URBAN WASTEWATER RECLAMATION FOR INDUSTRIAL REUSE: AN LCA CASE STUDY

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Abstract

Water scarcity is one of the major problems of the 21st century and one of the most sensitive environmental issues in the coming decades due to the uneven distribution of resources, treatment and climate change events. Wastewater reclamation is considered as an alternative source of fresh water in areas with problems of water availability or increased consumption.

The objective of this study is to use Life Cycle Assessment (LCA) methodology to identify and quantify the main environmental contributors derived from the treatment of urban wastewater and water reclamation opportunities in Tarragona, Spain. The wastewater treatment plant (WWTP) serves a population of about 150,000 inhabitants and has mechanical and biological treatment for the wastewater line and sludge processing. The primary data correspond to 2014, when 27,000 m^3/d of wastewater from urban collectors and rainwater were treated. Two scenarios are considered after the conventional treatment in the WWTP: a) direct discharge into a natural water stream and b) introduction of the tertiary treatment to facilitate water reuse in the nearby industrial area.

This study showed that the tertiary treatment contributes significantly to the environmental impacts. The category with the highest value is the cumulative energy demand (5.44 MJ-Eq) due to the large amount of energy required for the advanced treatment stages needed for reuse.

The results showed also that in the case of the "water reuse" scenario the indicator water depletion (WD) is $-4.39{\cdot}10^{-1}$ m^3 per m^3 of wastewater treated in Tarragona as compared with $5.74{\cdot}10^{-4}$ m^3 in the case of "no reuse" option. From a comparison of these alternatives it may be observed that in the case of the reuse scenario the value is negative which means that there is a net saving of water from nature. This indicator represents a measurement in a life cycle perspective of the effect of wastewater reuse in Spain, the non-potable use of reclaimed water reducing the stress on fresh water supplies.

Keywords: life cycle assessment, urban wastewater, reclaimed water, uncertainty analysis, Tarragona

Research highlights:

- Environmental impact comparison of two wastewater management solutions by LCA.
- The non-reuse scenario showed lower impacts in all categories but water depletion.
- Tertiary treatment application is recommended for net saving of water from nature.
- The uncertainty analysis showed inconclusive results for two impact categories.

1. Introduction

In a world with growing population and industrialization, water availability and use are of a major importance due to the uneven distribution of resources, treatment and consumption, as well as to the water scarcity and climate change extreme events (Valipour, 2015). In this sense, the sustainable use of water resources involves the concepts of integrated management, urban water use cycle, wastewater reuse strategies and materials and energy recovery, so as to offer opportunities for resources saving, better freshwater allocation and use, and the decrease of environmental impacts and risks towards the ecosystems and human health (Teodosiu et al., 2012). The World Health Organization has identified the major driving forces for global wastewater reuse as being closely related to the increase of: a) water scarcity and stress, b) populations and associated food security issues, c) environmental pollution from un-adequate wastewater disposal, d) recognition of the resource value of wastewater, excreta and greywater (WHO, 2006).

Water scarcity is one of the main problems faced by many societies in the 21st century and will become one of the most sensitive environmental issues in the coming decades. This water shortage is attributed to climate change and resulting drought, population growth and increased pollution. Many regions around the world are already facing this problem, southern states of the USA, southern Europe, North Africa, the Middle East and Australia. A country is considered “water stressed” when the amount of available freshwater per person per year is between 1,000 and 1,700 m^3. “Water-scarce” regions have the amount of available freshwater per person per year is less than 1,000 m^3/y (Harris, 2013). According to a European Commission Report, water scarcity is an increasingly frequent and worrying phenomenon that affects at least 11% of the European population and 17% of European Union (EU) territory (Alcalde Sanz and Gawlik, 2014).

The Wastewater Treatment Plants (WWTP) are conceived to decrease the environmental impacts of municipal and industrial discharges, but in the last decade they completed their facilities with advanced (tertiary) treatment, facilitating the wastewater recycling and reuse (Lyu et al., 2016), as well as recovery of materials or energy (Mo and

Zhang, 2013) for further use in the plant or for "export" to other activities. Such applications include: the gas production in biodigestors to reduce the energy consumption in WWTP, the application of sludge instead of mineral fertilizers in agriculture, wastewater reclamation and reuse for industrial applications.

The conventional treatment of municipal wastewater treatment plants (mechanical chemical and biological treatment) does not eliminate the priority pollutants from wastewaters that are considered for further reuse. Such priority (emerging) pollutants refer to a wide range of substances: pharmaceuticals and personal care products (PPCPs), different types of drugs, hormones and steroids, benzothiazoles, benzotriazoles, polychlorinated naphthalenes (PCNs), perfluorochemicals (PFCs), polychlorinated alkanes (PCAs), polydimethylsiloxanes (PDMSs), synthetic musks, quaternary ammonium compounds (QACs), bisphenol A (BPA), triclosan (TCS), triclocarban (TCC), polar pesticides, veterinary products, industrial compounds/by-products, food additives, engineered nano-materials (Lapworth et al., 2012). More than 700 emerging pollutants, their metabolites and transformation products are present in the European aquatic environment (Dulio and Von der Ohe, 2013), these chemicals causing known or suspected adverse ecological and (or) human health effects (high toxicity, carcinogenic and mutagenic effects) (Geissen et al., 2015).

The advanced (tertiary) treatment processes are mainly directed towards the removal of priority pollutants, but also to the removal of other type of pollutants that are of a great concern for reuse applications such as microorganisms, colloids, nutrients. More than one treatment process may be used for the advanced wastewater treatment so as to remove targeted pollutants and to achieve concentration levels that make the wastewater "adequate" for reuse applications. Such processes may be: membrane bioreactor and nanofiltration (Chon et al., 2011), forward osmosis and membrane distillation (Husnain et al., 2015), forward osmosis with coagulation/flocculation (Han et al., 2016).

Reverse osmosis is recognized as the most widely used membrane processes in water desalination, production of potable water and in wastewater treatment due to their competitive cost, simplicity, performances in separating both organic and inorganic pollutants, as well as microorganisms and colloids (Suarez et al., 2015). These technologies however generate also waste streams (concentrate) that require disposal with particular attention to minimizing their environmental impact (Jamil et al., 2015).

Wastewater reclamation is one of the recommended solutions for the problem of water scarcity because it recovers water inside the anthropic cycle avoiding the use of new freshwater from the natural cycle. In Europe, there are no legislative regulations regarding the reclamation of treated wastewater. However, the WWTP operators must take into account the requirements set out by EU environmental policy, in particular in the Water Framework Directive 2000/60/EC. Despite of the lack of water reuse criteria, several countries apply national or regional directives or guidelines for water reuse applications. Among the countries that have developed standards specifically for water reuse may be mentioned Cyprus, France, Greece, Spain, Italy and Portugal. In Spain the legal framework for the reuse of treated wastewater is the RD 1620/2007 (Alcalde Sanz and Gawlik, 2014). The major areas in which water is reused are: agricultural irrigation, groundwater recharge, urban applications, indirect potable reuse, recreational water use, environmental enhancement and aquaculture. In Spain, the targets for reused wastewater are: irrigation 79.2%, urban uses 8.1%, golf courses and recreational uses 6%, industrial uses 0.7% and ecological uses 6.0%. Spain has also the most important projection for wastewater reuse in 2025, the calculations suggest a value of over 1,200 Mm^3/y of reclaimed water, being a significant saving in the amount of freshwater that would be otherwise wasted (Raso, 2013).

However, the wastewater reclamation process may be complex, costly and resource and energy demanding, due to the combination of advanced processes needed to achieve the quality of the treated effluent (Husnain et al., 2015). Certain environmental indicators (primary energy demand, carbon footprint, etc.) could be unfavorable if compared only for the wastewater discharge and also the selection of treatment processes may be difficult both from the environmental and economical point of view. The analysis of such problems can be facilitated by Life Cycle Assessment (LCA), considered by many researchers to be the best practice regarding the evaluation of the environmental sustainability of a complex group of processes such as those of wastewater treatment plants or urban water cycles. LCA is used to evaluate the environmental aspects and potential impacts associated with all the stages of a product, process or service and it implies usually a *cradle to grave* approach.

When applied to municipal wastewater treatment, LCA will include the sewage system, infrastructure, raw materials, energy, additives, transport, etc. that are needed in WWTP and extended to the recovery systems where the outputs like gas, sludge and treated water are reused. After a detailed inventory of materials, mass and energy flows of the system considered, a set of environmental loads (emissions to air, water and soil) will be allocated to a unit of reference, called Functional Unit (FU). As a result, a set of indicators, called environmental profile, will be assigned to this FU.

Life Cycle Assessment proved to be a helpful tool that can be used to evaluate the environmental impact of wastewater treatment systems with different objectives as reviewed by Corominas et al. (2013) and Zang et al. (2015). Several LCA studies were applied to compare conventional wastewater treatment plants performance (Lorenzo-Toja et al., 2015; Piao et al., 2015). Other LCA studies compare different advanced treatment technology. For example, Bisinella de Faria et al. 2015 compared five wastewater treatment plant scenarios based on dynamic modelling and life cyle assessment. Pretel et al. 2016 reported the advantages of anaerobic and filtration-based technology by combining the steady-state performance modelling, LCA and LCC approaches. Moreover, LCA has been used in studies of nutrient removal from wastewater (Rodriguez-Garcia et al., 2014) and resource recovery technologies (Fang et al., 2016).

Some studies discuss the reverse osmosis membranes performances applied for wastewater reuse (Bunani et al., 2015; Pramanik et al., 2015), while others refer to the comparison of wastewater reuse with other water supply options like desalination or potable water production through the life cycle perspective (Meneses et al., 2010; Pasqualino et al., 2010).

However, only few studies focus on the environmental assessment by means of LCA of pilot or full-scale treatment for wastewater reuse applications for industry or agriculture. Theregowda et al. (2014) compared six tertiary alternatives to treat secondary municipal wastewater for reuse in a thermoelectric power plant cooling system, the alternatives were estimated using pilot plant scale results and only four categories of impacts. Muñoz et al. (2009) have used LCA to compare four different scenarios, including no reuse, reuse without tertiary treatment, reuse after tertiary treatment (ozonation) and reuse after processes combination (ozonation and hydrogen peroxide), with special focus on toxicity-related impact categories. Zhang et al. (2010) assessed a LCA hybrid to evaluate a wastewater treatment and water reuse project in China only in terms of energy consumption. Tong et al. (2013) investigated the water reuse in an industrial park assessing four scenarios (wastewater treated and discharged, 20% and 99% of wastewater is treated and reused as industrial process water, treated wastewater is used for horticulture).

