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Life cycle assessment study on polishing units for use of treated wastewater in agricultural reuse

Nurdan Büyükkamacı and Gökçe Karaca

ABSTRACT

A life cycle assessment (LCA) approach was used in the assessment of environmental impacts of some polishing units for reuse of wastewater treatment plant effluents in agricultural irrigation. These alternative polishing units were assessed: (1) microfiltration and ultraviolet (UV) disinfection, (2) cartridge filter and ultrafiltration (UF), and (3) just UV disinfection. Two different energy sources, electric grid mix and natural gas, were considered to assess the environmental impacts of them. Afterwards, the effluent of each case was evaluated against the criteria required for irrigation of sensitive crops corresponding to Turkey regulations. Evaluation of environmental impacts was carried out with GaBi 6.1 LCA software. The overall conclusion of this study is that higher electricity consumption causes higher environmental effects. The results of the study revealed that cartridge filter and UF in combination with electric grid mix has the largest impact on the environment for almost all impact categories. In general, the most environmentally friendly solution is UV disinfection. The study revealed environmental impacts for three alternatives drawing attention to the importance of the choice of the most appropriate polishing processes and energy sources for reuse applications.

Key words | agricultural reuse, environmental impact, LCA, membrane, UV

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INTRODUCTION

Population growth and water demand have risen worldwide to the point where available resources cannot meet the demand for water anymore. The lack of sufficient available water is leading the world into water scarcity, which can be caused by various factors such as overgrowth of pollution, and rising demand and overuse of water. It is estimated that, at least in some world regions, water use has been growing more than twice as fast than the human population. For instance, the total annual water withdrawal suffered a 6.3-fold increase, rising from less than 600 km^3/year at the beginning of the twentieth century, to more than 3,800 km^3/year by the beginning of the twenty-first century. The irrigation practices consume up to 70% of this withdrawal (Castro *et al.* 2015).

The amount of total volume of water is about 501 billion m^3/year; overall renewable surface water potential is 234 billion m^3/year in Turkey. The total of economically and technologically exploitable water resources potential is 112 billion m^3/year. Of this, about 40 billion m^3 water is currently used. Water-rich countries have available water resources greater than 10,000 m^3 per capita per year (Tas *et al.* 2015). According to the General Directorate of State Hydraulic Works, Turkey is a water-stressed country according to annual volume of water available per capita, which is approximately 1,500–1,735 m^3, and among the total economically exploitable water available in Turkey, 74% is used for agriculture, 15% for domestic needs and 11% for industrial uses. Thus, treated wastewater is increasingly being seen as a resource, particularly for agricultural irrigation. Considering water needs for irrigation, landscaping, recreational and industrial facilities in Turkey, reuse applications of reclaimed water are very important to manage the country's fresh water resources, as well as all over the world.

Although water reuse strategies are intended to address the problem of water scarcity, measures taken to solving this problem come at a price, such as exacerbating other environmental problems like human health or global warming. Hence, environmental impacts of reuse applications must be investigated carefully and, in this context, life cycle assessment (LCA) appears as one of the

doi: 10.2166/wst.2017.474

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methodologies. LCA is a technique to quantify the impacts associated with all the stages of a product, service or process from cradle to grave. Its principles and requirements are defined by ISO 14000 (ISO 2006) series standards. LCA consists of four main activities: goal and scope, inventory analysis, impact assessment, and interpretation. In the goal and scope part, the reason to make the assessment is defined. The inventory analysis accumulates all the data of the unit processes in a product system. Impact assessment converts numerical data to environmental effect equivalent via some determined factor multiplication. It is a transformation tool to convert mathematical data to environmentally significant pollution type and unit. Interpretation, where final assessment is made, is the last phase in LCA. The aim here is to draw conclusions that can support a decision or can ensure a readily comprehensible result of the LCA.

