Carbon footprint of constructed wetlands for winery wastewater treatment

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Abstract

The aim of this study was to estimate the carbon footprint (CFP) of constructed wetlands for winery wastewater treatment. In particular, a constructed wetland scenario was compared to the previous scenario (third-party management) and to an activated sludge system. CFP considered both indirect and direct greenhouse gas (GHG) emissions measured on-site. Moreover, an economic analysis of the considered scenarios was also addressed. The results showed that the constructed wetland scenario had the lowest CFP (1.2 kg CO_2eq m_{water}^{-3}), while the third-party management was the worst scenario (52 kg CO_2eq m_{water}^{-3}) followed by the activated sludge system (4.5 kg CO_2eq m_{water}^{-3}). This was mainly due to the high GHG emissions generated by wastewater and sludge transportation as well as chemicals and electricity consumption in the third-party and activated sludge scenarios compared to the constructed wetlands. In terms of costs, the constructed wetland system was shown to be a low-cost technology which would reduce the capital, operation and maintenance costs associated with winery wastewater treatment up to 50 and 98%, respectively. Finally, constructed wetlands are low-cost and environmentally friendly technologies which constitute a sustainable alternative to conventional solutions for winery wastewater treatment.

Keywords: activated sludge; treatment wetland; greenhouse gas emissions; life cycle assessment; winery wastewater.

1. Introduction

Climate change has become a major issue that has created a global concern. This phenomenon is attributed to the increase of anthropogenic greenhouse gas (GHG) emissions (e.g. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) from different human activities. In particular, it was estimated that wastewater treatment may account for around 10 per cent of anthropogenic methane emissions, both from domestic and industrial sources (IPCC, 2006; UNFCCC, 2018). The Carbon footprint (CFP) is a tool that can be used to estimate the contribution of wastewater treatment plants to global warming and to identify hotspots for its prevention and/or mitigation (Flores-Alsina et al., 2011; Wiedmann and Minx, 2008). Several studies, which assessed the CFP of conventional wastewater treatment plants (e.g. activated sludge system), pointed out that their contribution to the global GHG emissions is mainly due to energy and chemicals consumption for plants operation (Biswas and Yek, 2016; Caniani et al., 2018; Caivano et al., 2017; Chai et al., 2015; Flores-Alsina et al., 2011; Gu et al., 2016; Gustavsson and Tumlin, 2013; Parravicini et al., 2016; Rosso and Bolzonella, 2009; Vijayan et al., 2017).

Constructed wetland systems are natural technologies which constitute an alternative to activated sludge systems for urban and industrial wastewater treatment due to their low cost, low energy requirement and easy operation and maintenance (Arden and Ma, 2018; Vymazal, 2014). Specifically, they have been proved to be a suitable solution for winery wastewater treatment. Indeed, constructed wetlands, which can be perfectly integrated into the rural landscape, are able to couple with seasonal variation in wastewater flows and loadings that typically occur in some food industries (e.g. wine industry) (Ávila et al., 2016; Kim et al., 2014; Rozema et al., 2016; Serrano et al., 2011 Shepherd et al., 2001).

Previous studies comparing the environmental impacts of constructed wetland systems with conventional technologies pointed out that the former was the most environmentally friendly wastewater treatment option, mainly due to the low electricity and chemicals consumption (Dixon et al., 2013; Fuchs, et al., 2011; Garfí et al., 2017; Machado et al., 2007; Yildirim et al., 2012). Nevertheless, most of these studies considered systems treating urban wastewater. To the best of the authors´ knowledge, only one study analysed the environmental impacts of constructed wetlands treating winery wastewater (Flores et al., 2019a). However, in this study, direct GHG emissions from wastewater treatment were estimated considering the emissions rates from the literature. On the other hand, the importance of considering real GHG emissions measured on-site in full-scale wastewater treatment plants was pointed out by several studies in order to improve the quality of the assessment (Gallego-Schmid and Zepon-Tarpani, 2019; Flores et al., 2019a; Maktabifard et al., 2020; Nguyen et al., 2020).

In this context, the WETWINE project (http://wetwine.eu/en/) aimed to promote constructed wetlands as an environmentally friendly and innovative solution to treat effluents produced by wine industries in South-Western Europe (i.e. Spain, Portugal and the South of France) (SUDOE Programme). One of the main goals of the project was to quantify the environmental benefits in terms of GHG emissions reduction caused by the implementation of this technology compared to the existing solutions (i.e. activated sludge systems, third-party management). To this end, a constructed wetland system was implemented in a winery located in Galicia (Spain) and direct GHG emissions were monitored during the vintage season and the rest of the year.

The aim of this study was to estimate, for the first time, the CFP of constructed wetlands for winery wastewater treatment in the frame of the WETWINE project. In particular, the constructed wetland scenario was compared to the previous scenario (third-party management) and to an activated sludge system also implemented in another winery located in Galicia (Spain). The CFP considered both indirect and direct GHG emissions measured in all the systems. Moreover, an economic analysis of the considered scenarios was also addressed.