This study considers the environmental assessment of a wastewater treatment plant that includes tertiary treatment located in Tarragona, in the basin of the river Francoli on the Mediterranean coast. The evaluation is realized by means of the LCA methodology in order to identify and quantify the main environmental contributors derived from the treatment of urban wastewater and to assess the water reclamation opportunities in Tarragona, Spain. Two alternatives (scenarios) are considered after the secondary treatment of the WWTP: 1) direct discharge into a natural water stream and 2) a tertiary treatment stage with the purpose of water reuse in the nearby industrial area. For the first scenario the use of sludge from WWTP as fertilizer reduces the impact assigned to FU by considering a credit for the avoided production of equivalent chemical fertilizer. As discussed also later in more detail, in the second scenario, in addition to the benefit of the use of sludge as fertilizer, an extra credit is obtained by using reclaimed water for industrial uses instead of potable water from the local Potable Water Treatment Plant (PWTP).

For the sake of a better representativeness of the case study, data extracted for each of the activities/products considered were adapted whenever possible mainly in three ways: updating the Spanish electricity mix, adapting the transport type and deducting infrastructure since it has been reported negligible and similar in all possible scenarios.

The last section of the manuscript includes an uncertainty analysis to evaluate the reliance degree of the results. Uncertainty is an omnipresent topic in LCA, and its inclusion for supporting and quantifying the confidence of the model results is largely recommended in the guidelines of several regulatory bodies such as International Organization for Standardization (ISO), International Reference Life Cycle Data System (ILCD), United States Environmental Protection Agency (USEPA), Intergovernmental Panel of Climate Change (IPCC), etc. However, full uncertainty analyses are rarely carried out by LCA practitioners (Lloyd and Ries, 2007). In the present study, we performed a sampling propagation method to capture the variability and uncertainty of the estimated environmental outcomes. The results of this analysis provide further understanding and confidence indicators to support the findings extracted for the considered scenarios.

2. Methodology

The Life Cycle Assessment (LCA) methodology is standardized by ISO 14040:2006 (ISO, 2006a) and ISO 14044: 2006 (ISO, 2006b) which define LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle, from raw material acquisition to production, use and disposal of the wastes generated. The LCA study is conducted in four steps, according to the ISO 14040 specific guidelines: *definition of goal and scope, inventory analysis, impact assessment and interpretation of results*.

2.1. Definition of goal and scope

The general goal of this study is to assess the environmental profile of an urban wastewater and water reclamation system in the Mediterranean area (Spain) based on actual operation data. The Functional Unit (FU) used is 1 m^3 of wastewater entering the municipal WWTP. When applied to urban wastewater treatment, it will include all the energy and mass input and output flows for the operation stages of the WWTP and extended to the recovery systems where the treated water are reused. The system boundaries considered include all the processes involved from wastewater collection to final disposal or reuse in industry. The volume of reclaimed water is derived from the end of the water line in the WWTP to the tertiary system by demand for its use in the nearby industrial facilities.

As in the majority of LCA studies applied to municipal WWTP, only the operational activities were considered, the environmental impacts of the construction, dismantling and infrastructure of buildings or equipment were not part of the system (Corominas et al., 2013; Teodosiu et al., 2016). The data reference year is 2014 and Table 1 summarizes the inventory fluxes taken into account.

In Fig. 1, the main stages and the system boundaries are presented and the reference flows for the main activities are considered. Two different scenarios are assessed, before and after the use of the tertiary treatment plant (TTP). Details of the stages included in the subsystems WWTP, TTP, PWTP are presented in Fig. 1. With dashed lines rectangles are marked those activities that are considered as credits in the system because they represent environmental impacts that are avoided. Two alternative scenarios have been assessed:

- **Scenario 1: No wastewater reuse**- Wastewater goes through the primary and secondary treatment, and then the effluent is discharged into a natural water stream. This scenario represents the situation in most of the Spanish WWTPs;

- **Scenario 2: Wastewater reuse and potable water replacement**– After the TTP reclaimed water is reused for industrial use replacing potable water from the local PWTP.

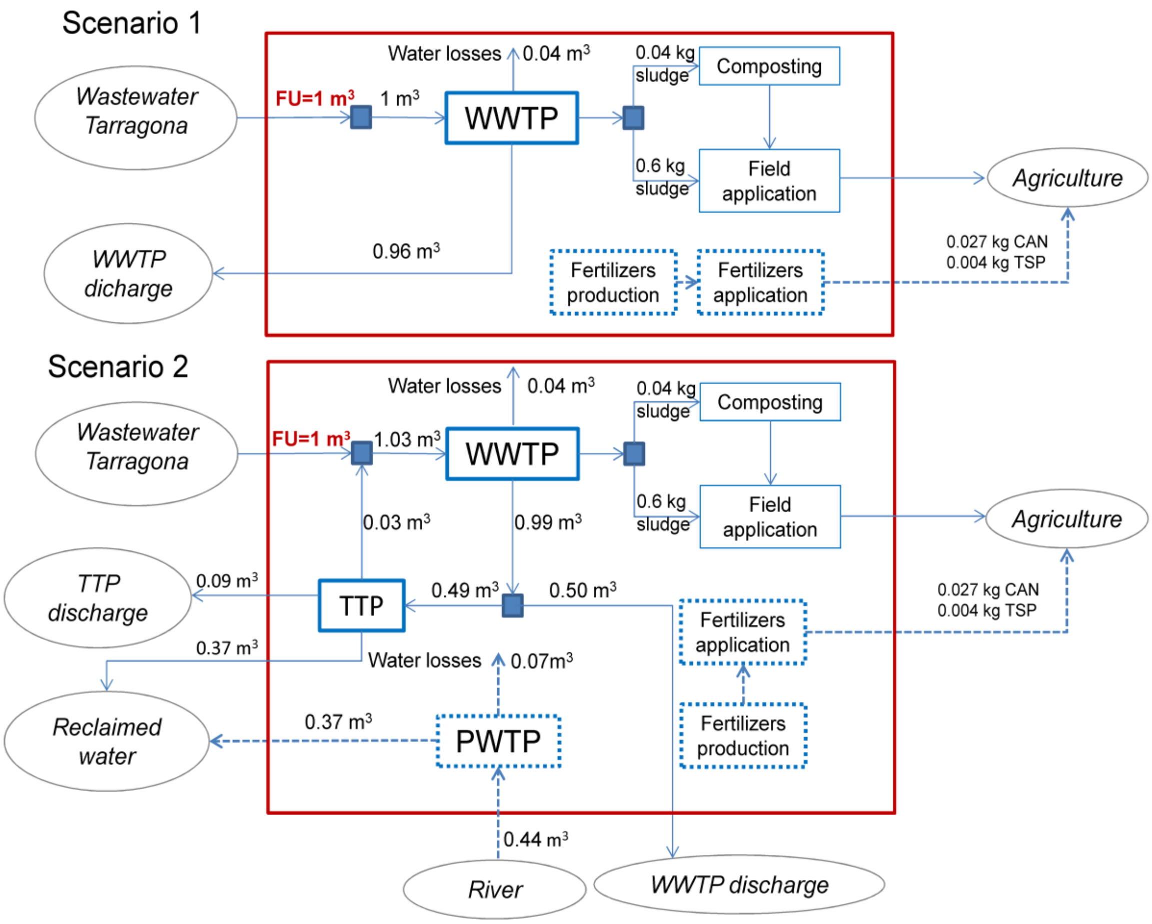

Fig. 1. The system boundaries, all units are expressed per FU (1 m^3 wastewater).

2.2. Inventory analysis

2.2.1 Wastewater treatment plant

The Tarragona WWTP, located at the basin of the river Francoli, treats an average of 25,000 m^3/d of residual water from the urban sewerage system and rainwater, serving a population of 132,000 inhabitants. The amount of wastewater entering the plant in 2014 was 9,122,810 m^3/y, which is provided by urban collectors and rainwater. As shown in Fig. 2 the plant consists of two main lines: water and sludge lines. The water line is structured into: bar screen, grit chamber/degreaser, primary settler, anaerobic reactor, aerobic reactor and secondary settler. The sludge line consists of: primary sludge sieve, gravity thickener, flotation thickener, mixing chamber, anaerobic digester, tampon storage, centrifuge dehydration, final storage and final disposal. The sludge is applied on agriculture and composting and the treated wastewater is discharged into the sea. Biogas is produced in the anaerobic digestion of sludge as a byproduct and is used to heat up the digester. The rest of biogas is usually burned without energy recovery. However, it should be noted that the biogas produced in the plant and burned internally in the digester can be considered a renewable energy source avoiding the use of electricity from the external grid.

The Life Cycle Inventory (LCI) was computed mainly from site specific operating data collected from personal interviews and internal reports from the Tarragona WWTP staff, as well as from some data in previous studies and the bibliography (Pasqualino et al., 2009). Data quality is assured by the accuracy of the plant operating data and the reported deviation of values from database. LCA inventory was performed with the assistance of Ecoinvent database V3.1 2014 (Swiss Centre for Life-Cycle Inventories, SCLCI 2009). We considered all the reagents used in the different treatment stages, including packaging and transport of these reagents, treatment and/or final disposal of the wastes generated by WWTP, service consumption, maintenance materials and the energy consumed during every treatment stage. Empresa Municipal Mixta de Aguas de

Tarragona, EMATSA, the company in charge of the wastewater management provided energy data for every treatment stage.

Since the energy consumption was expected to be significant in the analyzed system, the selected dataset in Ecoinvent database V3.1 (low voltage electricity for Spanish location) was modified in order to update the Spanish national profile for electricity production (including import and export flows), transformation from high voltage to medium voltage, and medium voltage to low voltage. Electricity production and import/export data were updated for 2014 (Red Eléctrica Española, 2014).

Chemical products representing the raw materials were directly selected from the Ecoinvent database V3.1. When the exact dataset was not found a proxy was used taking a material with similar chemical features and technical purpose. Particularly, polyacrylamide (PAM) was used for the production of the polyelectrolyte. Transport by lorry (Euro5, 7.5-16 t) was selected as standard transport for raw materials, waste and sludge. The distances from supplying facilities to WWTP were given by the Tarragona WWTP contact personnel, and an average distance of 13.6 km were considered for the waste disposal, 50 km for the sludge in field application and 7.5 km for compost plant.

