compare it with the biological treatment carry out in a Waste Water Treatment Plant (WWTP). To evaluate the environmental performance of good, products and services the LCA methodology is used. Life Cycle Assessment (LCA) is a powerful tool for assessing the environmental performance of a product, process or activity from "cradle to grave" [4]. In this work, the LCA methodology has been applied in order assess the environmental performance of a conventional biological treatment of a WWTP and the electrochemical oxidation process, comparing both technologies for wastewater treatment.

2 Materials and Methods

Aguilar the Campoo WWTP: Aguilar de Campoo is a village sited in Castilla y León (Spain). This WWTP serves a population of 14.188 inhabitants equivalents in Aguilar de Campoo and the surrounding area. In 2009, the plant had a nominal flow of $1,2 \cdot 10^6$ m^3/year and 300 ton/y of sludge were generated. The WWTP is divided in four main parts, including the water, sludge and gas line as well as the services.

Photovoltaic solar electro-oxidation (PSEO): The electrochemical oxidation driven by photovoltaic solar modules (PSEO) is carried out in a pilot plant. The plant consists on a Diacell reactor and the photovoltaic modules. The Diacell reactor is divided in three electrochemical lines. Each line consists of five DiaCell sets, containing each set ten DiaCells. (anode-cathode pair).This gives a total of 150 DiaCells (10 DiaCell per set x 5 sets per line) x 3 lines). Both the DiaCell pack and the DiaCells are arranged in parallel. Therefore, the total anode surface is 1.05 m^2. The electrode material is boron-doped diamond (BDD) both in the anode and the cathode. Their geometry is circular with an useful surface area of 70 cm^2 each and an electrode gap of 1 mm. In this pilot plant, the electric current is supplied by monocrystalline photovoltaic modules. Specifically, 7 photovoltaic modules of 85 Wp supply the required energy.

3 LCA Methodology

In this work the environmental assessment of the processes above described has been carried out according to the LCA methodology [4, 5].

3.1 Goal and Scope

The aim of this study is to assess the environmental performance of a biological treatment with sludge treatment in a WWTP and the photovoltaic solar electro-oxidation (PSEO) process. Finally, a comparison of both processes has been completed. In order to carry out a more thorough study several scenarios have been compared as it is shown in the Table 1.

Tab.1: Summary of studied scenarios.

Scenarios	Description
Scenario 1	Electro-oxidation (EO)
Scenario 2	Photovoltaic solar electro-oxidation (PSEO)
Scenario 3	WWTP Aguilar. Sludge final destination: Agriculture

Scenario 4	WWTP Aguilar. Sludge final destination: Landfill
Scenario 5	WWTP Aguilar photovoltaic modules. Sludge destination: Agriculture
Scenario 6	WWTP Aguilar photovoltaic modules. Sludge destination: Landfill

In this work the proposed electro-oxidation process is driven by photovoltaic solar modules; however, conventional electrochemical oxidation has also been studied. The opposite situation has been proposed for the WWTP that nowadays is supplied by the corresponding electric mix.

One of the keys elements to be set in the goal and scope definition of the study is the functional unit which is a measure of the performance of the functional outputs of the product system [4, 5]. In this work, the function of the system is to treat urban wastewater to remove pollutants so the quantity of wastewater treated in the whole lifespan of the plant has been selected as functional unit [6, 7]. Although the assessment of the electro-oxidation process is based on the pilot plant operation, the system has been modelled making a scale up of the plant in order to treat the same volume than the Aguilar de Campoo WWTP. About the system boundaries, all the energy and mass input (additives used and their transport and energy consumption) and output flows (waste generated their transport and treatment) were considered for the operation stage and the infrastructure of the WWTP and the scaled-up electrochemical oxidation plant. In Figure 1 a flow diagram of the systems under study is shown.

