Constructed wetlands for winery wastewater treatment: A comparative Life Cycle Assessment

Laura Flores, Joan García, Rocío Pena, Marianna Garfí

PII: S0048-9697(18)35241-0
DOI: https://doi.org/10.1016/j.scitotenv.2018.12.348
Reference: STOTEN 30182

To appear in: *Science of the Total Environment*

Received date: 20 November 2018
Revised date: 21 December 2018
Accepted date: 22 December 2018

Please cite this article as: Laura Flores, Joan García, Rocío Pena, Marianna Garfí , Constructed wetlands for winery wastewater treatment: A comparative Life Cycle Assessment. Stoten (2018), https://doi.org/10.1016/j.scitotenv.2018.12.348

Constructed wetlands for winery wastewater treatment: a comparative life cycle assessment

Laura Flores[1], Joan García[1], Rocío Pena[2], Marianna Garfí[1*]

[1]GEMMA-Group of Environmental Engineering and Microbiology, Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya-BarcelonaTech, c/ Jordi Girona, 1-3, Building D1, E-08034, Barcelona, Spain

[2]Aimen, Polígono Industrial de Cataboi SUR-PPI-2 (Sector) 2, Parcela 3, 36418 O Porriño, Spain

* Corresponding author:

Tel: +34 9340 16412

Fax: +34 93 4017357

Email: marianna.garfi@upc.edu

Abstract

A Life Cycle Assessment was carried out in order to assess the environmental performance of constructed wetland systems for winery wastewater treatment. In particular, six scenarios, which also included the most common winery wastewater treatment and management options in South-Western Europe, namely third-party management, activated sludge systems, were compared. Results showed that the constructed wetland scenarios were the most environmentally friendly alternatives, while the third-party management was the worst scenario followed by the activated sludge systems. Specifically, the potential environmental impacts of the constructed wetlands scenarios were 1.5-180 and 1-10 times lower compared to those generated by the third-party and activated sludge scenarios, respectively. Thus, under the considered circumstances, constructed wetlands showed to be an environmentally friendly technology which helps reducing environmental impacts associated with winery wastewater treatment by treating winery waste on-site with low energy and chemicals consumption.

Keywords: Activated sludge system; constructed wetland; environmental impact assessment; Life Cycle Assessment; winery wastewater.

1. Introduction

Wine industry generates large volumes of wastewater (up to 4 m^3 of wastewater per cubic meter of wine produced) originating from various processes and operations carried out during wine production (e.g. cleaning, washing down floors, equipment, tanks, barrels and transfer lines, cooling, bottling) (Anastasiou et al., 2009; Bolzonella et al., 2010; Litaor et al., 2015; Serrano et al., 2011). Winery wastewater is characterized by highly variable flows and loadings. Indeed, more than half of the annual wastewater flow and load is produced during the vintage season (around 30 days per year), when grape is harvested and grape juice is handled and managed (Ruggieri et al., 2009).

The South-Western Europe, which includes Spain, Portugal and the South of France, is considered one of the world's largest wine-producing region. Around 30% of total world wine is produced in this region (OIV, 2017). Nevertheless, most of the wineries located in this area still lack a proper wastewater treatment management. Indeed, many wineries discharge untreated or not properly treated wastewater into the environment or into the sewer system, without meeting the acceptance limits for both cases (Serrano et al., 2011; UPC, 2018). In other cases, winery effluents are transported for long distance (up to 200 km), treated and disposed by a third-party, which generates high costs (UPC, 2018). Only in a few cases, winery wastewater is treated on-site by conventional technologies, such as activated sludge system (UPC, 2018). Activated sludge systems mainly consist of an aeration tank and a secondary settling tank. These systems are costly to build and operate, require skilled personnel for operation and maintenance and high energy consumption (Ioannou et al., 2015; Lofrano and Meric, 2016; Valderrama et al., 2012).

Constructed wetland systems are nature-based technologies which have been proved to be appropriate solution for winery wastewater treatment worldwide, since they are able to couple with seasonal variation in wastewater flows and loadings (Ávila et al., 2016; Kim et al., 2014; Rozema et al., 2016; Shepherd et al., 2001). Constructed wetland systems for wastewater treatment consist of a shallow basin filled with some sort of filter material (substrate), usually sand or gravel, and planted with vegetation (e.g. common reed). In these systems, wastewater flows through the filter material and the treatment of wastewater is carried out by chemical, physical and biological processes. Constructed wetland technology can also be used for sludge treatment (i.e. sludge treatment wetlands, also known as sludge drying reed beds). In this system, sludge is dewatered and stabilised by means of natural processes, producing a final product which can be used as fertilizer for agricultural purposes (Brix, 2017). This technology can be a suitable on-site solution for the management of sludge from both constructed wetland and activated sludge systems.

In the recent years, constructed wetland systems for winery wastewater treatment have been gaining interest also in South-Western Europe (Serrano et al., 2011; Vymazal, 2014). It was due to the fact that they constitute an alternative to conventional systems (e.g. activated sludge systems) for winery effluents treatment due to their low cost, low energy requirement and easy operation and maintenance (Ávila et al., 2016).

In spite of the increasing interest in constructed wetlands, there is still no study comparing their environmental impacts to those generated by conventional strategies and technologies for winery wastewater treatment and management in South-Western Europe.

The aim of this study was to assess the environmental impacts associated with constructed wetland systems for winery wastewater treatment. To this aim, a Life Cycle Assessment (LCA) was carried out comparing six scenarios which also include the most common winery wastewater treatment and management options in South-Western Europe (i.e. third-party management, activated sludge systems).

2. Materials and methods

LCA is a standardized, systematic and comprehensive methodology to quantify the environmental impacts associated with a product, process or activity considering their entire life cycle. LCA is based on the analysis of all input and output flows of the studied system (i.e. raw materials and energy, emissions, waste). The methodological framework for LCA consists of the following phases: goal and scope definition; inventory analysis; impacts assessment and interpretation of the results (ISO, 2006a, 2006b). The following sections describe the specific contents of each phase.

2.1 Goal and scope definition

2.1.1 Objectives and functional unit

This research has been carried out in the frame of the WETWINE project which aims to promote environmentally friendly and innovative solutions to treat effluents produced by wine industries in the South-West of Europe (SUDOE Programme). The goal of the present study was to evaluate the potential environmental impacts associated with the constructed wetland system for winery wastewater treatment promoted by the WETWINE project. In particular, they were compared to those generated by the most common winery wastewater treatment and management solutions implemented in

South-Western Europe (i.e. third-party management, activated sludge systems). The final goal was to identify if constructed wetland technology could be a sustainable solution to be implemented in wineries which still lack a proper wastewater treatment. To this aim, the functional unit was defined as 1 m^3 of treated water, since the main function of the solutions considered was to treat wastewater.

2.1.2 Scenarios description

In total six scenarios were considered, which include the wastewater treatment and management alternatives implemented in different wineries (Ws) located in South-Western Europe. Their characteristics are summarized in Table 1.

The W1 scenario consisted of a third-party wastewater management implemented in a winery located in Galicia (Spain). In this winery, around 1,400 m^3 of wastewater were produced per year. Wastewater was stored in a septic tank and then transported (240 km), treated by means of aerobic biological processes and discharged by a third-party.

The W2 scenario consists of a constructed wetland system recently implemented in the same winery as the W1 scenario, in order to replace the third-party management. The constructed wetland system consists of a hydrolytic upflow sludge blanket (HUSB) reactor, followed by two vertical subsurface flow constructed wetlands (30 m^2), a horizontal subsurface flow constructed wetland (30 m^2), and a sludge treatment wetland (20 m^2). Treated wastewater is discharged into the sewer system, while stabilized sludge is reused as fertilizer or soil conditioner.

The W3 scenario consists of a constructed wetland system implemented in a winery located in Galicia (Spain). The system treats 1,900 m^3 of winery wastewater per year and comprises an upflow anaerobic sludge blanket (UASB) reactor followed by a vertical subsurface flow constructed wetland (50 m^2), and three horizontal subsurface flow constructed wetlands (100 m^2 each) (Serrano et al., 2011). Treated wastewater is discharged into the sewer system, while sludge is mixed with other organic waste to produce compost.

The W4 and W5 scenarios consist of activated sludge systems implemented in two wineries located in Galicia (Spain) and Vila Real (Portugal), respectively. The systems treat 4,832 m^3 and 11,500 m^3 of winery wastewater per year, respectively. After a pre-treatment, wastewater is treated in an activated sludge reactor with extended aeration followed by a secondary settler. Treated wastewater is discharged into the sewage system. In both scenarios, sludge from the secondary settler is stored on-site and then transported (150 km) by a third-party to an incineration facility.

The W6 scenario comprises an activated sludge system implemented in a winery located in Tarn (France). The system treats 12,141 m^3 of winery wastewater per year. In this case, treated wastewater is directly discharged into a water body. As for scenario W4 and W5, sludge from the secondary settler is stored on-site and then transported (6 km) by a third-party to an incineration facility.

All systems exclusively treat winery effluents and were designed in order to meet the national acceptance limits for discharge into the sewer system or into a water body, according to the individual case.