Although LCA is generally used for the production phase, it is also applied to the global environmental analysis of a wastewater treatment operation. The wastewater treatment plants (WWTPs) help us to protect the environment, but in contrast to their main commissioned purpose, they can damage the environment through energy consumption, greenhouse gas emission, the utilization of chemicals, and some toxic material outcomes (Buyukkamaci 2013). Within the field of wastewater treatment, LCA was first applied in the 1990s (Corominas *et al.* 2013). LCA allows for a better evaluation of wastewater treatment technologies in many different approaches. Owing to its holistic approach, LCA is becoming an increasingly significant decision-making tool in environmental management and it is used as a decision support tool to determine the most appropriate wastewater management strategy. LCA studies on wastewater treatment (Bravo & Ferrer 2011; Alyaseri 2016; Blanco *et al.* 2016; Garfí *et al.* 2017) and reuse applications (Opher & Friedler 2016; Lazic *et al.* 2017; Raghuvanshi *et al.* 2017) abound.

The aim of this study is to make a comparison between different WWTP effluent polishing alternatives, for the purpose of agricultural irrigation of sensitive crops, with respect to the environmental effects determined by the LCA. Water reclamation often refers to the treatment of storm-water, industrial wastewater and municipal wastewater for beneficial reuse (Vo *et al.* 2014), and required treatment techniques change depending on the end-use purposes. Health risk associated with pathogens is one of the main drawbacks of the agricultural reuse of reclaimed water and more stringent requirements on pathogen removal are required for the agricultural irrigation of sensitive crops. Therefore, care has been taken to select systems that can be especially used for pathogen removal, and within this context three cases were chosen: microfiltration + ultraviolet, cartridge filter + ultrafiltration, and ultraviolet. Microfiltration (MF) cannot be used alone because of the diameter of the pores; it cannot purify viruses and some bacteria. Therefore, ultraviolet (UV) disinfection or other types of disinfection methods must be applied afterwards. MF followed by UV disinfection is also recommended for the purpose of agricultural irrigation in the regulations of Turkey (Case 1). Alternatively, ultrafiltration (UF) has been capable of carrying out the function of MF and UV. UF was intended to be used with a pre-filter (Case 2) because when used alone they may give rise to clogging problems. Since the use of UV disinfection has increased in Turkey, the use of just UV disinfection was also investigated (Case 3). The results of this study may give rise to a different viewpoint in determining the polishing process of WWTP effluent prior to any reuse applications.

MATERIALS AND METHODS

LCA approach

In this study, the LCA studies were carried out using GaBi 6.1 Software (Thinkstep, Germany). The CML 2001 (Institute of Environmental Sciences, Leiden University) impact assessment method was used to assess the environmental impacts. The required data for the software was obtained from the literature and the Eco-invent database, which is integrated into the GaBi 6.1 software. Nine environmental mid-point impact categories were taken into consideration: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (ODP), abiotic depletion elements, fresh water aquatic ecotoxicity potential, human toxicity potential (HTP), terrestrial ecotoxicity potential (TETP), and photochemical ozone creation potential (POCP).

GaBi software runs according to a created flow diagram and introduced inputs and outputs. The inputs of this study are mainly treated wastewater and energy. Treated wastewater properties vary depending on several factors, such as influent wastewater properties, treatment processes used and operational conditions. In order to determine the average effluent quality several domestic/municipal WWTPs in Turkey were surveyed and, considering this data, WWTP effluent (input of the LCA study) quality was accepted as given in Table 1. The examined WWTPs are

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Table 1 | Accepted treated wastewater (WWTP effluent) quality parameters

Water quality parameters	Values (mg/L)
Chemical oxygen demand	85
Biological oxygen demand	15
Suspended solid	15
Total nitrogen	5
Total phosphorus	0.5

comprised of primary and secondary processes (with nutrient removal). Each flow scheme is started with physical treatment units in the order of coarse and fine screens, and oil/grit removal.