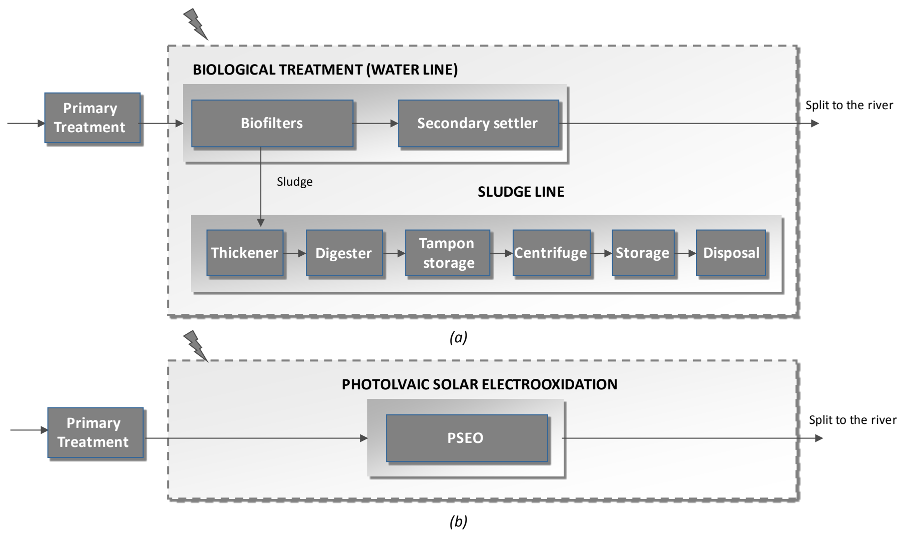

Fig.1: System boundaries (a) WWTP, (b) Eletrochemical oxidation.

In a WWTP, wastewater and sludge from the primary and secondary wastewater treatment are treated in different lines. However, in the electrochemical oxidation, neither sludge nor solid wastes is generated. Likewise chemical regents are not used in the electro-oxidation, in this case, the main inputs of the systems are the energy consumption and the infrastructure. So as in both cases the same primary treatment is required and the associated impacts are similar, this process hasn’t been considered in the study.

3.2 Inventory data

The inventory fluxes per functional unit of the biological treatment and sludge line of the WWTP of Aguilar the Campoo are shown in Table 2. LCA inventory was performance by adapting the data from the Ecoinvent database [8] to the Spanish energy mix. About the WWTP infrastructure, just the biological treatment has been study. This is due to the significant dimensions of the biological equipment composed of five biofilters lines. This way, this equipment will be the most representative of the entire WWTP infrastructure. The equipment is composed of a steel low alloyed axle, the HDPE discs, the cover of polyester and the support made of concrete.

Tab.2: WWTP inventory per functional unit (Functional unit: m^3 of treated water).

		Annual Consumption /Functional unit	**Unit**
Water Line (Biological treatment)			
Biofilters	Energy	3,65E-02	kWh/m^3
Secondary settler	Energy	1,82E-03	kWh/m^3
Sludge line			
Thickener	Energy	1,09E-04	kWh/m^3
Digester	Energy	1,85E-02	kWh/m^3
Tampon storage	Energy	2,63E-03	kWh/m^3
Centrifuge	Energy	1,01E-02	kWh/m^3
	Polyelectrolyte	6,47E-04	kg/ m^3
	Transport	4,69E-04	tkm/ m^3
Final storage	Energy	2,65E-4	kWh/m^3
Final disposal: agriculture	Biological sludge	1,03E-01	kg/ m^3
	Transport	1,47E-02	tkm/ m^3

application			
Final disposal: landfill	Biological sludge	1,03E-01	kg/ m^3
	Transport	1,17E-02	tkm/ m^3

In relation to the electro-oxidation process, 28 kWh/m^3 of energy (electric mix or solar energy) are consumed. About the infrastructure, the plant is composed of a stainless steel and polypropylene reactor and the BDD electrode.

3.3 Impact assessment

In this work the CML2001 impact method and the Ecoinvent database [8] have been used. Specifically the following impact categories have been considered: Acidification Potential (AP, kg SO_2 eq.), Global Warming Potential (GWP100a, kg CO_2 eq.), Eutrophication Potential (EP, kg PO_4 eq.), Photochemical oxidation (PHO, kg formed ozone), Stratospheric Ozone Depletion (ODP, kg CFC-11 eq.), Depletion of Abiotic Resources (DAR, kg antimony eq.), Fresh Aquatic Ecotoxicity (FAE, kg 1,4-DCB eq.), Marine Aquatic Ecotoxicity (MAE, kg 1,4-DCB eq.), Human Ecotoxicity (HE, kg 1,4-DCB eq.), Terrestrial Ecotoxicity (TE, kg 1,4-DCB eq.), Ecotoxicity Potential (EP, kg 1,4-DCB eq.).