2.1.3 System boundaries

System boundaries included systems construction, operation and maintenance over a 20-years period (Figure 1). Input and output flows of materials (i.e. construction materials and chemicals) and energy resources (electricity) were systematically studied for all scenarios. Direct emissions to air (i.e. NH_3 and greenhouse gases (GHGs)) and soil (i.e. heavy metals) associated with wastewater treatment as well as sludge reuse and application to agricultural soil were also included in the boundaries. As the final effluents are discharged into the environment, direct emissions to water were also taken into account. In the case of scenario W1, inputs and outputs associated with wastewater transportation and disposal were accounted for. In the case of the activated sludge systems (scenarios W4, W5 and W6), inputs and outputs associated with sludge transportation and disposal (i.e. incineration) were also included in the boundaries. In the case of constructed wetland systems (scenarios W2 and W3), the system expansion method has been used in order to consider the avoided burdens of using the fertilizer obtained from the sludge instead of a conventional fertilizer (Guinée, 2002; ISO, 2006b). The end-of-life of infrastructures and equipment as well as the transportation of construction materials were neglected, since the impact would be marginal compared to the overall impact (Lopsik, 2013; Niero et al., 2014).

2.2 Inventory analysis

Inventory data for the investigated scenarios are shown in Table 2, 3 and 4. Due to the seasonal variation in wastewater flows and loadings, and, subsequently, in systems operation and performance, inventory data were presented considering two seasons (i.e. the vintage season and the rest of the year). For all scenarios, inventory data regarding construction materials and operation were based on the specific case studies and were collected by means of a survey carried out during 2017 and 2018. These data included information on construction materials, electricity and chemicals consumption, wastewater and/or sludge transportation distances and sludge as well as wastewater characteristics. Two campaigns were carried out in order to obtain data regarding wastewater and sludge quality during the vintage season and the rest of the year (August/September and February/March). Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorous (TP) were analysed according to the Standard Methods (APHA-AWWA, 2017). Heavy metals, TN and TP concentration in sludge were analysed as described by Solé-Bundó et al. (2017). With regards to constructed wetland and activated sludge scenarios (W2 to W6), direct GHG emissions from wastewater treatment were estimated considering the emissions rates obtained and used in previous studies (Corbella and Puigagut, 2014; Fuchs et al., 2011; Garfí et al., 2017; Lavola, 2015). Similarly, direct emissions to air due to sludge reuse and application to soil were obtained using the emissions rates proposed by the literature (Arashiro et al., 2018; IPPC, 2006; Lundin, 2000). All data were referred to the functional unit considering lifespan, amount, consumption and emissions rates of materials, energy and waste (ISO, 2006b). Background data (i.e. data of construction materials, chemicals, energy production, avoided fertilizer, transportation, sludge incineration process, wastewater treatment in a municipal wastewater treatment plant and wastewater treatment by a third-party) were obtained from the *Ecoinvent 3.1* database (Moreno-Ruiz et al., 2014; Weidema et al., 2013). The Spanish, Portuguese and French electricity mix was used for the electricity requirements (IEA, 2017; Red Eléctrica Española, 2017).

2.3 Impact assessment

Potential environmental impacts were calculated using the software *SimaPro® 8* (Pré Consultants, 2014) and the *ReCiPe (H) mid-point* method (Goedkoop et al., 2013). Characterisation phase was performed considering the following impact categories: Climate Change, Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication, Marine Eutrophication, Photochemical Oxidant Formation, Human Toxicity, Terrestrial Ecotoxicity, Particulate Matter Formation, Metal Depletion and Fossil Depletion. For all scenarios, potential environmental impacts generated during the vintage season and the rest of the year were calculated, in order to assess their fluctuations over the year.

2.4 Sensitivity analysis

A sensitivity analysis was carried out in order to evaluate how the uncertainty on inventory data may influence the final results. Thus, the following parameters, which represented the main assumptions of the study, were considered: CH_4 emissions released by the constructed wetland systems in scenarios W2 and W3; N_2O emissions released by the wastewater treatment systems in scenarios W2 to W6; CH_4, N_2O and NH_3 emissions caused by fertilizer application to agricultural soil in W2 and W3. It has to be mentioned that: N_2O emissions only affect the Climate Change Potential; CH_4 emissions influence both Climate Change and Photochemical Oxidant Formation Potentials, and, NH_3 emissions affect Terrestrial Acidification, Marine Eutrophication and Particulate Matter Formation Potentials. A variation of ±10% was considered for all studied parameters and the sensitivity coefficient was calculated using the Eq. (1) (Dixon et al., 2003):

$$Sensitivity\ coefficient\ (S) = \frac{(Output_{high} - Output_{low})/Output_{default}}{(Input_{high} - Input_{low})/Input_{default}} \quad \text{(Eq. 1)}$$

where Input is the value of the input variable (i.e. N_2O, CH_4 and NH_3 emissions) and Output is the value of the environmental indicator (i.e. Climate Change, Photochemical Oxidant Formation, Terrestrial Acidification, Marine Eutrophication and Particulate Matter Formation Potentials).

3. Results and Discussion

3.1 Life Cycle Assessment

The potential environmental impacts associated with each alternative are shown in Figure 2.

On the whole, the constructed wetland scenarios (scenarios W2 and W3) showed to be the most environmentally friendly alternatives, while the third-party management (scenario W1) was the worst scenario followed by the activated sludge systems (scenarios W4-W6). Specifically, the potential environmental impacts of the constructed wetlands scenarios were 1.5-180 and 1-10 times lower compared to those generated by the third-party and the activated sludge scenarios, respectively. This was mainly due to the high environmental impacts generated by wastewater and sludge transportation as well as chemicals and electricity consumption in the third-party and activated sludge scenarios. This is in accordance with previous LCAs which observed that constructed wetland systems helped to reduce environmental impacts associated with urban wastewater compared with conventional technologies especially in small communities (Dixon et al., 2003; Garfí et al., 2017; Yildirim and Topkaya, 2012).

As expected, the environmental impacts generated during the vintage season were higher (up to 4 times) than those generated during the rest of the year, especially for the activated sludge scenarios. As mentioned above, winery wastewater is characterized by fluctuations in terms of quality and quantity during the whole year, which depend on several factors like as the adopted industrial process chain and its seasonality or the kind of produced wine (Wu et al., 2015). In the wineries considered in this study, organic loadings (i.e. Chemical Oxygen Demand) and flow rates generated during the vintage season were around 10 times higher than those produced during the rest of the year, when winery effluents are comparable to urban wastewater (UPC, 2018). For this reason, during the vintage season higher amount of electricity (e.g. for aeration) and chemicals are needed per cubic meter of wastewater (Table 3 and 4).

Regarding Climate Change, Ozone Depletion, Terrestrial Acidification, Photochemical Oxidant Formation, Particulate Matter Formation, Metal Depletion and Fossil Depletion Potentials, the life-cycle was mainly influenced by wastewater and sludge transportation (10-99% of the total impact), and chemicals and energy consumption (10-70% of the total impact) in the third-party (scenario W1) and activated sludge scenarios (scenarios W4- W6). On the other hand, construction materials (15-50% of the total impact) and the additional treatment at the municipal wastewater treatment plants (20-75% of the total impact) accounted for the highest contribution of the overall impact in the constructed wetlands scenarios (scenarios W2 and W3) in the same impact categories. This is in accordance with previous studies which observed that the major impact of activated sludge systems was due to the operation phase (i.e. electricity and chemicals consumption), while construction phase mainly influenced constructed wetlands life-cycle (Corbella et al., 2017; Garfí et al., 2017; Piao and Kim, 2016). In all scenarios, direct GHG emissions accounted for less than 25% of the overall impact in the climate change impact category. In constructed wetlands scenarios (scenarios W2 and W3), NH_3 emissions to air derived from sludge reuse and application to agricultural soil accounted for 15-40% of the overall impact in the terrestrial acidification and particulate matter formation impact categories. On the other hand, sludge reuse (i.e. avoided fertilizer) reduced the overall environmental impact by up to 10% in the climate change, ozone depletion, photochemical oxidant formation, metal depletion and fossil depletion impact categories in the same scenarios.

Freshwater Eutrophication and Marine Eutrophication Potentials were mainly affected by wastewater and sludge transportation (10-75% of the total impact), the additional treatment at the municipal wastewater treatment plants (10-55% of the total impact) and direct emissions to water (20-90% of the total impact) in the third-party (scenario W1) and activated sludge scenarios (scenarios W4 to W6). On the other hand, the potential environmental impacts in constructed wetlands scenarios (scenarios W2 and W3) were almost entirely influenced by direct emissions to water (85-99% of the total impact) and the additional treatment at the municipal wastewater treatment plants in these impact categories. The better environmental performance of constructed wetlands scenarios in these impact categories was mainly due to the fact that they are decentralized technologies to treat not only wastewater, but also sludge on-site avoiding its transportation. Indeed, it has been demonstrated that sludge management and disposal had a high contribution to the overall environmental impact, especially if its management takes place outside the wastewater treatment plant. Dewatering and reusing sludge on-site strongly decrease potential environmental impacts associated with wastewater treatment (Corominas et al., 2013; Dixon et al., 2003; Suh and Rousseaux, 2002). For this reason, in order to reduce the environmental impacts generated by the activated sludge systems already implemented in the wineries located in South-Western Europe, sludge treatment wetlands can be implemented in order to avoid sludge transportation.