For membrane units, energy requirements for operation and backwash pumping, the cleaning chemical type and the amount of chemical material for membrane units, and finally the energy need for UV were considered in the calculations.

Goal of the study

The main purpose of this investigation was to assess the environmental impacts of some effluent polishing units for the reuse of treated wastewater for agricultural irrigation of sensitive crops. Impacts of two different energy sources, electric grid mix and natural gas, on the environment were also investigated as a part of the goal.

Functional unit

The functional unit is defined to quantify the environmental impact associated with the various management regimes and thus provide a basis for comparing the results (Lozada 2011). Since the main function of this study is to reuse treated wastewater, the functional unit was chosen to be delivery of 1 m^3 of recycled water to be used for irrigation.

System boundaries

The system boundary defines which inputs and outputs to include. Since this study focused on the polishing units of effluents, a 'gate to gate' approach was selected, which included the materials and processes from the further treatment phase only (Figure 1). The effects of the effluent transportation and irrigation applications were ignored. The treatment units used in these cases were chosen considering pathogen removal and effluent quality requirements

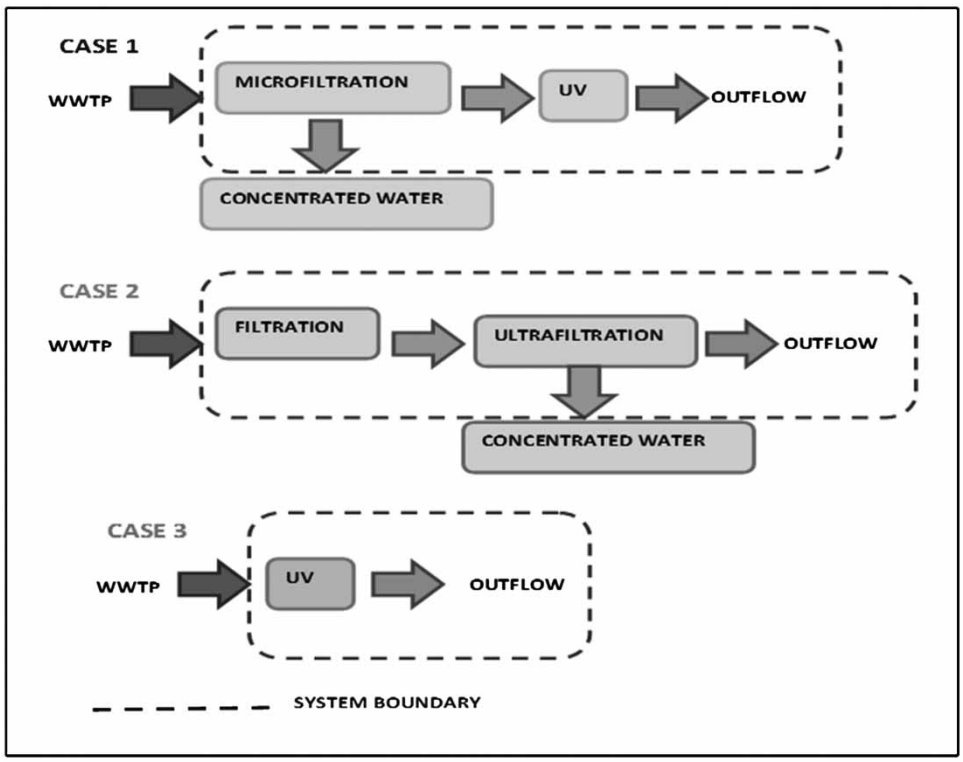


Figure 1 | The system boundaries.

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for sensitive crop irrigations in *Water Pollution Control Regulations Notification for Technical Principles*, Table E7.1 (Official Gazette 2010). Two energy sources were chosen: electric grid mix for Turkey (Scenario 1) and natural gas to electricity for Turkey (Scenario 2).