4 Results

4.1 WWTP of Aguilar de Campoo

According to the Figure 2, where the environmental impacts of the WWTP infraestrucutre are given, the HDPE of the biodiscs has the most important contribution in AP (81%), GWP (76%), EP (64%), PHO (83%) and DAR (93%). This is due to the high coal, gas natural and oil consumption and the generation of SO_x, CO_2, CH_4, NO_x, HNO_3 and phosphate in the manufacture of the HDPE. In FAE, MAE, HE, TE and EP, carbon steel used in the axle manufacturing is the most important contributor due to the emission of Polycyclic Aromatic Hydrocarbons (PAHs) and heavy metals. Finally, in the Stratospheric Ozone Depletion category the reinforced concrete presents the highest impact.

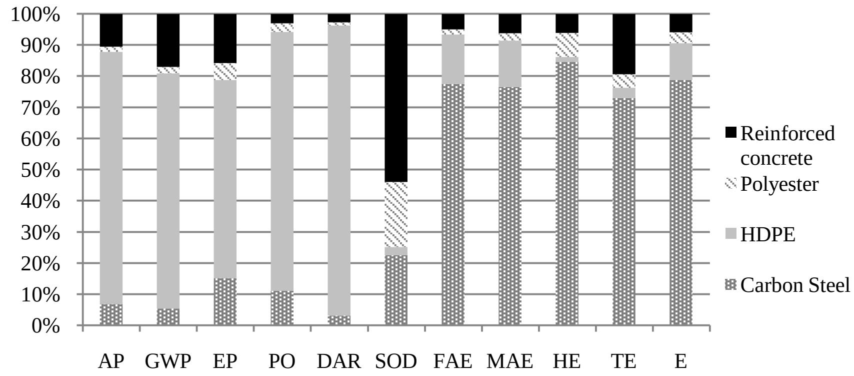

Fig.2: **Infrastructure impacts of the WWTP.**

About the operation stage, in Figure 3 and 4 the environmental impacts of the WWTP when the final sludge destination is the use as fertilizer and the landfill are shown respectively.

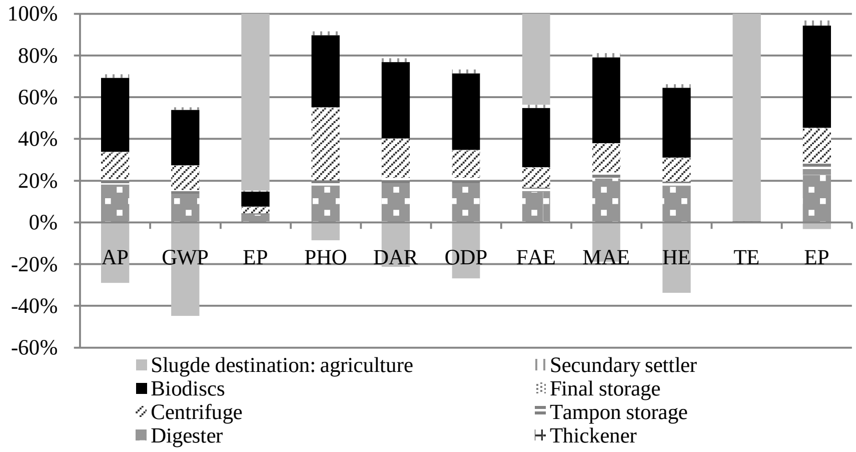

Fig.3: **Environmental impacts of the WWTP when sludge destination is the agriculture application.**

High impacts are observed in EP, FAE, TE when the sludge is used as fertilizer. The concentration of excess of nutrients and heavy metals in the sludge causes this situation. Negatives results corresponding to avoided burdens are obtained in the rest of impact categories due to the environmental benefit from substituting the use of chemical fertilizers by agriculture use of sludge.

On the other hand, when the sludge is sent to landfill, no avoided burdens are obtained, being the sludge destination the highest contributor in all the impact categories excepting in AP, GWP and EP.