Concerning Human Toxicity and Terrestrial Ecotoxicity Potentials, the major impact was due to wastewater and sludge transportation (20-99% of the total impact) as well as chemical consumptions (15-55% of the total impact) in the third-party (scenario W1) and activated sludge scenarios (scenarios W4 to W6). On the contrary, emissions to soils (i.e. heavy metals) due to sludge reuse as fertilizer strongly influenced constructed wetlands life cycle (up to 90% of the overall impact). For this reason, constructed wetlands scenarios (scenarios W2 and W3) showed higher environmental impact compared to activated sludge scenarios (scenarios W4 to W6), but still lower compared to the third-party management scenario (scenario W1) in the terrestrial ecotoxicity impact category. Nevertheless, it has to be mentioned that the fertilizer obtained from winery sludge has a high content of organic matter which improves soil quality (INRA, 2018). However, these benefits were not taken into account in this study.

In conclusion, constructed wetland systems are environmentally friendly technologies which help to reduce environmental impacts associated with winery wastewater treatment, by treating winery waste on-site with low energy and chemicals requirements.

3.2 Sensitivity analysis

The results of the sensitivity analysis are shown in Table 5, where the most sensitive inventory components are indicated by bold type. Results showed that Photochemical Oxidant Formation, Marine Eutrophication and Particulate Matter Formation Potentials were not sensitive to any of the parameters considered (sensitivity coefficient < 0.3). On the contrary, Climate Change and Terrestrial Acidification Potentials were somewhat sensitive to CH_4 emissions from the wastewater treatment systems and NH_3 emissions from fertilizer application, respectively (sensitivity coefficients between 0.12 and 0.32, Table 5). Indeed, a 10% increase in CH_4 emissions in constructed wetlands scenarios (scenarios W2 and W3) would increase Climate Change Potential by 1.2-2.4%. On the other hand, a 10% increase in NH_3 direct emissions would increase Terrestrial Acidification Potential by 2.2% and 0.9-3.2% in W2 and W3 scenarios, respectively.

Finally, it can be concluded that the main findings of this study are not strongly dependent on the assumptions considered.

4. Conclusions

In this study, an LCA was carried out in order to assess the environmental performance of constructed wetland systems for winery wastewater treatment. The results showed that the constructed wetland scenarios were the most environmentally friendly alternatives, while the third-party management was the worst scenario followed by the activated sludge systems. Specifically, the potential environmental impacts of the constructed wetlands scenarios were 1.5-180 and 1-10 times lower compared to those generated by the third-party and activated sludge scenarios, respectively. Moreover, it has been demonstrated that, in order to reduce the environmental impacts generated by the activated sludge systems already implemented in the wineries located in South-Western Europe, sludge treatment wetlands can be implemented in order to avoid sludge transportation.

In conclusion, constructed wetlands are decentralized technologies for winery wastewater treatment which help reducing environmental impacts by avoiding wastewater and sludge transportation and reducing electricity and chemicals consumption compared to conventional solutions. An economic assessment should be carried out in order to test the economic feasibility and further promote the dissemination of these systems.

Acknowledgements

This research was funded by the European Regional Development Fund (Interreg V-B SUDOE programme, WETWINE SOE1/P5/E0300) (http://wetwine.eu/). Laura Flores is grateful to the Ministry of Education and Culture (MECD) (Spain) for the FPU16/01491 scholarship. Marianna Garfí is grateful to the Spanish Ministry of Economy and Competitiveness (Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016, Subprograma Ramón y Cajal (RYC) 2016). The authors are grateful for the support provided by the WETWINE consortium and the wineries involved in this study.

References

Anastasiou, N., Monou, M., Mantzavinos, D., Kassinos, D., 2009. Monitoring of the quality of winery influents/effluents and polishing of partially treated winery flows by homogeneous Fe(II) photo-oxidation. Desalination 248, 836–842.

Arashiro, L.T., Montero, N., Ferrer, I., Acién, F.G., Gómez, C., Garfí, M., 2018. Life Cycle Assessment of high rate algal ponds for wastewater treatment and resource recovery. Sci. Total Environ. 622–623, 1118–1130.

APHA-AWWA, 2017. Standard Methods for the Examination of Water and Waste-water. 23rd ed. American Public Health Association, Washington, DC.

Ávila, C., García, J., Garfí, M., 2016. Influence of hydraulic loading rate, simulated storm events and seasonality on the treatment performance of an experimental three-stage hybrid constructed wetland system. Ecol. Eng. 87, 324–332.

Bolzonella, D., Fatone, F., Pavan, P., Cecchi, F., 2010. Application of a membrane bioreactor for winery wastewater treatment. Water Sci. Technol. 62, 2754–2759.

Brix, H. 2017. Sludge dewatering and mineralization in sludge treatment reed beds. Water 9(3), 160.

Corbella, C., Puigagut, J., Garfí, M., 2017. Life cycle assessment of constructed wetland systems for wastewater treatment coupled with microbial fuel cells. Sci. Total Environ. 584–585, 355–362.

Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: State of the art. Water Res. 47, 5480–5492.

Dixon, A., Simon, M., Burkitt, T., 2003. Assessing the environmental impact of two options for small-scale wastewater treatment: Comparing a reedbed and an aerated biological filter using a life cycle approach. Ecol. Eng. 20, 297–308.

Fuchs, V.J., Mihelcic, J.R., Gierke, J.S., 2011. Life cycle assessment of vertical and horizontal flow constructed wetlands for wastewater treatment considering nitrogen and carbon greenhouse gas emissions. Water Res. 45, 2073–2081.

Garfí, M., Flores, L., Ferrer, I., 2017. Life Cycle Assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds. J. Clean. Prod. 161, 211–219.

Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J., van Zelm, R., 2013. ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation. 133.

Guinée, J.B., 2002., Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards, Springer, New York.

INRA, 2018. The WETWINE project: Agronomic field trials. Available at: http://wetwine.eu/

International Energy Agency (IEA), 2017. Energy systems overview. Available at: www.iea.org

Ioannou, L.A., Puma, G.L., Fatta-Kassinos, D., 2015. Treatment of winery wastewater by physicochemical, biological and advanced processes: A review. J. Hazard. Mater. 286, 343–368.

IPCC (Intergovernmental Panel on Climate Change), 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

ISO, 2006a. ISO 14040: environmental management — Life cycle assessment — Principles and framework. Geneva.

ISO, 2006b. ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. Geneva.

Kim, B., Gautier, M., Prost-Boucle, S., Molle, P., Michel, P., Gourdon, R., 2014. Performance evaluation of partially saturated vertical-flow constructed wetland with trickling filter and chemical precipitation for domestic and winery wastewaters treatment. Ecol. Eng. 71, 41–47.

Lavola 1981 S.A., 2015. Case study: Life Cycle Assessment of a wastewater treatment plant. Available at: http://sostenibilitat.lavola.com

Litaor, M.I., Meir-Dinar, N., Castro, B., Azaizeh, H., Rytwo, G., Levi, N., Levi, M., MarChaim, U., 2015. Treatment of winery wastewater with aerated cells mobile system. Environ. Nanotechnology, Monit. Manag. 4, 17–26.

Lopsik, K., 2013. Life cycle assessment of small-scale constructed wetland and extended aeration activated sludge wastewater treatment system. Int. J. Environ. Sci. Technol. 10, 1295–1308.

Lundin, M., 2000. Life Cycle Assessment of Wastewater Systems : Influence of System Boundaries and Scale on Calculated Environmental Loads. Environ. Sci. Technol. 34, 180–186.

Moreno-Ruiz, E., Lévová, T., Bourgault, G., Wernet, G., 2014. Documentation of changes implemented in ecoinvent Data 3.1. Zurich: ecoinvent.

Niero, M., Pizzol, M., Bruun, H.G., Thomsen, M., 2014. Comparative life cycle assessment of wastewater treatment in Denmark including sensitivity and uncertainty analysis. J. Clean. Prod. 68, 25–35.

OIV, 2017. International Organisation of Vine and Wine. Situation Report for The World Vitivinicultural Sector in 2017. Available at: www.oiv.org

Piao, W., Kim, Y., 2016. Evaluation of monthly environmental loads from municipal wastewater treatment plants operation using life cycle assessment. Environ. Eng. Res. 21, 284–290.

Pré Consultants, 2014. SimaPro Database Manual. PRé 1–48.

Red Eléctrica Española, 2016. The Spanish Electricity Generation Mix System. Report 2016. Available at: http://www.ree.es/en/statistical-data-of-spanish-electrical-system/annual-report

Rozema, E.R., Rozema, L.R., Zheng, Y., 2016. A vertical flow constructed wetland for the treatment of winery process water and domestic sewage in Ontario, Canada: Six years of performance data. Ecol. Eng. 86, 262–268.