The final disposal of sludge to agriculture (94.4%) and composting (5.6%) is assumed to replace the usage of synthetic fertilizers. Calcium ammonium nitrate (CAN) and the triple superphosphate (TSP) were considered to be the industrial products avoided as synthetic fertilizers, this approach being also considered in similar studies (Hospido et al., 2005; Lundin et al., 2000). The sludge dosage to soil has been calculated according to bibliographic data (Pasqualino et al., 2009).

About 51% of the treated wastewater is discharged into the sea after secondary treatment. The remaining approx. 49% undergoes the tertiary treatment, where it reaches the standard of quality required for reuse in non-potable application (chemical industry).

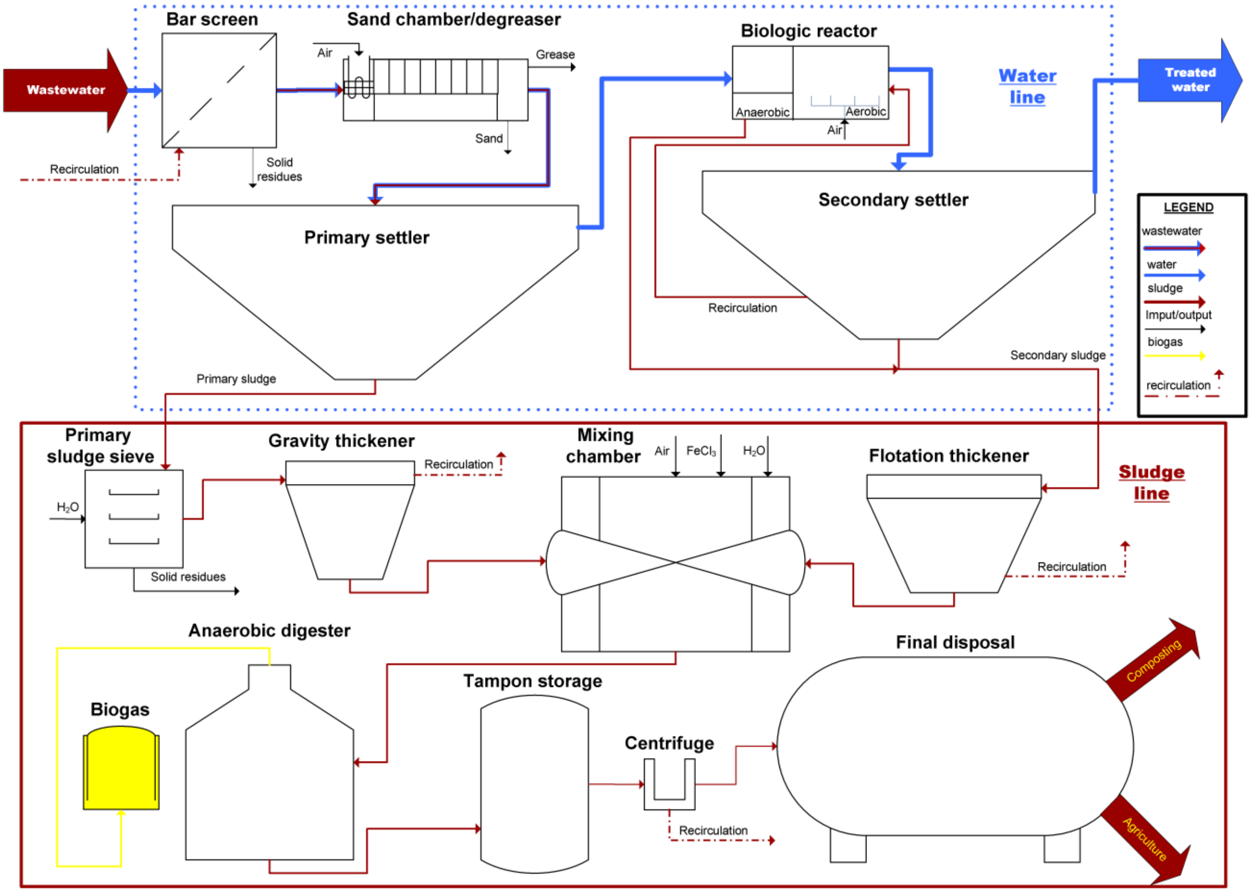

Fig. 2. Wastewater treatment plant flow-sheet, Tarragona, Spain.

2.2.2. Water reclamation plant (Tertiary treatment)

About 8,800 m^3/d (3,215,031 m^3/y) of reclaimed water is produced in this plant and used for non-potable purposes, replacing other sources of potable water and saving a valuable resource. The reclaimed water is used primarily in cooling towers. After the secondary treatment, the effluent from Tarragona WWTP is sent to coagulation-flocculation, followed by micro-screen filtration technology and then two-stage sand filtration (as presented in Fig. 3). The anti-fouling agent used to prevent salt precipitation on the membranes is Na_2SO_3. The next stage of the TTP is the reverse osmosis system operating with double pass racks, with each pass having 3 stages. The water from the reverse osmosis stage undergoes disinfection by ultraviolet light so as to remove any trace of organics that might have passed through the membranes and also microorganisms, in compliance with the Spanish Royal Decree 1620/2007 water standard for industrial application. Finally, sodium hypochlorite is added to maintain a residual disinfection capacity in the distribution system. Reverse osmosis also comprises a chemical cleaning system and its effluent is pumped to the WWTP outlet pipeline along with the reject (concentrate) stream.

We used the operating data provided by staff of the TTP as primary data of the plant processes, as well as some site specific bibliography (Veolia Water Technologies, 2013) for detailed material and energy inputs and outputs for the plant operation during the year 2014. Secondary data for the flows of the background system (raw materials and energy production, transport and waste disposal activities, etc.) were extracted from the Ecoinvent database V3.1.

Similarly to the WWTP situation, the dataset for low voltage electricity consumption was updated for the year 2014 based on the Spanish national profile of electricity production (Red Eléctrica Española 2014).

Chemical products were directly selected from the Ecoinvent database V3.1. When the exact dataset was not found, a proxy was used by taking a material with similar chemical features and technical purposes. Particularly, aluminium hydroxide production was used as coagulant for the analysis. A very common polymeric flocculating agent, PAM (polyacrylamide), was used to represent the polyelectrolyte with the commercial name HYDREX. Transport by lorry (7.5 – 16 t) was considered for the raw materials to the plant site, by assuming a distance of 100 km, estimated as the worst case, considering also the proximity of the reclamation plant to the industrial facilities of Tarragona and Barcelona (that can provide any of the necessary raw materials). The membranes were supplied by Dow Water&Process Solutions and have a warranty time period of 3 years. In the year of this study (2014), the membranes were not changed. The life of membranes was excluded from this assessment since, as proven by other studies, membrane renewal has negligible environmental impacts (Meneses et al., 2010).

After the tertiary treatment plant, the resulting water (75% of the total water entering the TTP) is used instead of potable water for industrial (non-potable) uses. To account the avoided impacts due to this alternative, the system was extended to include the environmental load of the PWTP that would provide the same amount of water in the industrial area.

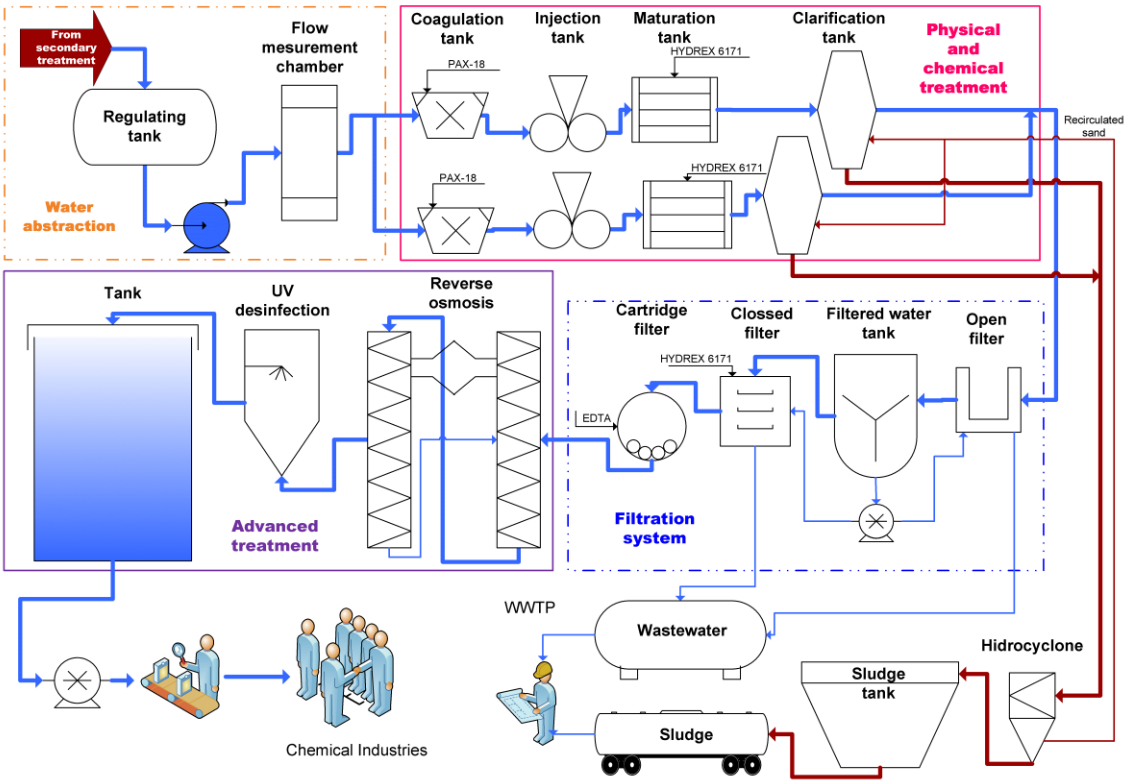

Fig.3. Tertiary Treatment Plant flow sheet, Tarragona, Spain.