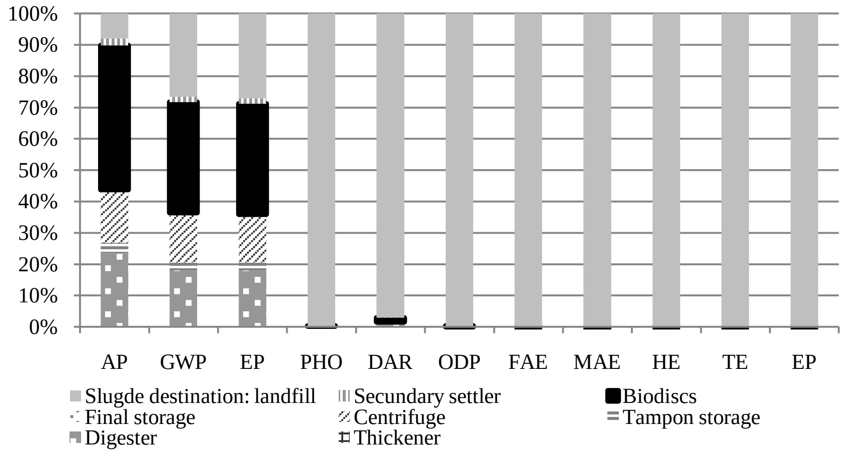

Fig.4: **Environmental impacts of the WWTP when sludge is sent to the landfill.**

4.2 Electro-oxidation process WWTP of Aguilar de Campoo

This process has been studied using two types of energy supply: an electric mix (EO) and photovoltaic modules (PSEO). The environmental impacts of the EO and PSEO processes are shown in Figure 5 and 6 respectively.

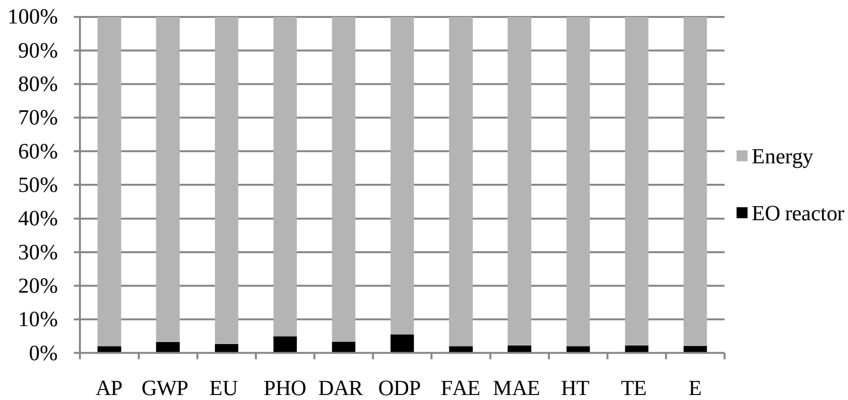

Fig.5: **Electro-oxidation (EO) impacts.**

The results show that as the electro-oxidation is a very intensive energy process, the highest impact corresponds in both cases to the energy consumption. However, in the PSEO the environmental impact is due to the infrastructure of the photovoltaic modules.

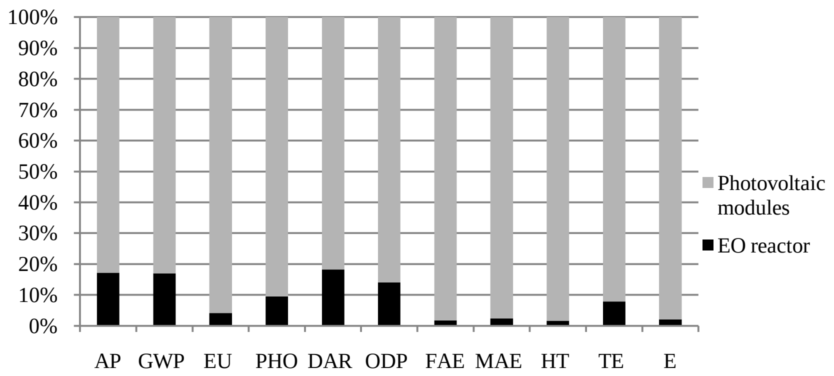

Fig.6: Photovoltaic Solar Electro-oxidation (PSEO) impacts.

4.3 Comparison of the WWTP impacts and the Photovoltaic Solar Electro-oxidation process

A comparison between PSEO (Scenario 2) and the WWTP using electric mix and taken into account two sludge destinations, landfill (Scenario 3) and agriculture applications (Scenario 4) is given in the Figures 7 and 8 respectively.