RESULTS AND DISCUSSION

The results are given and discussed depending on each of the environmental impact categories. A summary of the different cases and scenarios is given in Table 2.

Global warming potential

The GWP impacts are directly related to electricity use. Direct electrical consumption by the WWTPs makes the most significant contribution to GWP and other environmental impacts, such as abiotic resource depletion, photochemical oxidation, and acidification, and this is a common finding for WWTPs, with energy consumption (e.g. pumping and aeration) often dominating the environmental impacts (Li *et al.* 2013). According to Figure 2, Case 3 is clearly the most environmentally friendly polishing application for both scenarios. It means that UV treatment has less GWP impact than the other cases and this result is closely followed by the MF and UV combination (Case 1). This is mainly due to the higher energy requirements of the membrane systems for both operations and especially the cleaning phase (Chang *et al.* 2017). The chart also revealed the energy source effect for GWP. Natural gas has 26% lower greenhouse gas emissions compared to electric grid mix. Cherchi *et al.* (2017) also showed that the on-site natural gas or liquefied natural gas option for desalination plants under co-located configurations with a power generation plant has the potential to be more economically and environmentally favorable than the direct power purchased from the grid. Cases 1–3 have smaller effects than Case 2, which consumes relatively more energy than the others. For both energy sources, GWP impacts of the CF and UF combination (Case 2) are about 25 times higher than UV (Case 3).

Table 2 | Summary of cases and scenarios

Abbreviations	Explanation
Case 1-S1	Case 1 (MF + UV) – Scenario 1 electric grid mix
Case 2-S1	Case 2 (CF + UF) – Scenario 1 electric grid mix
Case 3-S1	Case 3 (UV) – Scenario 1 electric grid mix
Case 1-S2	Case 1 (MF + UV) – Scenario 2 Natural gas
Case 2-S2	Case 2 (CF + UF) – Scenario 2 Natural gas
Case 3-S2	Case 3 (UV) – Scenario 2 Natural gas

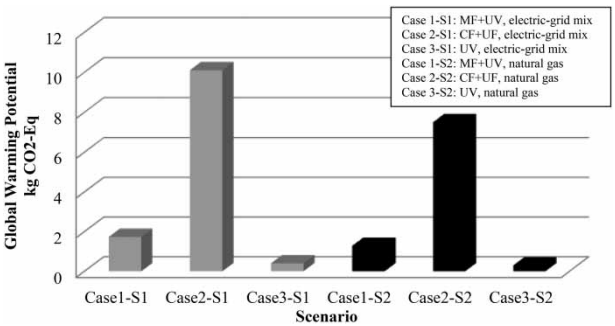


Figure 2 | Contribution of all alternative scenarios to GWP impact category.

Acidification potential

Acidification has regional/local effects on the environment and it is commonly associated with atmospheric pollution. Sulfur dioxide, ammonia and oxides of nitrogen are the most significant acidifying gases (Goedkoop *et al.* 2009). It can be seen from Figure 3 that Case 3 for Scenario 2 (UV) is clearly the most environmentally friendly polishing unit application from the AP point of view. Case 1 for Scenario 2 (MF + UV) also has a small impact. The CF + UF combination has 25 times higher AP than UV. The chart also revealed significant energy source effects on AP. Much like GWP, AP is directly related to energy production. Coal is the major source for electricity generation in Turkey and there are significant life cycle impacts of coal used for electricity generation, such as heavy metal emissions and acidification (Sengül *et al.* 2016). Electric grid mix usage as an energy source has a drastic negative effect on AP compared to natural gas. Almost 89% lower AP was calculated for natural gas compared to electric grid mix.