2.2.3 Potable water treatment plant (PWTP)

The water consumed in Tarragona is supplied from the Ebro river basin and is directly pumped to the PWTP located in Ampolla, Tarragona. In 2014, this plant treated 3,858,037 m^3/y of river water to obtain the correspondent amount of water produced after tertiary treatment. This quantitative value was determined considering 20% water losses

(Amores et al., 2013). This potable water treatment plant consists of two main lines: water and sludge, as detailed in Fig. 4.

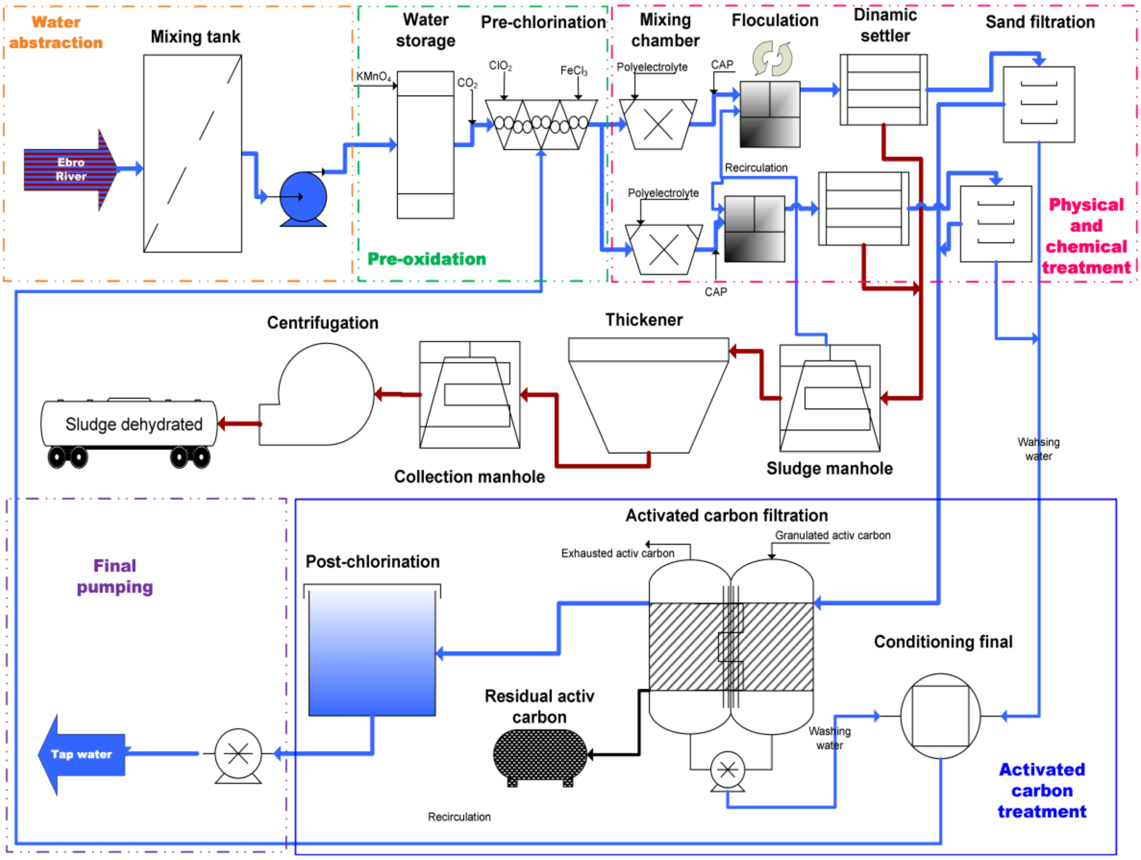

Fig. 4. Potable Water Treatment Plant flow sheet, Tarragona, Spain

Homogenization of water composition is made in the mixing tank, followed by pre-oxidation, the physical and chemical treatment comprising flocculation, sedimentation and sand filtration stages. The flowsheet is completed by the activated carbon filters in order to improve taste and odour properties and to remove the micropollutants. After that, chorine is added for disinfection and for preventing the microorganism growth in the distribution system. The sand separated as waste is sent to the sludge line where the sludge is collected, thickened and finally dried. Primary data were provided by the Consorci d´Aigues de Tarragona (CCAAIT, 2014) to model the plant processes and secondary data were extracted from Ecoinvent database V3.1. Like for the WWTP and the TTP, the main raw materials and energy consumption for the different treatment stages, including packaging and transport, as well as waste treatment and/or final disposal activities are included in the PWTP model. Apart from this, the same updated electricity dataset was used, as explained in previous subsections. Particularly, PAM was used for the production of the polyelectrolyte and aluminum hydroxide was used as flocculant.

Transport by lorry (7.5 – 16 t) was considered for the raw materials to the plant site, assuming a distance of 100 km, estimated as the worst case, considering the proximity of the PWTP to Tarragona and Barcelona that can provide whatever necessary raw material.

2.2.4. Life Cycle Inventory

Table 1 shows the input and output energy and mass flows considered in the two mentioned scenarios.

Table 1. Main inventory inputs and outputs (data from 2014) for the treatment of 1 m^3 wastewater in Tarragona, Spain.

Wastewater treatment	**Inputs**	**Outputs**	**Energy Consumption**	**Process considered**
Wastewater treatment plant	$6.58 \cdot 10^{-3}$ kg $FeCl_3/m^3$ (transported $6.58 \cdot 10^{-4}$ tkm/m^3) $1.64 \cdot 10^{-3}$ kg polyelectrolyte/m^3 (transported $1.64 \cdot 10^{-4}$ tkm/ m^3) Transport freight	$1.36 \cdot 10^{-2}$ kg/m^3 solid waste (transported $1.85 \cdot 10^{-4}$ tkm/m^3) $4.13 \cdot 10^{-3}$ kg/m^3 sand (transported $5.61 \cdot 10^{-5}$ tkm/m^3) $5.13 \cdot 10^{-4}$ kg/m^3 grease (transported $6.98 \cdot 10^{-6}$ tkm/m^3) $2.79 \cdot 10^{-3}$ kg/m^3 solid waste (transported $3.80 \cdot 10^{-5}$ tkm/ m^3) Sludge production: $6.64 \cdot 10^{-1}$ kg/m^3 Transport by lorry (7.5-16t)	$8.43 \cdot 10^{-1}$ kWh/m^3	Water line: bar screen, sand chamber/ degreaser, primary settler, anaerobic reactor, aerobic reactor, secondary settler Sludge line: primary sludge sieve, gravity thickener, flotation thickener, mixing chamber, anaerobic digester, tampon storage, centrifuge dehydration, final storage, final disposal
Water Reclamation Plant (Tertiary treatment)	$3.26 \cdot 10^{-2}$ kg $Al(OH)_3$ (transported $3.26 \cdot 10^{-3}$ tkm/m^3) $4.91 \cdot 10^{-4}$ kg polyelectrolite/m^3 (transported $4.91 \cdot 10^{-5}$ tkm/m^3) $3.42 \cdot 10^{-3}$ kg Na_2SO_3 /m^3 (transported $3.42 \cdot 10^{-4}$ tkm/m^3) $1.32 \cdot 10^{-2}$ kg NaClO/m^3 (transported $1.32 \cdot 10^{-3}$ tkm/m^3) Transport by lorry (7.5-16t)	Waste production: $6.89 \cdot 10^{-2}$ kg/m^3	1.19 kWh/m^3	Coagulation-flocculation, microscreen filtration, two-stage sand filtration, reverse osmosis, UV treatment

Wastewater treatment	**Inputs**	**Outputs**	**Energy Consumption**	**Process considered**
Potable water treatment plant	$1.42 \cdot 10^{-2}$ kg $FeCl_3$/ m^3 (transported $1.42 \cdot 10^{-3}$ tkm/m^3) $9.30 \cdot 10^{-4}$ kg polyelectrolyte PoliDamac/m^3 (transported $9.30 \cdot 10^{-5}$ tkm/m^3) $1.95 \cdot 10^{-3}$ kg Cl_2/m^3 (transported $1.95 \cdot 10^{-3}$ tkm/m^3) $1.31 \cdot 10^{-2}$ kg CO_2/m^3 (transported $1.31 \cdot 10^{-3}$ tkm/m^3) $4.06 \cdot 10^{-3}$ kg $NaClO_2$/ m^3 (transported $4.06 \cdot 10^{-4}$ tkm/m^3) $7.60 \cdot 10^{-2}$ kg GAC/ m^3 (transported $7.60 \cdot 10^{-3}$ tkm/m^3) Transport by lorry (7.5 – 16t)	$8.27 \cdot 10^{-4}$ kg/m^3 solid waste (transported $8.27 \cdot 10^{-5}$ tkm/m^3) Sludge production: $1.08 \cdot 10^{-1}$ kg/m^3 Transport by lorry (7.5 – 16t)	$8.21 \cdot 10^{-1}$ kWh/m^3	Water line: preoxidation, coagulation, flocculation, decantation, sand filters, active carbon filters, post chloration Sludge line: collection, thickening, sludge drying, drying zone

2.3 Life Cycle Impact Assessment (LCIA)

ReCiPe method (Goedkoop et al., 2008) at midpoint level (Hierarchist (H) perspective) was used as impact assessment procedure. The main inventory inputs and outputs are presented in Table 1, for each of the treatment variants considered in this study. The impact categories considered were: TA (terrestrial acidification, kg SO_2-Eq), CC (climate change, kg CO_2-Eq), FE (freshwater eutrophication, kg P-Eq), ME (marine eutrophication, kg N-Eq), POF (photochemical oxidant formation, kg NMVOC), MD (metal depletion, kg Fe-Eq), FD (fossil depletion, kg oil-Eq), OD (ozone depletion, kg CFC-11-Eq), TT (total toxicity, 1,4-DCB-Eq) and WD (water depletion, m^3). The total toxicity is considered as the addition of freshwater ecotoxicity, human toxicity, marine ecotoxicity and terrestrial ecotoxicity. These impact categories were selected because they are expected to be the most important impacts based on the studied literature. Additionally, taking into account the energy demanding nature of the assessed systems, the cumulative energy demand (MJ-Eq) from CML 2001 methodology, was also evaluated, because it measures the environmental implications of non-renewable energy consumption.

3. Results and discussion

3.1. Scenario 1: Wastewater treatment plant with no wastewater reuse

Table 2 presents the results for the environmental impact profile of the Tarragona WWTP which represent the first scenario at midpoint level. All these calculations have been made based on operational data and the results reflect the current situation in many WWTPs in Spain with similar technologies. The relative contribution of the environmental profiles of the main treatment stages of the plant is displayed in Fig. 5. Negative values mean benefits to the environment, and positive values mean damages.