Ruggieri, L., Cadena, E., Martínez-Blanco, J., Gasol, C.M., Rieradevall, J., Gabarrell, X., Gea, T., Sort, X., Sánchez, A., 2009. Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyses of the composting process. J. Clean. Prod. 17, 830–838.

Serrano, L., de la Varga, D., Ruiz, I., Soto, M., 2011. Winery wastewater treatment in a hybrid constructed wetland. Ecol. Eng. 37, 744–753.

Shepherd, H.L., Grismer, M.E., Tchobanoglous, G., 2001. Treatment of High-Strength Winery Wastewater Using a Subsurface-Flow Constructed Wetland. Water Environ. Res. 73, 394–403.

Solé-Bundó, M., Cucina, M., Folch, M., Tapias, J., Gigliotti, G., Garfí, M., Ferrer, I., 2017. Assessing the agricultural reuse of the digestate from microalgae anaerobic digestion and co-digestion with sewage sludge. Sci. Total Environ. 586, 1-9.

Suh, Y.J., Rousseaux, P., 2002. An LCA of alternative wastewater sludge treatment scenarios. Resour. Conserv. Recycl. 35, 191–200.

UPC, 2018. The WETWINE project: Life Cycle Inventory (E4.1.1). Available at: http://wetwine.eu/resultados/

Valderrama, C., Ribera, G., Bahí, N., Rovira, M., Giménez, T., Nomen, R., Lluch, S., Yuste, M., Martinez-Lladó, X., 2012. Winery wastewater treatment for water reuse purpose: Conventional activated sludge versus membrane bioreactor (MBR). A comparative case study. Desalination. 306, 1–7.

Vymazal, J., 2014. Constructed wetlands for treatment of industrial wastewaters: A review. Ecol. Eng. 73, 724–751.

Yildirim, M., Topkaya, B. 2012. Assessing Environmental Impacts of Wastewater Treatment Alternatives for Small-Scale Communities. Clean – Soil, Air, Water, 40 (2), 171–178.

Weidema B.P., Bauer C., Hischier R., Mutel C., Nemecek T., Reinhard J., Vadenbo C. O., Wernet G., 2013. Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1 (v3). St. Gallen: The ecoinvent Centre.

Wu, S., Wallace, S., Brix,H., Kuschk,P., Kirui , W.K., Masi., F., Dong., R., 2015. Treatment of industrial effluents in constructed wetlands: Challenges, operational strategies and overall performance. Environ. Pollution. 201, 107-120.

Table 1. Main characteristics of the wineries and their wastewater treatment systems and management strategies considered in this study

		Scenarios				
	Unit	**W1 and W2**	**W3**	**W4**	**W5**	**W6**
General data						
Location	-	Galicia (Spain)	Galicia (Spain)	Galicia (Spain)	Vila Real (Portugal)	Tarn (France)
Total wine production	L yr^{-1}	368,000	350,000	3,850,000	5,500,000	7,750,000
Vintage season duration	d yr^{-1}	26	27	15	40	65
Wastewater treatment and management						
Wastewater flows						
Total	m^3 yr^{-1}	1,400	1,900	4,832	11,500	12,141
Vintage season	m^3 during the vintage season	620	436	2,416	2,400	3,996
Rest of the year	m^3 during the rest of the year	780	1,464	2,416	9,100	8,145
Wastewater treatment/management alternatives	-	W1: third-party management (previous scenario) W2: constructed wetlands (current scenario)	Constructed wetlands	Activated sludge system	Activated sludge system	Activated sludge system
Sludge management	-	W1: third-party management (previous scenario) W2: sludge treatment wetlands (current scenario)	On-site composting	Third-party management	Third-party management	Third-party management
Wastewater quality characteristics (vintage season)						
pH	-	5	4	7	6	4.5
COD	mg L^{-1}	1,031	5,263	11,957	10,000	16,825
BOD$_5$	mg L^{-1}	650	3,047	4,110	2,500	10,300
TSS	mg L^{-1}	706	523	2,190	1,300	2,000
TN	mg L^{-1}	9.7	-	-	-	109.2
TP	mg L^{-1}	1.5	-	-	-	17.7
Wastewater quality characteristics (rest of the year)						
pH	-	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5	7.5
COD	mg L^{-1}	< 500	< 2,000	< 2,000	< 2,000	< 2,000
BOD$_5$	mg L^{-1}	< 250	< 1,000	< 1,000	< 1,000	< 1,000

TSS	mg L^{-1}	< 200	< 300	< 1,000	< 1,000	< 1,000
TN	mg L^{-1}	< 20	-	-	-	< 100
TP	mg L^{-1}	< 10	-	-	-	< 50

Note: COD: Chemical Oxygen Demand; BOD_5; Biochemical Oxygen Demand; TSS: Total Suspended Solids; TN: Total Nitrogen; TP: Total Phosphorous. The W2 scenario consisted of a constructed wetland system recently implemented in the same winery as the W1 scenario, in order to replace the third-party management (W1).

Table 2. Inventory results referred to the functional unit (1 m^3 of treated water) for the construction of the wastewater treatment systems

	Unit	Scenarios					
		W1	**W2**	**W3**	**W4**	**W5**	**W6**
Inputs							
Concrete	m^3 m^{-3}	5.944E-04	1.339E-04	3.532E-04	2.405E-04	1.123E-04	9.467E-05
Reinforcing steel	kg m^{-3}	5.944E-02	7.340E-03	3.532E-02	2.379E-02	1.113E-02	9.415E-03
Steel	kg m^{-3}	2.336E-04	1.170E-03	3.442E-04	6.766E-05	2.843E-05	2.693E-05
Copper	kg m^{-3}	3.507E-04	1.756E-03	5.168E-04	1.016E-04	4.270E-05	4.044E-05
Cast iron	kg m^{-3}	7.014E-04	3.512E-03	1.034E-03	2.032E-04	8.539E-05	8.088E-05
PVC	kg m^{-3}	-	6.385E-03	6.385E-03	6.207E-04	2.609E-04	2.471E-04
Gravel	m^3 m^{-3}	-	1.967E-03	1.967E-03	-	-	-
Sand	m^3 m^{-3}	-	2.145E-04	2.145E-04	-	-	-
Geotextile	kg m^{-3}	-	2.989E-03	2.989E-03	-	-	-
Geomembrane	kg m^{-3}	-	6.401E-03	6.401E-03	-	-	-
Polyethylene	kg m^{-3}	-	3.755E-02	-	-	-	-
Glass fibre reinforced plastic	kg m^{-3}	-	6.705E-03	-	-	-	-

Scenarios: W1: third-party management; W2 and W3: constructed wetland systems; W4, W5 and W6: activated sludge systems**.**

Table 3. Inventory results referred to the functional unit (1 m^3 of treated water) for the operation of the wastewater treatment systems and management during the vintage season

	Unit	**Scenarios**					
		W1	**W2**	**W3**	**W4**	**W5**	**W6**
Inputs							
Electricity	kWh/m^3	0.000E+00	5.032E-01	1.858E-01	2.000E+00	2.250E+00	2.150E+00
Flocculant	kg/m^3	-	-	-	1.242E-01	1.242E-01	3.754E-02
Sodium hydroxide	kg/m^3	-	-	-	4.139E-01	4.139E-01	-
Urea	kg/m^3	-	-	-	6.623E-01	6.623E-01	8.133E-02
Phosphoric acid	kg/m^3	-	-	-	4.139E-01	4.139E-01	-
Hydrogen peroxide	kg/m^3	-	-	4.587E-01	-	-	-
Sulphuric acid	kg/m^3	-	-	-	-	-	7.257E-01
Outputs							
Sludge	kg/m^3	-	-	-	9.934E+00	2.500E+01	2.628E+01
Sludge transportation	tkm/m^3	-	-	-	1.490E+00	3.750E+00	1.577E-01
Wastewater transportation	tkm/m^3	2.400E+02	-	-	-	-	-
Direct emissions to air (released by wastewater treatment systems)							
CH_4	g/m^3	-	1.089E+01	1.089E+01	-	-	-
N_2O	g/m^3	-	1.686E-02	1.686E-02	1.100E-01	1.100E-01	1.100E-01
Direct emissions to air (due to fertilizer application to soil)							
CH_4	g/m^3	-	9.518E-01	1.113E+00	-	-	-
N_2O	g/m^3	-	8.848E-02	1.907E-01	-	-	-
NH_3	g/m^3	-	1.843E+00	3.974E+00	-	-	-
Direct emissions to soil (due to fertilizer application to soil)							
Fe	g/m^3	-	9.690E+00	9.194E+00	-	-	-
Co	g/m^3	-	2.342E-03	2.222E-03	-	-	-
Mn	g/m^3	-	1.639E-01	1.555E-01	-	-	-
Mo	g/m^3	-	1.531E-03	1.452E-03	-	-	-
Cr	g/m^3	-	4.038E-02	3.831E-02	-	-	-
Ni	g/m^3	-	2.027E-02	1.924E-02	-	-	-
Cu	g/m^3	-	1.951E-01	1.851E-01	-	-	-
Zn	g/m^3	-	5.007E-01	4.750E-01	-	-	-
Cd	g/m^3	-	2.875E-04	2.727E-04	-	-	-
Hg	g/m^3	-	1.618E-04	1.535E-04	-	-	-
Pb	g/m^3	-	2.235E-02	2.120E-02	-	-	-

Direct emissions to water							
BOD_5	g/m^3	2.500E+01	2.500E+01	2.500E+01	2.500E+01	2.500E+01	3.000E+01
COD	g/m^3	1.250E+02	1.250E+02	1.250E+02	1.250E+02	1.250E+02	1.500E+02
TN	g/m^3	1.500E+01	1.500E+01	1.500E+01	1.500E+01	1.500E+01	3.000E+01
TP	g/m^3	2.000E+00	2.000E+00	2.000E+00	2.000E+00	2.000E+00	5.000E+00
TSS	g/m^3	3.500E+01	3.500E+01	3.500E+01	3.500E+01	3.500E+01	4.000E+01
Avoided products							
N as Fertiliser (from sludge reuse as fertilizer)	g/m^3	-	7.373E+00	1.589E+01	-	-	-
P as Fertiliser (from sludge reuse as fertilizer)	g/m^3	-	4.074E+00	2.326E+00	-	-	-

Scenarios: W1: third-party management; W2 and W3: constructed wetland systems; W4, W5 and W6: activated sludge systems.