Eutrophication potential

EP due to the remaining nutrients in the effluent has been considered the most relevant environmental issue when performing environmental evaluation of WWTPs. It is demonstrated that the EP impact category of a WWTP is mostly associated with the emissions to water, mainly due to the phosphorus, nitrogen and to a lower extent, degradable organics chemical oxygen demand in wastewater effluent (Zang *et al.* 2015). Unlike other environmental

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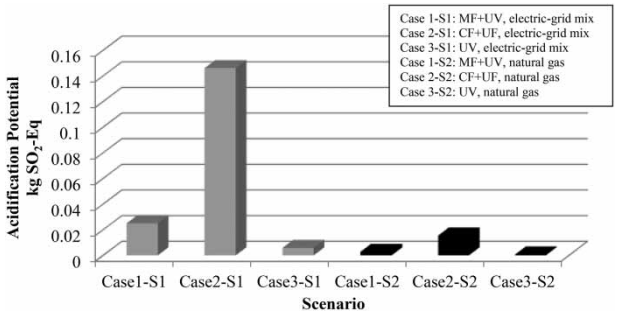


Figure 3 | Contribution of all alternative scenarios to AP impact category.

effects, Case 2 for Scenario 2 is a more environmentally friendly application from the EP point of view (Figure 4). However, in general all options have almost the same EP effects, which ranges between 5.85×10^{-3} and 7.65×10^{-3} kg PO_4^2-Eq.

Ozone layer depletion potential

The ozone layer depletion is caused by the release of ozone-depleting substances, such as chlorofluorocarbons and bromofluorocarbons, in the stratospheric ozone layer (Itsubo & Inaba 2012). ODPs of all options are given in Figure 5.

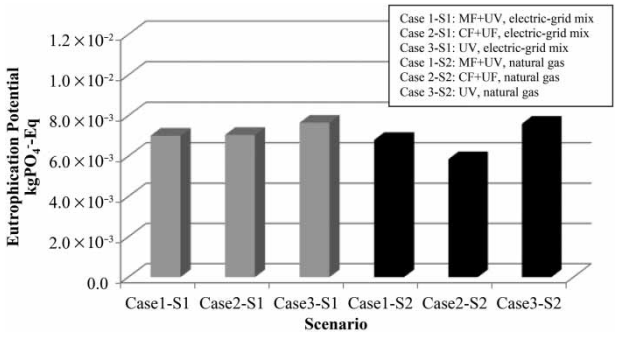


Figure 4 | Contribution of all alternative scenarios to EP impact category.

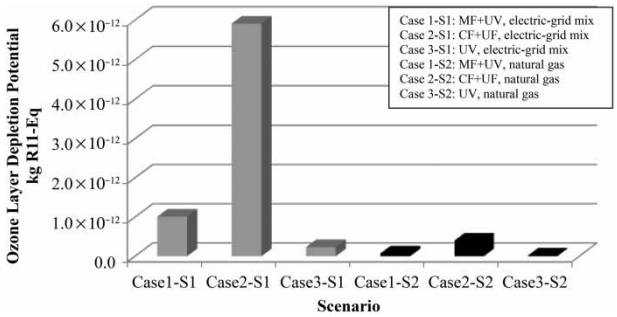


Figure 5 | Contribution of all alternative scenarios to ozone layer depletion impact category.

According to the results it was found that electric grid mix usage and CF + UF combination has more impact on ODP. Scenario 2 and Case 3 has the smallest effect on ODP and an approximately 375 times better result was achieved with UV (natural gas) comparing to CF + UF (electric grid mix), which is the worst-case scenario. The results suggest that energy from natural gas has the lower impacts and its ozone layer depletion is 93% lower than for electric grid mix.

Toxicity potential

Toxicity can affect humans and the environment, such as water and soil. In the scope of this study, toxicity potentials for the three impact categories, freshwater aquatic ecotoxicity, human toxicity, and terrestrial ecotoxicity, were calculated for each scenario. Human toxicity category concerns the effects of toxic substances on humans. Freshwater aquatic ecotoxicity and terrestrial ecotoxicity describes the amount of water and soil pollution, respectively. The results of toxicity potentials are given in Figure 6.