Table 2. Environmental profile for the WWTP operational stages, referred to the treatment of 1 m^3 of wastewater produced in the city of Tarragona.

Environmental impact category	Unit	Primary treatment	Secondary treatment	Sludge line	Services
Terrestrial acidification, TA	kg SO_2-Eq	$7.97\cdot10^{-5}$	$3.39\cdot10^{-4}$	$-8.93\cdot10^{-4}$	$1.87\cdot10^{-6}$
Climate change, CC	kg CO_2-Eq	$9.95\cdot10^{-3}$	$4.16\cdot10^{-2}$	**$-1.59\cdot10^{-1}$**	$4.89\cdot10^{-4}$
Freshwater eutrophication, FE	kg P-Eq	$6.42\cdot10^{-7}$	$2.74\cdot10^{-6}$	$3.20\cdot10^{-4}$	$1.84\cdot10^{-8}$
Marine eutrophication, ME	kg N-Eq	$1.36\cdot10^{-6}$	$5.67\cdot10^{-6}$	$-4.07\cdot10^{-5}$	$4.51\cdot10^{-8}$
Photochemical oxidant formation, POF	kg NMVOC	$3.79\cdot10^{-5}$	$1.58\cdot10^{-4}$	$-2.71\cdot10^{-4}$	$2.09\cdot10^{-6}$
Metal depletion, MD	kg Fe-Eq	$6.68\cdot10^{-4}$	$2.84\cdot10^{-3}$	$-2.72\cdot10^{-3}$	$2.03\cdot10^{-4}$
Fossil depletion, FD	kg oil-Eq	$2.35\cdot10^{-3}$	$9.87\cdot10^{-3}$	$-1.48\cdot10^{-2}$	$1.91\cdot10^{-4}$
Ozone depletion, OD	kg CFC-11-Eq	$1.29\cdot10^{-9}$	$5.46\cdot10^{-9}$	$-4.81\cdot10^{-9}$	$6.75\cdot10^{-11}$
Total toxicity, TT	kg 1,4-DCB-Eq	$1.11\cdot10^{-3}$	$3.27\cdot10^{-3}$	**3.56**	$3.16\cdot10^{-4}$
Water depletion, WD	m^3	$5.28\cdot10^{-5}$	$2.26\cdot10^{-4}$	$2.93\cdot10^{-4}$	$1.25\cdot10^{-6}$
Cumulative energy demand, CED	MJ-Eq	$2.85\cdot10^{-1}$	1.22	$-1.06\cdot10^{-1}$	$8.37\cdot10^{-3}$

Compared with water and sludge line the influences of the services are negligible. The treatment stage with the largest environmental impact is the secondary (biological) treatment, with a contribution of between 20% and 90%. The secondary treatment has the highest environmental impacts for most of the indicators, with the exception of freshwater eutrophication (FE). The environmental impact of the secondary treatment is mainly caused by the high energy consumption in the aerobic reactor and the chemical reagents used. The indicator with the highest environmental impact in the sludge line is the total toxicity (TT) 3.56 kg 1,4-DCB-Eq mainly because of the release of heavy metals. There are also significant benefits in marine eutrophication (ME), climate change (CC) and terrestrial acidification (TA). For example, the climate change (CC) is $-1.59 \cdot 10^{-1}$ kg CO_2-Eq avoiding the CO_2 emissions caused by the manufacture of chemical fertilizers. In Fig. 5 we observe that the sludge line has negative values which means environmental benefits. This is due to the use of sludge in agriculture and composting, avoiding the production of synthetic fertilizers and supporting the important role of a sustainable sludge management (Pasqualino et al., 2009).

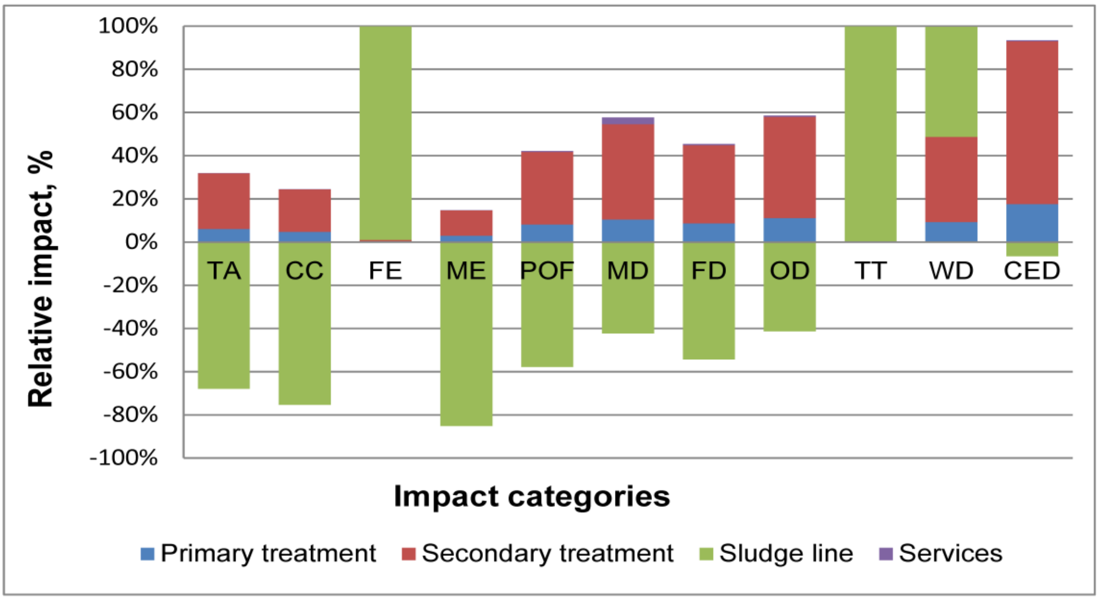

Fig. 5. Relative contribution of the WWTP treatment stages.

3.2. Scenario 2: Wastewater reuse and potable water replacement

In this case, wastewater is reused after applying a tertiary treatment consisting on several stages including reverse osmosis. The wastewater is used instead of potable water for non-potable use (industrial). For this scenario we have considered the whole treatment at the WWTP (including the tertiary treatment applied to 49% of the secondary effluent) as an environmental load, and we have counted the environmental impacts of producing potable water as an avoided load (as presented in Table 3).

The addition of tertiary treatment to a WWTP increases the environmental impacts in the majority of the impact category with the exception of total toxicity (TT) $1.45 \cdot 10^{-1}$ kg 1,4-DCB-Eq and freshwater eutrophication (FE) $2.33 \cdot 10^{-5}$ kg P-Eq. These categories have the lowest environmental impacts for the treatment stages due to the high amount of nutrients from sludge use for soil application. Freshwater eutrophication and total toxicity had a lower impact than that of the WWTP because the amounts of P discharged were lower.

The impacts increased in tertiary treatment are due to the large amount of energy required for the advanced treatment stages. The energy impact is proven by the cumulative energy demand (CED) value as depicted in Table 3, where in the case of the WWTP direct discharge CED is 1.40 MJ-Eq as compared with 5.44 MJ-Eq per m^3 of wastewater entering the system in the case of tertiary treatment. The total electricity consumption of the tertiary treatment plant is 1.19 kWh/m^3. Any increase of the impacts is compensated by the fact that reclaimed water can replace potable water for industrial uses.

The influence of each stage of operation on the total environmental impacts is presented in Fig. 6. The most significant environmental impact of the tertiary treatment is due to its energy intensive processes.

Table 3. Environmental profile of the direct discharge and reclaimed water options referred to 1 m^3 of wastewater entering the whole system.

Environmental impact category	Unit	WWTP Direct discharge	Tertiary treatment	Subtotal	PWTP	Total
Terrestrial acidification, TA	kg SO_2-Eq	$-4.72 \cdot 10^{-4}$	$1.67 \cdot 10^{-3}$	$1.18 \cdot 10^{-3}$	$9.21 \cdot 10^{-4}$	$2.77 \cdot 10^{-4}$
Climate change, CC	kg CO_2-Eq	$-1.07 \cdot 10^{-1}$	$1.95 \cdot 10^{-1}$	$8.43 \cdot 10^{-2}$	$1.20 \cdot 10^{-1}$	$-3.20 \cdot 10^{-2}$
Freshwater eutrophication, FE	kg P-Eq	$3.24 \cdot 10^{-4}$	**$2.33 \cdot 10^{-5}$**	$3.57 \cdot 10^{-4}$	$7.80 \cdot 10^{-6}$	$3.40 \cdot 10^{-4}$
Marine eutrophication, ME	kg N-Eq	$-3.37 \cdot 10^{-5}$	$2.91 \cdot 10^{-5}$	$-5.68 \cdot 10^{-6}$	$1.71 \cdot 10^{-5}$	$-2.17 \cdot 10^{-5}$
Photochemical oxidant formation, POF	kg NMVOC	$-7.32 \cdot 10^{-5}$	$7.84 \cdot 10^{-4}$	$7.06 \cdot 10^{-4}$	$4.42 \cdot 10^{-4}$	$2.69 \cdot 10^{-4}$
Metal depletion, MD	kg Fe-Eq	$9.95 \cdot 10^{-4}$	$1.35 \cdot 10^{-2}$	$1.43 \cdot 10^{-2}$	$8.11 \cdot 10^{-3}$	$6.39 \cdot 10^{-3}$
Fossil depletion, FD	kg oil-Eq	$-2.41 \cdot 10^{-3}$	$4.85 \cdot 10^{-2}$	$4.59 \cdot 10^{-2}$	$2.89 \cdot 10^{-2}$	$1.72 \cdot 10^{-2}$
Ozone depletion, OD	kg CFC-11-Eq	$2.01 \cdot 10^{-9}$	$2.87 \cdot 10^{-8}$	$3.07 \cdot 10^{-8}$	$1.91 \cdot 10^{-8}$	$1.16 \cdot 10^{-8}$
Total toxicity, TT	kg 1,4-DCB-Eq	3.57	**$1.45 \cdot 10^{-1}$**	3.83	$1.31 \cdot 10^{-2}$	3.70
Water depletion, WD	m^3	$5.74 \cdot 10^{-4}$	$1.00 \cdot 10^{-3}$	$1.59 \cdot 10^{-3}$	$4.41 \cdot 10^{-1}$	$-4.39 \cdot 10^{-1}$
Cumulative energy demand, CED	MJ-Eq	**1.40**	**5.44**	6.88	3.31	3.53

The energy consumption could not be allocated to each stage of the wastewater reclamation plant due to the lack of information. We have used the total energy consumed in the tertiary treatment. It is for this reason that in Fig. 6 the concept “energy” appears separated with respect to the stages of the system, as if it was a stage in the process itself. In this way, the outputs in the different categories of environmental impact can be evaluated and compared for the process stages though in terms of other concepts as materials use, transport, waste management, etc.