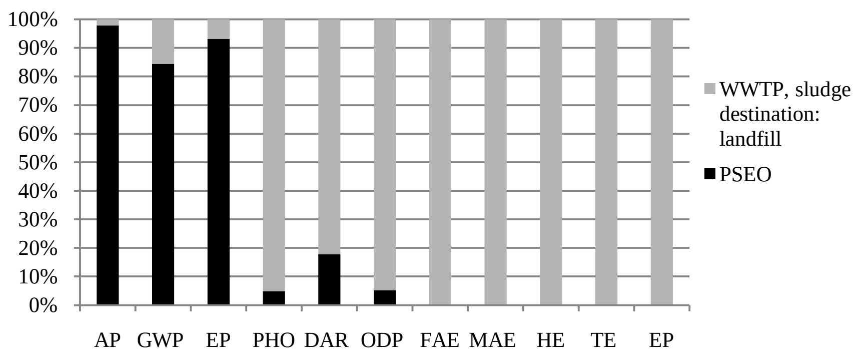

Fig.7: Comparison of the PSEO and WWTP, final destination: landfill.

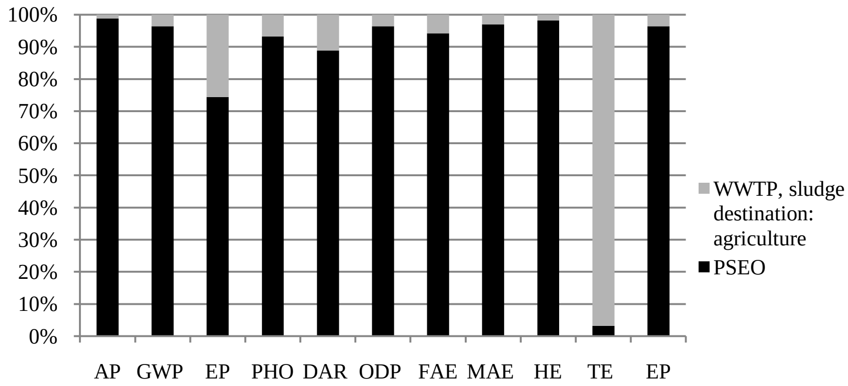

Fig.8: **Comparison of the PSEO and WWTP final destination: agriculture.**

When the sludge is sent to the landfill, the highest impacts in AP, GWP and EP are obtained in the PSEO process. However, in the rest of categories, the WWTP arises higher impacts than the PSEO process due to the high contribution of the sludge destination to the landfill. On the other hand, when the sludge is used as fertilizer, in all the impact categories except in TE higher impacts are obtained in the PSEO process than in the WWTP. This come up due to the environmental benefit obtained due to the use of the sludge as fertilizer.

In Figures 9 and 10 the PSEO (Scenario 2) is compared with the WWTP but supposing that the energy is supply by photovoltaic modules.

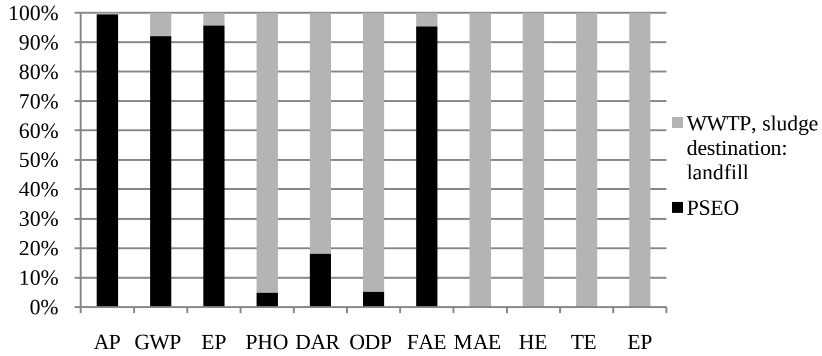

Fig.9: **Comparison of the PSEO and WWTP (photovoltaic modules), final destination: landfill.**