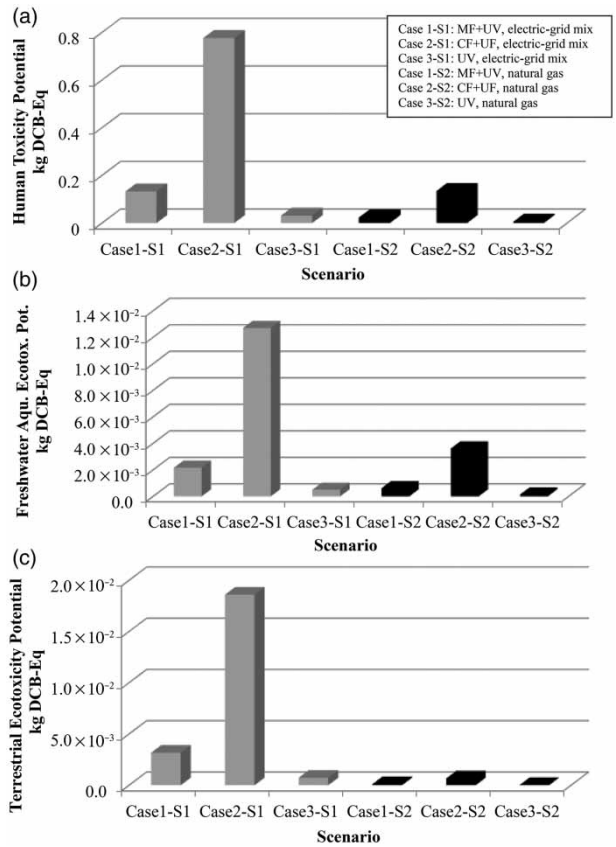


Figure 6 | Contribution of all alternative scenarios to toxicity potential effects: (a) human toxicity potential, (b) freshwater aquatic ecotoxicity potential, (c) terrestrial ecotoxicity potential.

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Case 2 has the highest effects on freshwater aquatic ecotoxicity, especially when the energy source is an electric grid mix. Seventy-one per cent lower freshwater aquatic ecotoxicity potential values were calculated for natural gas. This result may have derived from energy providing activity values of the GaBi Database calculation. A similar explanation applies to all charts as well.

HTP and TETP were also affected by energy source and polishing unit selection for agricultural reuse application. Case 2 Scenario 1 has a significant effect on both HTP and TETP, which means that UF membrane with electric grid mix energy source gives higher negative impacts to humans and land. HTP and TETP of scenarios using natural gas were 83 and 96% lower than scenarios using electric grid mix, respectively.

Abiotic depletion elements

Abiotic resource depletion is the decrease of availability of the total reserve of potential functions of resources (Oers *et al.* 2002). Abiotic resource depletion is grouped as the depletion of elements and the depletion of fossil fuels. In the scope of this study, only abiotic depletion element effects were taken into consideration and the highest abiotic depletion element effects were determined for Case 2 (CF + UF) Scenario 1 (electric grid mix). For both energy sources, CF + UF combination has higher effects compared to other applications (Figure 7). Compared to the electric grid mix energy source, 51% lower abiotic depletion elements was determined for natural gas. The electricity generation from coal is mainly responsible for all environmental impacts for base and future situations in Turkey. However, the consumption of fossil fuels not only contributes to global warming, but also has effects on the elemental basis of abiotic depletion due to raw material consumption for plant infrastructure (Günkaya *et al.* 2016).

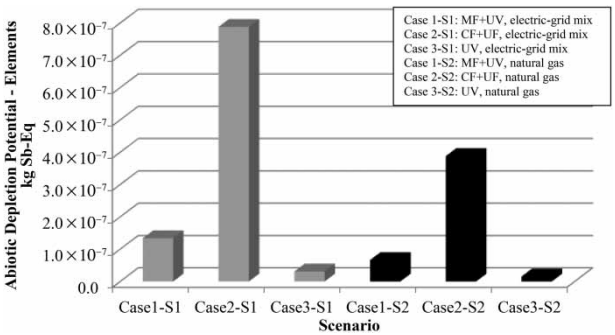


Figure 7 | Contribution of all alternative scenarios to abiotic depletion potential-elements.