We can observe that the environmental impact for all the treatment stages are approximately the same. For most of the impact categories, the environmental impact of physical and chemical treatment is related to the reagents coagulant (PAX-18) and flocculant (HYDREX 6171) used. Freshwater eutrophication (FE) and total toxicity (TT) are affected by the sludge line.

As it may be observed from Fig. 7, energy, followed by chemicals and waste, contributes to a high extent to the environmental impacts. The energy requirement for pumping wastewater from the secondary to the tertiary treatment and from tertiary treatment to the final destination has not been considered. As expected, the most significant environmental impact of the tertiary treatment plant is due to its energy intensive process. Energy consumption is clearly related to the final environmental impacts, as it can be observed from the high influence of the reverse osmosis stage. We should take into account that in this WWTP, the TTP was added to the process after several years of operation. This is why the energy required for the TTP is quite significant, but in the case of a new plant these impacts can be reduced through the integrated plant design or by using renewable energies.

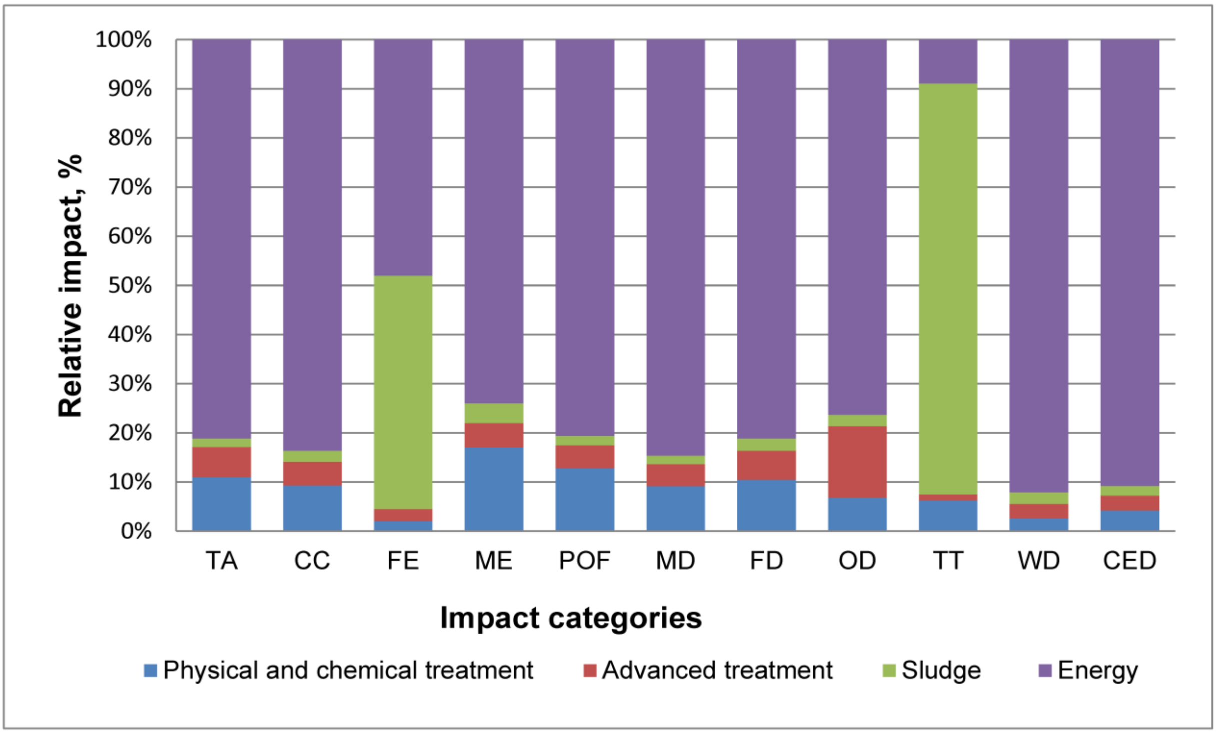

Fig. 6. Environmental profile of the tertiary treatment stages.

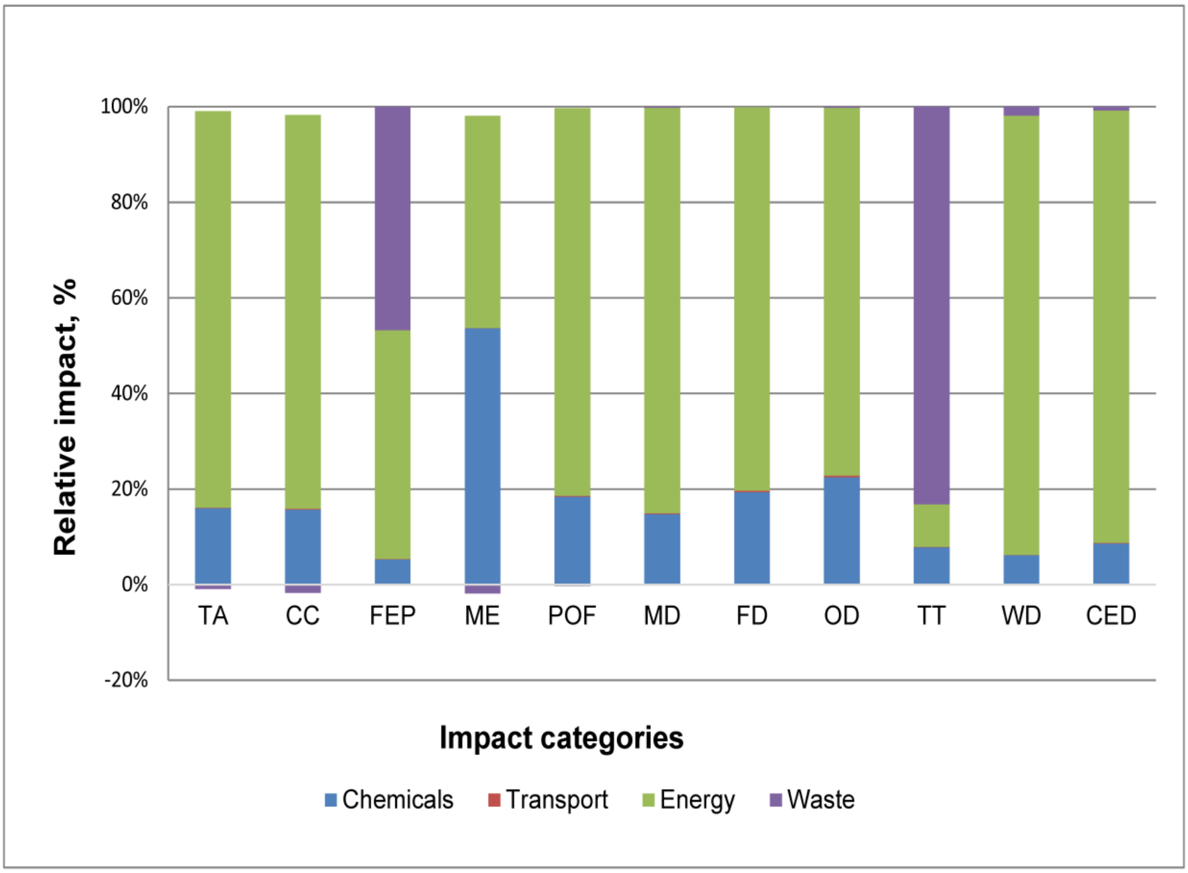

Fig. 7. Fluxes of the tertiary treatment stages.

3.3. Scenarios comparison

In Table 4, a comparison of the environmental impacts is made by considering the alternatives of “no reuse” and “reuse” scenarios. Scenario 1 (“no reuse”) reflects the impacts of the primary, secondary, sludge treatments of the WWTP and discharge of the treated wastewater into the sea. Although this is the easiest scenario from the treatment and costs point of view, it means the waste of a precious resource, water. One can see that the replacement of potable water with tertiary treatment added to a traditional WWTP increases the environmental impact for all the categories studied.

The most remarkable difference was found by analyzing the water depletion (WD) indicator. We may see that in the case of the water reuse scenario the value is negative (-$4.39{\cdot}10^{-1}$ m^3) which means an environmental benefit as compared with the “no wastewater reuse” scenario ($5.74{\cdot}10^{-4}$ m^3).

This reuse option is a straightforward solution to augment freshwater resources, this fact is important especially in water-stressed areas such as the Mediterranean region.

It should be highlighted that different treatment stages and technologies, distances, efficiency of pumps will lead to different levels of energy consumption, which could make the environmental profile of the two scenarios similar or different. Thus we cannot generalize and conclude that the tertiary treatment would have a higher impact than the potable water production.

Table 4. Comparison of Scenario 1 and Scenario 2, functional unit is 1 m^3 of wastewater entering the whole system.