Table 4. Inventory results referred to the functional unit (1 m^3 of treated water) for the operation of the wastewater treatment systems and management during the rest of the year.

	Unit	Scenarios					
		W1	**W2**	**W3**	**W4**	**W5**	**W6**
Inputs							
Electricity	kWh/m^3	0.000E+00	1.743E-01	2.309E-02	6.900E-01	3.956E-01	3.800E-01
Flocculant	kg/m^3	-	-	-	1.034E-01	1.034E-01	1.842E-02
Sodium hydroxide	kg/m^3	-	-	-	1.241E-01	1.241E-01	-
Urea	kg/m^3	-	-	-	3.310E-01	3.310E-01	3.683E-02
Phosphoric acid	kg/m^3	-	-	-	2.069E-01	2.069E-01	-
Sulphuric acid	kg/m^3	-	-	-	-	-	7.244E-01
Outputs							
Sludge	kg/m^3	-	-	-	4.137E+00	1.000E+01	1.051E+01
Sludge transportation	tkm/m^3	-	-	-	6.206E-01	1.500E+00	6.380E-02
Wastewater transportation	tkm/m^3	2.400E+02	-	-	-	-	-
Direct emissions to air (released by wastewater treatment systems)							
CH_4	g/m^3	-	1.089E+01	1.089E+01	-	-	-
N_2O	g/m^3	-	1.686E-02	1.686E-02	1.100E-01	1.100E-01	1.100E-01
Direct emissions to air (due to fertilizer application to soil)							
CH_4	g/m^3	-	9.518E-01	2.209E-01	-	-	-
N_2O	g/m^3	-	8.848E-02	3.787E-02	-	-	-
NH_3	g/m^3	-	1.843E+00	7.889E-01	-	-	-
Direct emissions to soil (due to fertilizer application to soil)							
Fe	g/m^3	-	9.690E+00	1.825E+00	-	-	-
Co	g/m^3	-	2.342E-03	4.411E-04	-	-	-
Mn	g/m^3	-	1.639E-01	3.088E-02	-	-	-
Mo	g/m^3	-	1.531E-03	2.883E-04	-	-	-
Cr	g/m^3	-	4.038E-02	7.606E-03	-	-	-
Ni	g/m^3	-	2.027E-02	3.819E-03	-	-	-
Cu	g/m^3	-	1.951E-01	3.676E-02	-	-	-
Zn	g/m^3	-	5.007E-01	9.431E-02	-	-	-
Cd	g/m^3	-	2.875E-04	5.415E-05	-	-	-

Hg	g/m^3	-	1.618E-04	3.048E-05	-	-	-
Pb	g/m^3	-	2.235E-02	4.210E-03	-	-	-
Direct emissions to water							
BOD_5	g/m^3	2.500E+01	2.500E+01	2.500E+01	2.500E+01	2.500E+01	2.500E+01
COD	g/m^3	1.250E+02	1.250E+02	1.250E+02	1.250E+02	1.250E+02	8.000E+01
TN	g/m^3	1.500E+01	1.500E+01	1.500E+01	1.500E+01	1.500E+01	2.500E+01
TP	g/m^3	2.000E+00	2.000E+00	2.000E+00	2.000E+00	2.000E+00	2.000E+00
TSS	g/m^3	3.500E+01	3.500E+01	3.500E+01	3.500E+01	3.500E+01	3.500E+01
Avoided products							
N as Fertiliser (from sludge reuse as fertilizer)	g/m^3	-	7.373E+00	3.156E+00	-	-	-
P as Fertiliser (from sludge reuse as fertilizer)	g/m^3	-	4.074E+00	4.619E-01	-	-	-

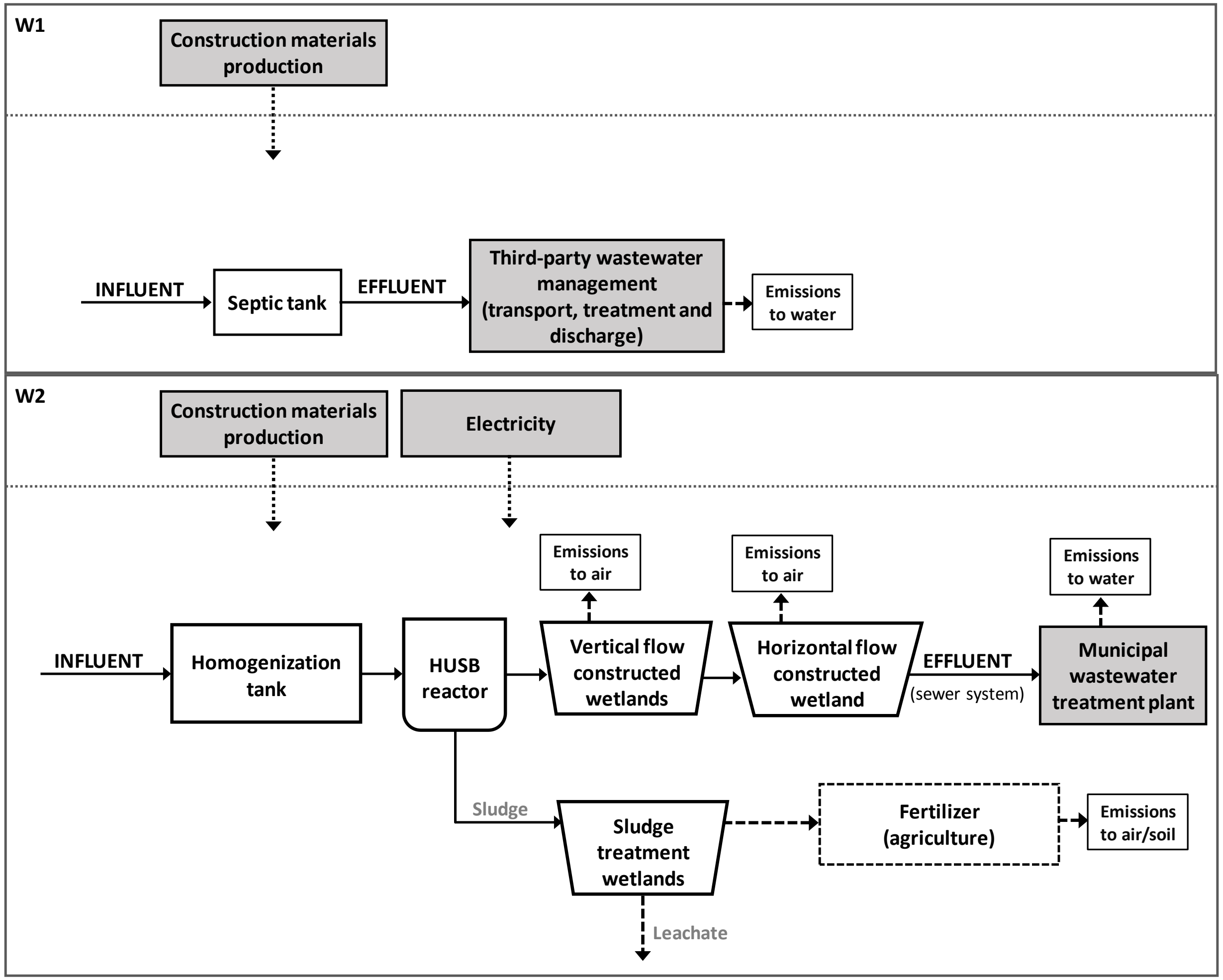
Scenarios: W1: third-party management; W2 and W3: constructed wetland systems; W4, W5 and W6: activated sludge systems