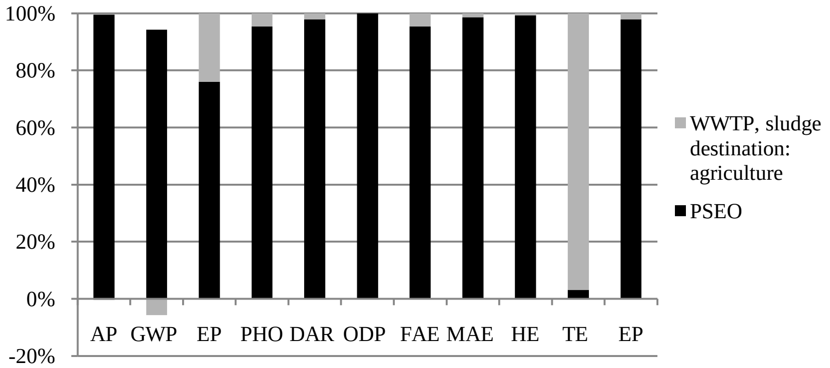

Fig.10: Comparison of the PSEO and WWTP (photovoltaic modules), final destination: agriculture.

When PSEO (Scenario 2) is compared with the WWTP being the final sludge destination the landfill (Scenario 6), the highest impacts correspond to the PSEO process in AP, GWP, EP and FAE. The opposite situation arises for the rest of categories due to the high contribution of the sludge destination to the landfill. However, when the sludge is used as fertilizer (Scenario 5), higher impacts are obtained in the PSEO process than in the WWTP in all the categories except in TE. Likewise a negative value is obtained in the category of GWP due to environmental benefit of using the sewage sludge as fertilizer.

5 Conclusions

In this work the environmental performance and the comparison of the conventional biological of a WWTP and the photovoltaic solar electro-oxidation (PSEO) has been carried out applying the LCA methodology.
About the infrastructure WWTP results, the materials that arisen the highest impacts are the HDPE of the biodiscs (in the categories AP, GWP, E, PO, DAR) and the carbon steel from the biodiscs axle (in SOD, and all the ecotoxicity categories). In relation to the operation stage, when the sludge is allocated for agriculture applications, negatives values are obtained in all the categories except in EP and TE, due the environmental benefit associated to the substitution of the chemical fertilizer by the agriculture use of sludge. However, the high values in

the EP and TE are caused to high concentration of nutrients and heavy metals in the sludge.

About the EO assessment, the higher impacts are associated to the electric consumption. However, when the electric mix is substituted by the photovoltaic modules, the infrastructure of the modules becomes the highest contributor to the total impact of the plant.

Finally, when PSEO is compared with the WWTP being the sludge destination the landfill, the WWTP present the highest impacts in all the categories except in AP, GWP and EP. On the other hand, when the sludge is allocated by agriculture application, the PSEO present the highest impacts in all the categories except in TE. Using photovoltaic modules in the WWTP has not a quite influence in the final results because the final sludge destination is the most representative process.

To conclude, the PSEO process is shaping up as a feasible environmental alternative to the conventional biological treatment when the sewage sludge is sent to the landfill. However, its application in those WWTP where the sludge is used as fertilizer is not still proved as the best environmental alternative.

6 References

[1] Martinez-Huitle CA, Ferro S. Electrochemical oxidation of organic pollutants for the wastewater treatment: direct and indirect process. Chemical Society Reviews, Vol. 35, 2006, pp. 1324-1340.

[2] Anglada A, Urtiaga A and Ortiz I. Contributions of electrochemical oxidation to wastewater treatment: fundamentals and review of applications. J Chem Technol Biotechnol, Vol. 84, 2009, pp. 1747-1755.

[3] Muñoz I, Peral J, Ayllon JA, Malato S, Passarinho P and Domenech X. Life cycle assessment of a coupled solar photocatalytic–biological process for wastewater treatment. Water Research, Vol. 40, 2006, pp. 353-3540.

[4] International Standard ISO 14040, 2006: Environmental management - Life cycle assessment - Principles and framework.

[5] International Standard ISO 14044, 2006: Environmental management - Life cycle assessment -Requirements and guidelines.

[6] Hospido A., Moreira M.T, Fernandez-Couto M., Feijoo G. Environmental Performance of a Municipal Wastewater Treatment Plant. Int J LCA, Vol. 9, No. 4, pp. 261-271.

[7] Hospido A., Moreira M.T, Feijoo G. A comparison of municipal wastewater treatment plants for big centres of population in Galicia (Spain). Int J LCA, Vol. 13, No.1, 2008, pp. 57-64.

[8] <http://www.ecoinvent.ch/>, (Accessed 25.10.2010).