Environmental impact category	**Unit**	**SCENARIO 1** *No wastewater reuse*	**SCENARIO 2** *Wastewater reuse and potable water replacement*
Terrestrial acidification, TA	kg SO_2-Eq	$-4.72\cdot10^{-4}$	$2.77\cdot10^{-4}$
Climate change, CC	kg CO_2-Eq	$-1.07\cdot10^{-1}$	$-3.20\cdot10^{-2}$
Freshwater eutrophication, FE	kg P-Eq	$3.24\cdot10^{-4}$	$3.40\cdot10^{-4}$
Marine eutrophication, ME	kg N-Eq	$-3.37\cdot10^{-5}$	$-2.17\cdot10^{-5}$
Photochemical oxidant formation, POF	kg NMVOC	$-7.32\cdot10^{-5}$	$2.69\cdot10^{-4}$
Metal depletion, MD	kg Fe-Eq	$9.95\cdot10^{-4}$	$6.39\cdot10^{-3}$
Fossil depletion, FD	kg oil-Eq	$-2.41\cdot10^{-3}$	$1.72\cdot10^{-2}$
Ozone depletion, OD	kg CFC-11-Eq	$2.01\cdot10^{-9}$	$1.16\cdot10^{-8}$
Total toxicity, TT	kg 1,4-DCB-Eq	3.57	3.70
Water depletion, WD	m^3	**$5.74\cdot10^{-4}$**	**$-4.39\cdot10^{-1}$**
Cumulative energy demand, CED	MJ-Eq	1.40	3.53

The results from the comparison of the two scenarios are presented in Fig. 8, where the relative scores taking as reference the highest value are depicted for each different impact category. The figure displays the common tendency of higher impacts for scenario 2, with the exception of water depletion. Wastewater treated by conventional and tertiary treatment is a promising candidate to replace freshwater due to its availability in urban areas. However, chemical industries demand large quantities of water of high quality as compared to other uses of reused water such as: fire protection, ornamental fountains, construction (Meneses et al., 2010). In this study, we have considered only 49% of wastewater undertaking a tertiary treatment. The results demonstrate the utility of LCA for decision-making regarding what type of advanced treatment is needed for the reuse of water from municipal wastewater treatment plants.

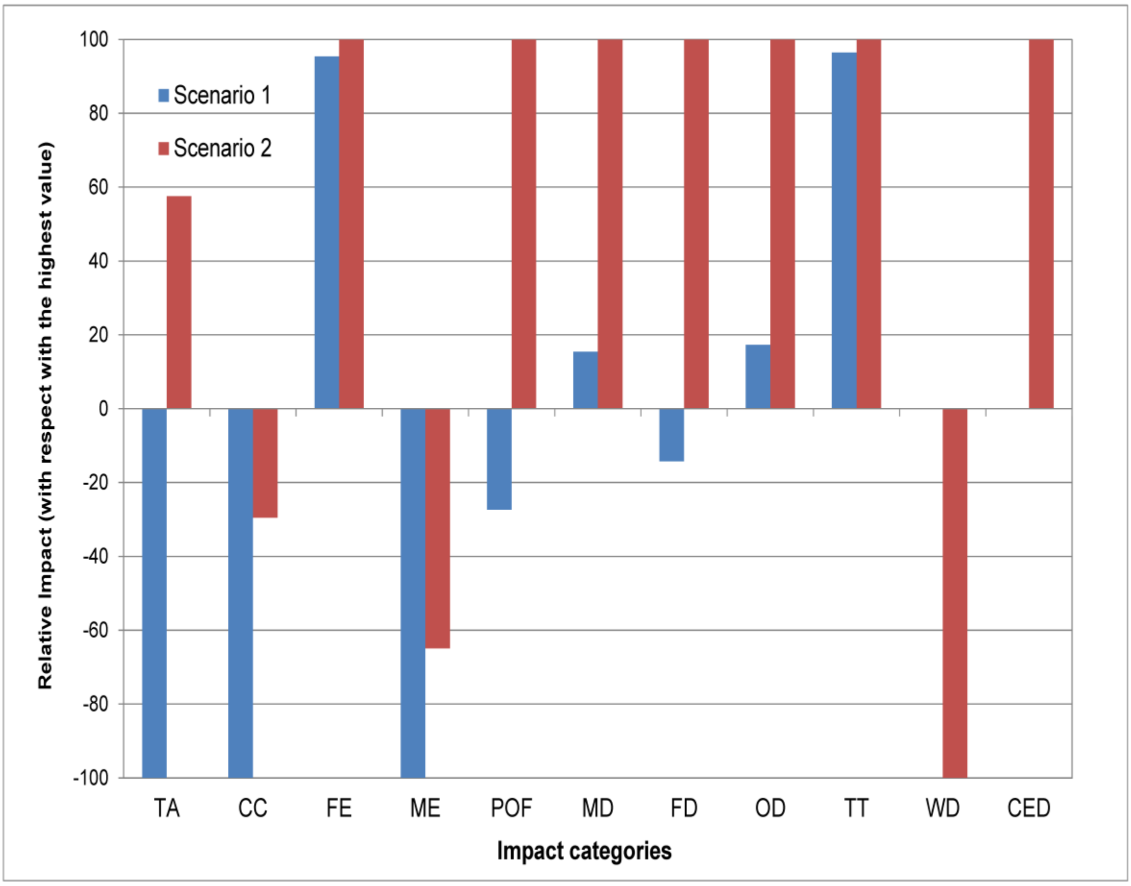

Fig. 8. Comparison of environmental impacts of both scenarios taking the highest value of each category as the reference.

4. Uncertainty analysis

Uncertainty appears in many ways in all stages of LCA. It shows up due to the uncertainty of the input data and the choices and assumptions made during the LCA procedure (Heijungs and Lenzen, 2014). In this study, only parametric uncertainty is considered, model uncertainty and other types of uncertainty, as for instance, that derived from setting system boundaries, allocation, time horizon and other choices were excluded. Among the parametric uncertainty, two sources were studied: on the one hand, variation and stochastic errors of the input data that describe the exchanges between the system and environment; on the other hand, the uncertainty due to the use of background data and characterization factors from LCA databases. The former implies the use of estimates, lacking verification, incompleteness, temporal, spatial and technological extrapolation. In order to assess the uncertainty that arise from these sources, the procedure for the error propagation is based on the detailed guidance of the ILCD Handbook about data quality concept and approach (European Commission, 2010) and the data quality guidelines for Ecoinvent database (Weidema et al., 2012).

Parametric uncertainty is represented by a lognormal probability distribution using the Pedigree Matrix approach that relates quality indicators to uncertainty ranges. Both basic and additional uncertainty, through variances of the underlying normal distribution, can be assigned. Basic uncertainty of the activity data and characterization factors are quantified for each LCA vector included in the inventory, as well as additional uncertainty according to five independent characteristics: reliability, completeness, temporal correlation, geographical correlation and further technological correlation.

Once the probability distributions of each of the input parameters are stablished, the error propagation is conducted using Monte Carlo simulations. With this sampling method, a sample of results were obtained, from which several statistics can be computed. In this case, 5,000 simulations were run for each scenario, allowing their comparison taking into account the evaluated uncertainties.

Fig. 9 shows the level of uncertainty for the two scenarios and the different impact categories. The length of the bars represents how far from the most expected values the results can be within the 95% of confidence interval. Certain categories show lower expected error, such as freshwater eutrophication, total toxicity, water depletion and cumulative energy demand, for which the error percentage is lower than 40%, particularly less than 10% for water depletion impact. The lower deviation of these scores can be explained by the high sensitivity that these impacts have to certain few parameters that besides do not present high variability.

Meanwhile, some categories of impact show great deviations. Specifically, fossil depletion impact in scenario 1 can take values ranging from -0.013 to 0.01 kg oil-eq/m^3. A sensitivity analysis of the unit processes that have more influence in the fossil depletion impact explains its high uncertainty. The analysis revealed high influence of a pair of polluting activities to which relatively high uncertainty was assigned. In fact, more than 55% of the impact comes from a dataset for the production of calcium ammonium nitrate at regional storehouse. This dataset was used in the model to compute part of the avoided environmental charges due to the substitution of nitrogen sources of chemical fertilizers with the sludge application in agriculture. The assigned uncertainty to this activity was high, given the perception of low representativeness. The error propagation originated by the combination of high sensitivity of activities with high uncertainty caused the large variability depicted in the fossil depletion impact.

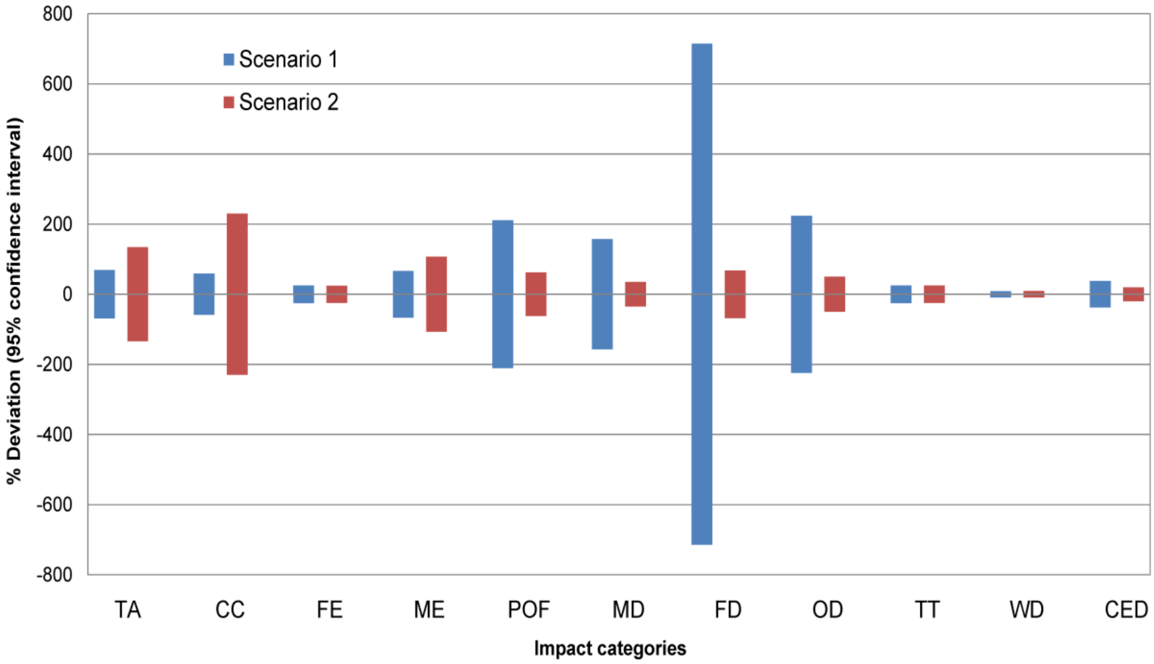

Fig. 9. Uncertainty comparison between scenarios measured by the percentage of deviation of the bounds of 95% confidence interval with respect to the most probable value.