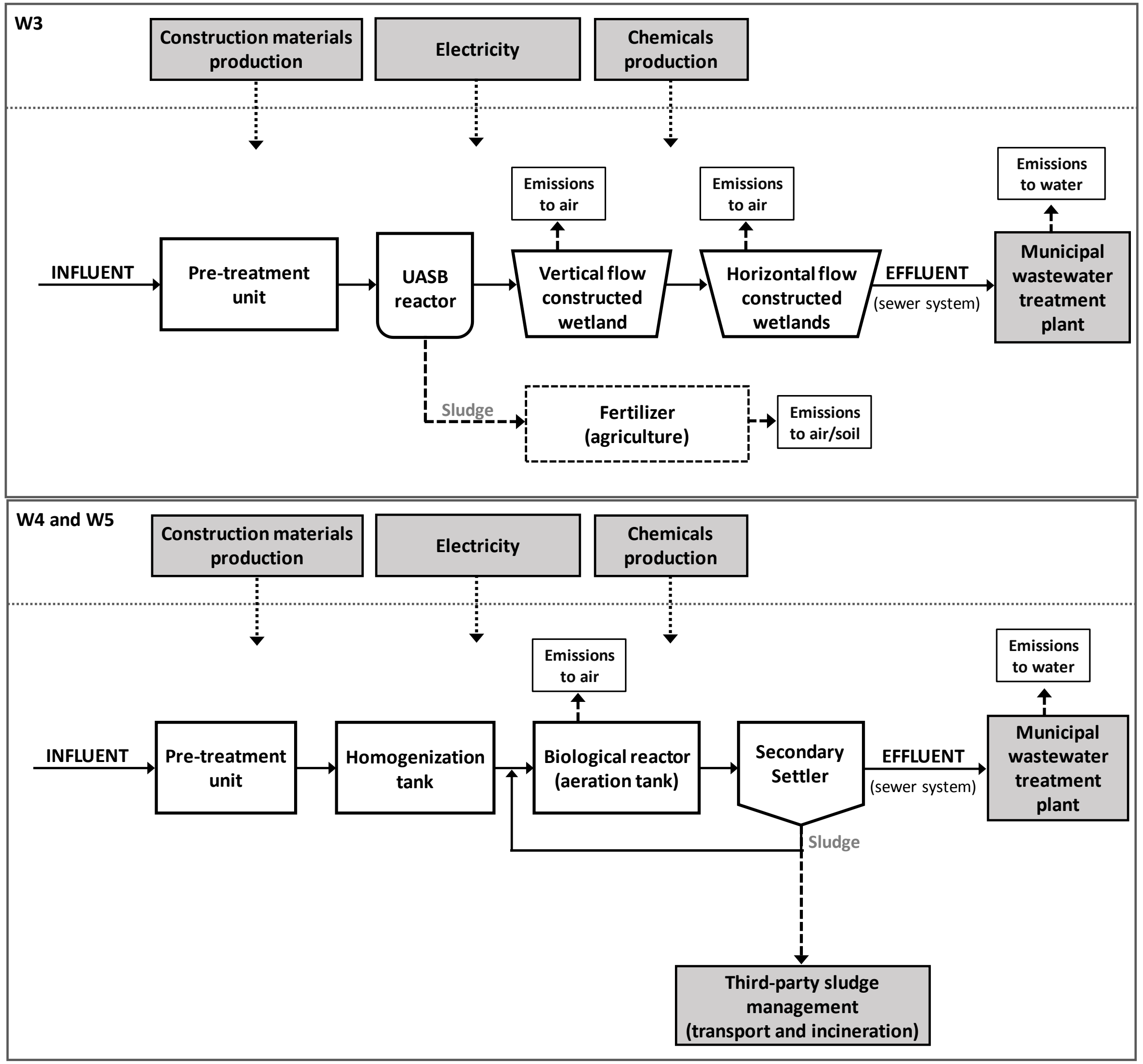
Table 5. Results of the sensitivity analysis for the considered parameters: CH$_4$ emissions released by the constructed wetland systems in scenarios W2 and W3; N$_2$O emissions released by the wastewater treatment systems in scenarios W2 to W6; CH$_4$, N$_2$O and NH$_3$ emissions caused by fertilizer application to agricultural soil in W2 and W3.

Parameters	**Scenarios**	**Impact categories**									
		Climate Change		**Photochemical Oxidant Formation**		**Terrestrial Acidification**		**Marine Eutrophication**		**Particulate Matter Formation**	
		vintage season	**rest of the year**	**vintage season**	**rest of the year**	**vintage season**	**rest of the year**	**vintage season**	**rest of the year**	**vintage season**	**rest of the year**
CH$_4$ emissions from the wastewater treatment systems	**W2**	***±0.190***	***±0.210***	±0.025	±0.028	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W3	***±0.120***	***±0.240***	±0.017	±0.032	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
N$_2$O emissions from the wastewater treatment systems	**W2**	±0.003	±0.004	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W3	±0.002	±0.005	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W4	±0.006	±0.012	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W5	±0.004	±0.002	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W6	±0.009	±0.003	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
CH$_4$ emissions from fertilizer application	**W2**	±0.005	±0.006	±0.001	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W3	±0.005	±0.007	±0.001	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
N$_2$O emissions from fertilizer application	**W2**	±0.001	±0.001	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
	W3	±0.001	±0.001	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000	±0.000
NH$_3$ emissions from fertilizer application	**W2**	±0.000	±0.000	±0.000	±0.000	***±0.220***	***±0.220***	±0.001	±0.001	±0.005	±0.005

W3	±0.000	±0.000	±0.000	±0.000	***±0.320***	±0.090	±0.001	±0.001	±0.010	±0.001

Scenarios: W1: third-party management; W2 and W3: constructed wetland systems; W4, W5 and W6: activated sludge systems


W1
Construction materials production
INFLUENT
Septic tank
EFFLUENT
Third-party wastewater management (transport, treatment and discharge)
Emissions to water
W2
Construction materials production
Electricity
INFLUENT
Homogenization tank
HUSB reactor
Emissions to air
Vertical flow constructed wetlands
Emissions to air
Horizontal flow constructed wetland
EFFLUENT
(sewer system)
Emissions to water
Municipal wastewater treatment plant
Sludge
Sludge treatment wetlands
Fertilizer (agriculture)
Emissions to air/soil
Leachate


W3
Construction materials production
Electricity
Chemicals production
Emissions to air
Emissions to air
Emissions to water
INFLUENT
Pre-treatment unit
UASB reactor
Vertical flow constructed wetland
Horizontal flow constructed wetlands
EFFLUENT
(sewer system)
Municipal wastewater treatment plant
Sludge
Fertilizer (agriculture)
Emissions to air/soil
W4 and W5
Construction materials production
Electricity
Chemicals production
Emissions to air
Emissions to water
INFLUENT
Pre-treatment unit
Homogenization tank
Biological reactor (aeration tank)
Secondary Settler
EFFLUENT
(sewer system)
Municipal wastewater treatment plant
Sludge
Third-party sludge management (transport and incineration)