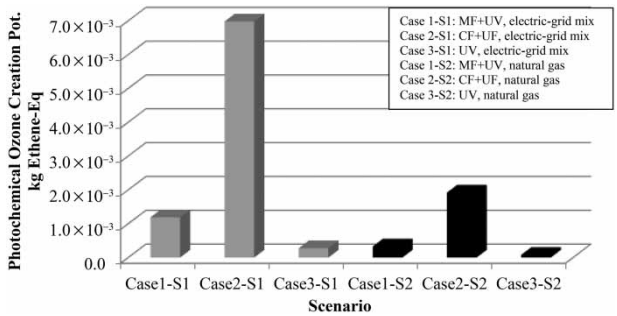


Figure 8 | Contribution of all alternative scenarios to POCP.

Photochemical ozone creation potential

POCP has been used to classify compounds according to their ability to form ozone (Andersson-Sköld & Holmberg 2000), and it is typically used in life cycle impact assessment to address the impact category 'photo-oxidant formation' and only provides factors for particular volatile organic compounds and does not take into account background concentrations and meteorological conditions (Labouze *et al.* 2004). POCP reacts to energy source selection and reuse application chosen at the same time. Case 2 Scenario 1 has a drastic effect on POCP. Hence, Case2-S1 has more effects on the environment and relatively also has more effects on the POCP (Figure 8). Seventy-two per cent lower POCP was calculated with natural gas compared to electric grid mix.

CONCLUSIONS

LCA has been widely used as a decision support tool to determine the most appropriate wastewater management strategy. In the scope of this study, different scenarios were generated for the polishing of effluents for the irrigation of sensitive crops, and the environmental effects of these scenarios were compared using an LCA tool. In accordance with this study, the following conclusions were obtained.

- The overall impacts of reclamation alternatives especially depend on the energy sources.
- Case 2 (CF + UF) Scenario 1 (electric grid mix) has the largest impact on the environment in almost all impact categories. The reason for this result is mostly the high

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pressure need of UF, which leads to high energy usage, and the electric grid mix certainly has a great influence on the environment. However, it should be noted that the potential environmental impact of the membrane processes are absolutely dependent on operating parameters, such as flux and the maximum transmembrane pressure.

- Case 3 (UV) Scenario 2 (natural gas) has the minimum impact for the most impact categories because natural gas is known as a cleaner energy source than the electric grid mix which is mostly obtained from coal in Turkey. In addition, UV is a less energy-consuming process than membrane technologies. Therefore, if disinfection alone is enough to obtain appropriate quality irrigation water, UV should be preferred instead of membrane processes, such as MF and UF.

LCA is a compelling tool to determine the most suitable and feasible wastewater treatment alternatives. The scope of this study compared more than one scenario and more importantly observes the membrane technology's impact on the environment. LCA calculation heavily depends on the functional unit and the system boundaries. Since the functional unit of this study is 1 m^3 treated wastewater, the result of the study can be multiplied with any wastewater treatment facility's flow-rate to calculate the total impact. This study may be developed more with the help of extending the system boundaries further.

In this study, the LCA studies were carried out via the GaBi 6.1 software and CML 2001 impact assessment methodology to determine the environmental impact. The GaBi database is extensive as it is, but unfortunately it mainly focuses on industrial processes and flows, which are used for material transfer. There is a detailed calculation in the GaBi database for the industrial process though it is lacking for water/wastewater treatment technologies and other environmental technologies. It is humbly suggested that further additions regarding environmental processes must also be added to the database to improve the software.

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First received 9 May 2017; accepted in revised form 15 August 2017. Available online 7 September 2017

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