In the light of the uncertainty outcomes, the question about which scenario is the less environmentally harmful would not have a straightforward answer. The comparison does not involve only single scores but intervals with a probability distribution. Table 5 shows the results of the Monte Carlo analysis considering each impact category. Where the last column presents the probability of the hypothesis that Scenario 2 produces higher environmental damage than Scenario 1 for the specific impact category. It is clear that, in general, the impacts of Scenario 2 are higher than for Scenario 1, especially in the impact categories of terrestrial acidification, climate change, photochemical oxidant formation, metal and fossil depletion, ozone depletion and cumulative energy demand, for which the probability that Scenario 1 is worse is lower than 5%. At the same time, it is also evident that water depletion impact is sharply defined as a benefit of Scenario 2.

Table 5. Statistical analysis of the Monte Carlo simulation for comparison of Scenario 1 and Scenario 2.

	SCENARIO 1 No wastewater reuse		**SCENARIO 2 Wastewater reuse and potable water replacement**		**Probability SC2>SC1 (%)**
	Most probable value	*Standard deviation*	*Most probable value*	*Standard deviation*	*P(SC1-SC2<0)*
Terrestrial acidification kg (SO_2-Eq/m^3)	*$-4.73\cdot10^{-4}$*	$1.64\cdot10^{-4}$	$2.92\cdot10^{-4}$	$1.96\cdot10^{-4}$	99.86
Climate change (kg CO_2-Eq/m^3)	$-1.07\cdot10^{-1}$	$3.15\cdot10^{-2}$	$-2.93\cdot10^{-2}$	$3.37\cdot10^{-2}$	95.35
Freshwater eutrophication (kg P-Eq/m^3)	*$3.27\cdot10^{-4}$*	$4.16\cdot10^{-5}$	$3.43\cdot10^{-4}$	$4.22\cdot10^{-5}$	60.45
Marine eutrophication (kg N-Eq/m^3)	$-3.28\cdot10^{-5}$	$1.10\cdot10^{-5}$	$-2.04\cdot10^{-5}$	$1.10\cdot10^{-5}$	78.71
Photochemical oxidant formation (kg NMVOC/m^3)	$-6.63\cdot10^{-5}$	$7.00\cdot10^{-5}$	$2.81\cdot10^{-4}$	$8.82\cdot10^{-5}$	99.90
Metal depletion (kg Fe-Eq/m^3)	$1.10\cdot10^{-3}$	$8.65\cdot10^{-4}$	$6.66\cdot10^{-3}$	$1.18\cdot10^{-3}$	99.99
Fossil depletion (kg oil-Eq/m^3)	$-1.57\cdot10^{-3}$	$5.61\cdot10^{-3}$	$1.84\cdot10^{-2}$	$6.25\cdot10^{-3}$	99.12
Ozone depletion (kg CFC-11-Eq/m^3)	$2.33\cdot10^{-9}$	$2.61\cdot10^{-9}$	$1.22\cdot10^{-8}$	$3.06\cdot10^{-9}$	99.31
Total toxicity (kg 1,4-DCB-Eq/m^3)	3.61	$4.62\cdot10^{-9}$	3.74	$4.69\cdot10^{-1}$	58.11
Water depletion (m^3/m^3)	$5.80\cdot10^{-4}$	$2.68\cdot10^{-5}$	$-4.40\cdot10^{-1}$	$2.14\cdot10^{-2}$	0.00
Cumulative energy demand (MJ-Eq/m^3)	1.45	$2.75\cdot10^{-1}$	3.58	$3.56\cdot10^{-1}$	100.00

However, there are certain impact categories for which the analysis retrieves less probability that Scenario 2 has higher environmental impacts, which are freshwater eutrophication, marine eutrophication and total toxicity. Fig. 10 shows the shape of the probability distributions of these impact categories along with the climate change to illustrate graphically the scores of both scenarios. Understandably, the probability of that Scenario 1 has higher impacts becomes stronger when the overlapping interval between the curves of each scenario is bigger. Inasmuch as the curves are more separated the conclusion appears clearer, it is the case of the cumulative energy demand where a virtual 100% of probability was obtained because during the 5,000 simulations recorded the value for Scenario 1 was never higher or equal to the value for Scenario 2.

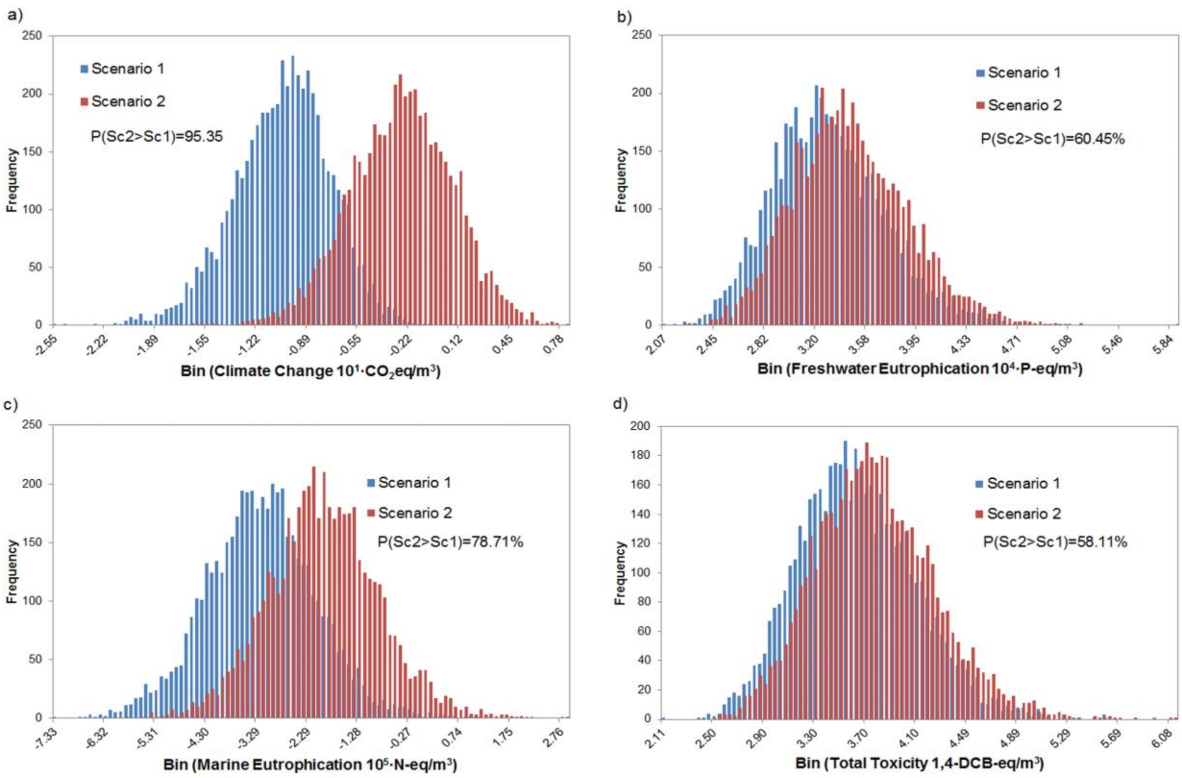

Fig. 10. Histograms of the Monte Carlo analysis: a) climate change, b) freshwater eutrophication, c) marine eutrophication and d) total toxicity.

5. Conclusions

Life Cycle Assessment is a powerful tool to analyze environmental improvements in wastewater treatment plants because its capability to consider all the supply chain of the process and also including final destination of treated wastewater and sludge. It allows the detailed comparison between process options under the same standardized rules.

The results obtained were in accordance with previous results reported in LCA studies dealing with reclaimed water at least in terms of water depletion (WD). The value of water depletion (WD) after applying a tertiary treatment to replace potable water is -

$4.39{\cdot}10^{-1}$ m^3 per each m^3 of wastewater entering the treating system; similar results were founded in Tong et al. (2013) with a value for the water depletion (WD) category of -$6.86{\cdot}10^{-1}$ m^3. This indicator represents the most important effect of water reuse, because it is in direct connection with a decreased pressure over the fresh water consumption.

Regarding the Cumulative Energy Demand the result obtained is 5.44 MJ-Eq, while in Pasqualino et al. (2010) was 11.0 MJ-Eq per m^3 treated and in Meneses et al. (2010) was 2.81 MJ-Eq per m^3 treated in the tertiary treatment. The differences between CED results are explained by the use of different technologies which lead to different levels of energy consumption.

It is also important to highlight the fact that the tertiary treatment has lowest impact in total toxicity (TT) and freshwater eutrophication (FE) as compared with WWTP direct discharges.

When choosing an option for wastewater treatment, one should take into account the local conditions, the economic and technological characteristics of the plant depending on the effluent quality requirements and expected application of the reclaimed water. In all the treatment processes, electricity consumption has been identified as the major hotspot. The reverse osmosis stage is the main contributor to the environmental impact of the tertiary treatment of urban wastewater. The results obtained for a certain geographical area cannot be extrapolated to other areas.

The consumption of renewable energies can reduce the environmental impacts of wastewater treatment. It can be concluded from this study that by substituting potable water with treated wastewater obtained from tertiary treatment does not lead to a substantial improvement of environmental impact for most of the indicators, but it is recommended for water-stressed situations because it is a net saving of water from nature. The main implication of these results is that, when and wherever it possible, we should reuse water from WWTP for non-potable purposes, such as chemical industry.

Wastewater reuse strategies are intended to solve the water scarcity problem without promoting other environmental problems.

The uncertainty analysis performed over the input parameters of the model demonstrates that conclusions extracted from single scores of an LCA must be taken carefully. Although the LCA performed at the two scenarios points out Scenario 1 as the less damaging for all impact categories but for water depletion, the uncertainty results displayed substantial probabilities (near 40%) for specific impacts to be higher in the case of Scenario 1.

Acknowledgments

The authors would like to acknowledge the valuable collaboration and support of Iván Fraga and Francisco Oliva from Empresa Municipal Mixta de Aguas de Tarragona (EMATSA) and Nena Bruni from Aguas Industriales de Tarragona Sociedad Anónima (AITASA).

Special thanks are addressed to the Environmental Analysis and Management Research Group, AGA (*Anàlisi i Gestió Ambiental)*, Department of Chemical Engineering, Rovira I Virgili University, Spain, for offering to Loredana Pintilie the support during her research stage mobility.

The support of the Romanian National Authority for Scientific Research, CNDI–UEFISCDI, Project no. 60/2012 (PNII Parteneriate), "*Integrated System for Reducing Environmental and Human-related Impacts and Risks in the Water Use Cycle*" (WATUSER) is also acknowledged.

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