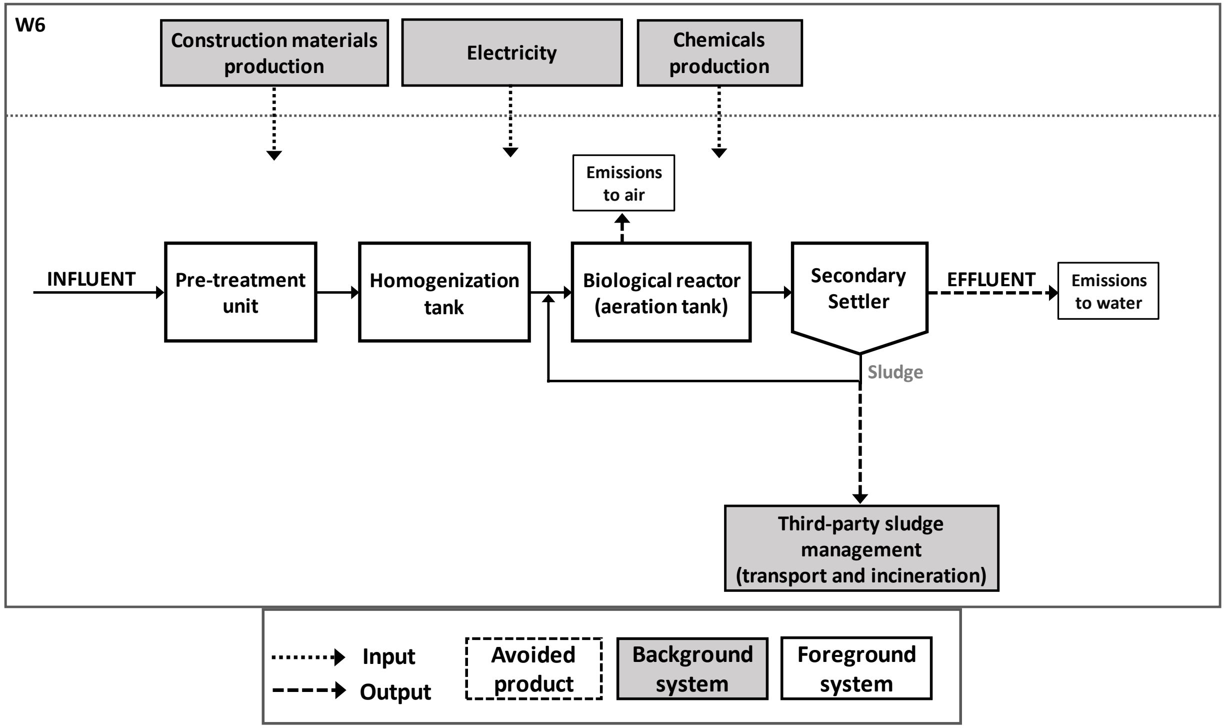
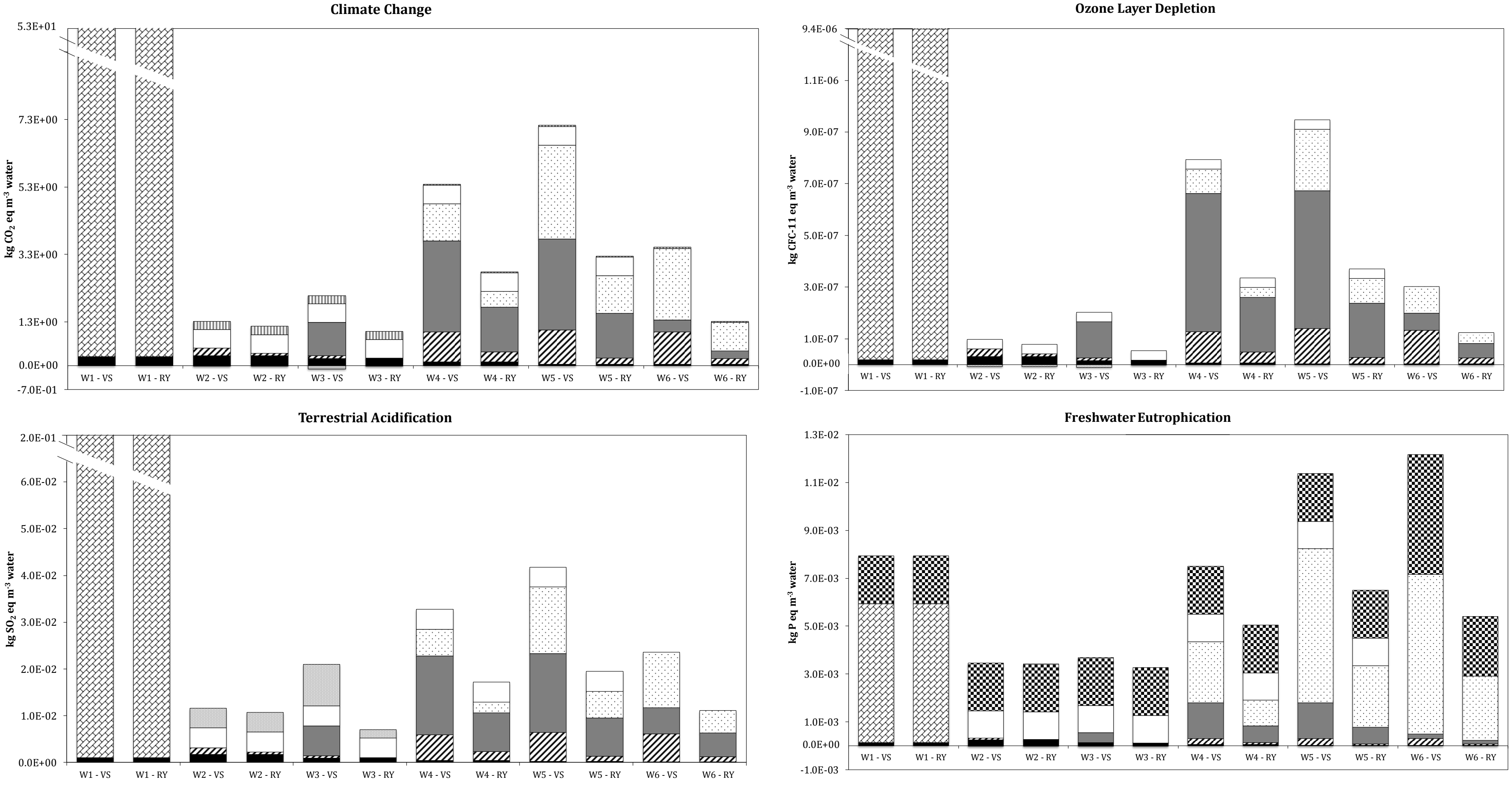
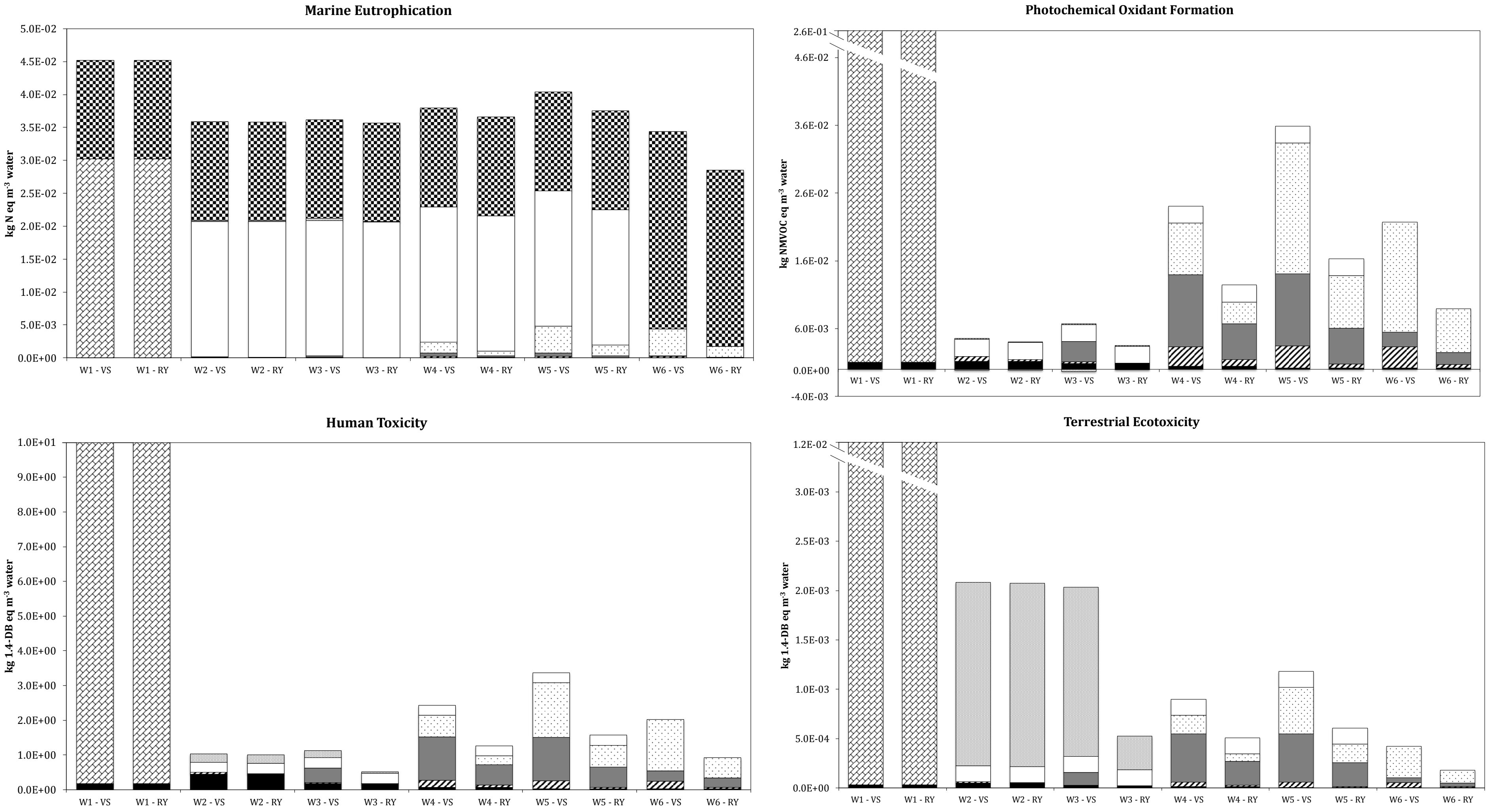
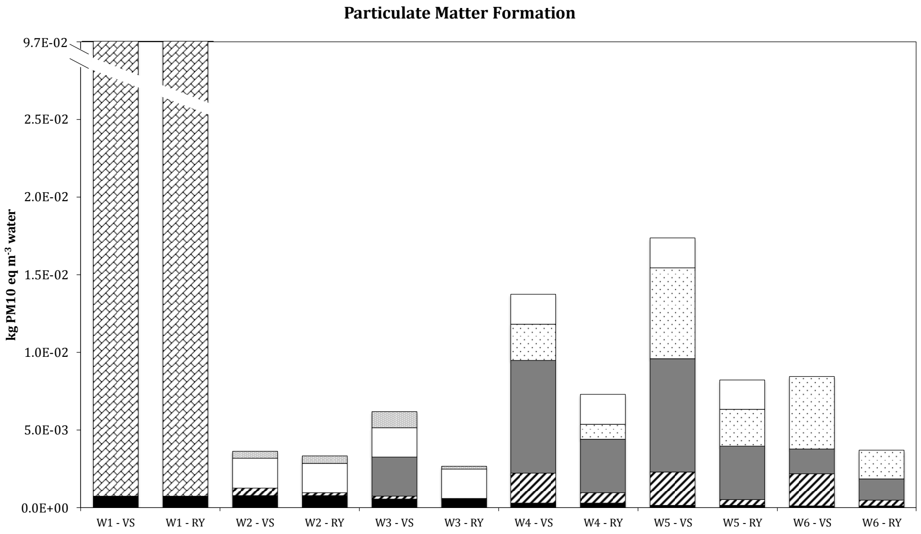


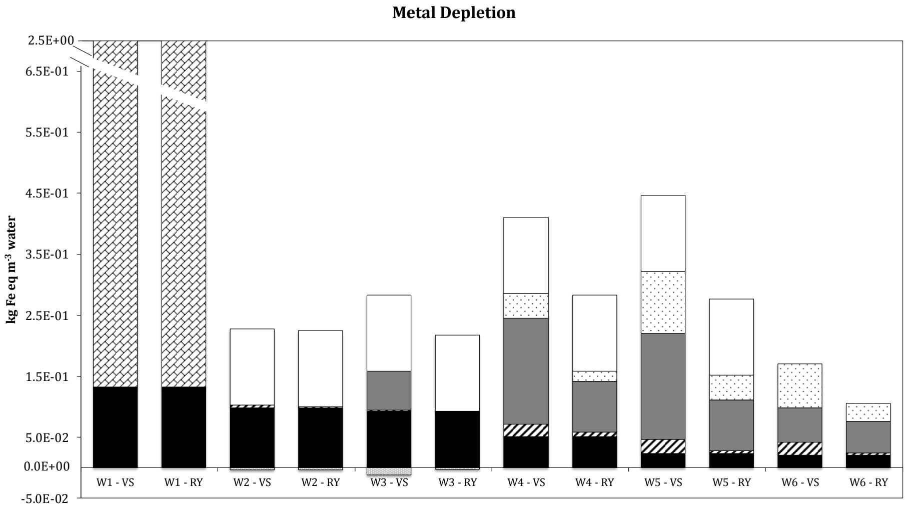
Figure 1. System boundaries of the alternatives considered in this study: W1: third-party management; W2 and W3: constructed wetland systems; W4, W5 and W6: activated sludge systems.


Climate Change
kg CO_2 eq m^{-3} water
5.3E+01
7.3E+00
5.3E+00
3.3E+00
1.3E+00
0.0E+00
-7.0E-01
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY
Ozone Layer Depletion
kg CFC-11 eq m^{-3} water
9.4E-06
1.1E-06
9.0E-07
7.0E-07
5.0E-07
3.0E-07
1.0E-07
0.0E+00
-1.0E-07
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY
Terrestrial Acidification
kg SO_2 eq m^{-3} water
2.0E-01
6.0E-02
5.0E-02
4.0E-02
3.0E-02
2.0E-02
1.0E-02
0.0E+00
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY
Freshwater Eutrophication
kg P eq m^{-3} water
1.3E-02
1.1E-02
9.0E-03
7.0E-03
5.0E-03
3.0E-03
1.0E-03
0.0E+00
-1.0E-03
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY

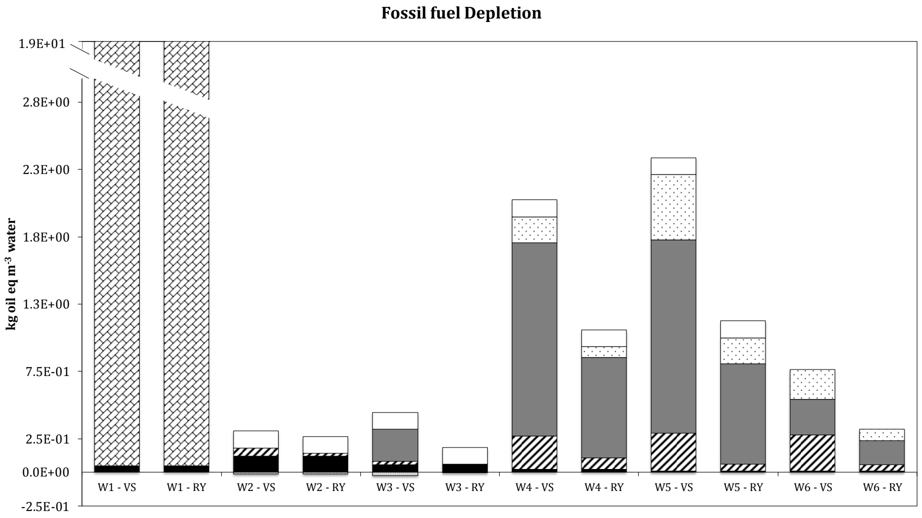

Marine Eutrophication
kg N eq m^{-3} water
5.0E-02
4.5E-02
4.0E-02
3.5E-02
3.0E-02
2.5E-02
2.0E-02
1.5E-02
1.0E-02
5.0E-03
0.0E+00
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY
Photochemical Oxidant Formation
kg NMVOC eq m^{-3} water
2.6E-01
4.6E-02
3.6E-02
2.6E-02
1.6E-02
6.0E-03
0.0E+00
-4.0E-03
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY
Human Toxicity
kg 1.4-DB eq m^{-3} water
1.0E+01
9.0E+00
8.0E+00
7.0E+00
6.0E+00
5.0E+00
4.0E+00
3.0E+00
2.0E+00
1.0E+00
0.0E+00
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY
Terrestrial Ecotoxicity
kg 1.4-DB eq m^{-3} water
1.2E-02
3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
W1 - VS
W1 - RY
W2 - VS
W2 - RY
W3 - VS
W3 - RY
W4 - VS
W4 - RY
W5 - VS
W5 - RY
W6 - VS
W6 - RY



Particulate Matter Formation



Metal Depletion

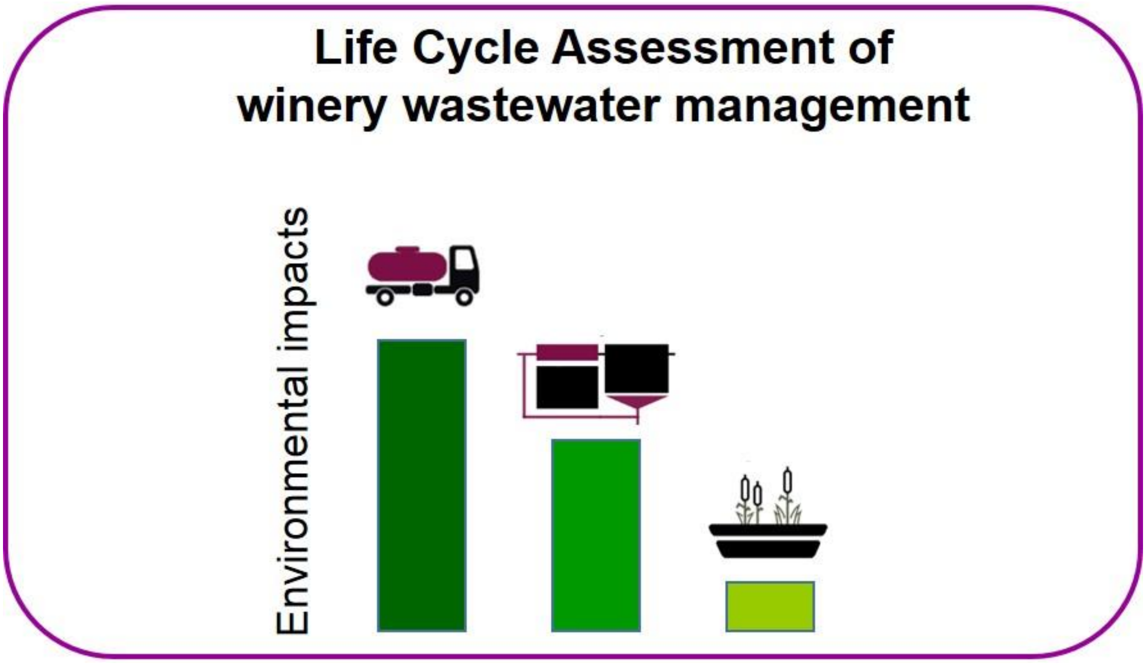


Fossil fuel Depletion

■ Construction materials
▨ Third-party wastewater transportation and disposal
▦ Fertilizer avoided and application to soil
◩ Electricity
☐ Third-party sludge transportation and disposal
▥ Direct emissions to air
■ Chemicals
☐ Treatment at municipal wastewater treatment plant
▚ Direct emissions to water

Figure 2. Potential environmental impacts for the six scenarios considered during the vintage season (VS) and the rest of the year (RY). Values are referred to the functional unit (1 m^3 of treated water). Scenarios: W1: third-party management; W2 and W3: constructed wetland systems; W4, W5 and W6: activated sludge systems.

Graphical Abstract



Highlights

- A Life Cycle Assessment of winery wastewater treatment was performed
- Constructed wetlands, third-party management and activated sludge were considered
- Constructed wetlands showed to be the most environmentally friendly solution
- Environmental impacts of constructed wetlands were up to 180 times lower