2. Materials and methods

The CFP is defined as the total set of GHG emissions caused by an activity or product expressed as carbon dioxide equivalent (CO_2eq). It is a measure of the total amount of GHG (e.g. CO_2, CH_4 and N_2O) emissions of a defined system or activity, considering the whole life cycle (ISO, 2013; Vijayan et al., 2017). It is calculated by converting the estimated GHG emissions into carbon dioxide equivalents (CO_2eq) by global warming potentials (GWPs) over 100 years (e.g. 1, 28 and 265 CO_2eq for CO_2, CH_4, and N_2O respectively) (IPPC, 2006, 2014).

2.1 Scenarios description

In this study, three real winery wastewater treatment and management alternatives implemented in two wineries (Ws) located in Galicia (Spain) were considered. 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 are produced per year. Wastewater was stored in a septic tank and then transported (240 km), treated and discharged by a third-party.

The W2 scenario consisted of a constructed wetland system recently implemented in the same winery as the W1 scenario in the frame of the WETWINE project, 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), one horizontal subsurface flow constructed wetland (30 m^2), and a sludge treatment wetland (20 m^2). Treated wastewater is discharged into the sewer system and treated in a municipal wastewater treatment plant. Stabilized sludge is reused as fertilizer or soil conditioner.

The W3 scenario consisted of an activated sludge system implemented in a winery which treats approximately 4,800 m^3 of winery wastewater per year. After a pre-treatment, wastewater is treated in an extended aeration reactor followed by a secondary settler. Treated wastewater is discharged into the municipal sewer system and treated in a municipal wastewater treatment plant. The sludge produced is stored on-site, centrifuged and transported (150 km) by a third-party to an incineration facility.

2.2 System boundaries and functional unit

System boundaries included systems construction, operation and maintenance over a 20-years period. Input and output flows of materials (i.e. construction materials and chemicals) and energy resources (electricity) were systematically studied for all scenarios. Direct GHG emissions associated with wastewater treatment as well as sludge reuse and application to agricultural soil were also included in the boundaries. In the case of scenario W1 (third-party management), inputs and outputs associated with wastewater transportation and disposal were also accounted for. In the case of the activated sludge system (scenario W3), inputs and outputs associated with sludge transportation and disposal (i.e. incineration) were also included in the boundaries. In the case of the constructed wetland system (scenario W2), 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 functional unit was defined as 1 m^3 of treated water, since the main function of the solutions considered was to treat wastewater.

2.3 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 (UPC, 2018).

Direct GHG (i.e. CO_2, CH_4 and N_2O) emissions generated in the septic tank (scenario W1), the constructed wetlands (scenario W2) and the activated sludge system (scenario W3) were measured by using a Gasmet DX4015 Fourier transform infrared (FTIR) gas analyser. The measurements of CO_2, CH_4 and N_2O fluxes were done using the static chamber method for the constructed wetlands (scenario W2) (Chen et al., 1997; De la Varga et al., 2015; Uggetti et al., 2012) and the floating chamber method for the activated sludge treatment plant (scenario W3) (Czepiel et al., 1995; Hwang et al., 2016; Ribera-Guardia et al., 2019). Two campaigns were carried out during the vintage season (August/September 2018) and the rest of the year (February/March 2018). Different points of each treatment unit of the systems were monitored to envisage the spatial variation of the emissions. Moreover, for the constructed wetlands, feeding and resting periods and in between feeding pulses periods were considered for the measurements. This let to take into account the difference between the constructed wetlands types (Mander et al., 2014). Further details on the methodology used and the results obtained can be found elsewhere (Flores et al., 2019b; Flores et al., submitted).

Regarding the constructed wetlands (scenario W2), CO_2 uptake due to plants photosynthesis was taken into account considering sequestration rate from the literature (Kanungo et al., 2017; Mitsch et al., 2012). They were withdrawn from the overall CO_2 emissions (Table 3 and 4). it has to be mentioned that CO_2 from biogenic sources does not contribute to Climate Change Potential (Doorn et al., 2006). Thus, the LCA results do not depend on plants species.

Direct GHG (i.e. CH_4 and N_2O) emissions due to sludge reuse and application to soil were obtained using the emission rates proposed by the literature (Arashiro et al., 2018; Flores et al., 2019a; IPCC, 2006; Lundin, 2000). GHG emissions associated with the production and transportation of construction materials and chemicals, electricity consumption, wastewater and sludge transportation and disposal, and the avoided fertilizer were obtained from the *Ecoinvent 3* database (Moreno-Ruíz et al., 2014; Weidema et al., 2013).

2.5 Impact assessment

The impact assessment is the transformation of the direct and indirect GHG emissions associated with the construction and operation of the systems to CO_2 equivalents (CO_2eq). The CFP was calculated using the software SimaPro® 8 (Pré Consultants, 2018) and the IPCC Global Warming Potential method (IPCC GWP 100 years). For all the scenarios, the CFP was calculated for the vintage season and the rest of the year in order to assess their fluctuations over the year.

2.6 Economic analysis

An economic analysis was conducted comparing the capital cost and the operation and maintenance costs of each scenario for a lifespan of 20 years. Data regarding systems design was based on specific case studies and were collected by means of a survey (UPC, 2018). Prices were provided by local companies. The capital cost included the cost for earthmoving, construction materials purchase and electrical works. The operation and maintenance costs included the prices of electricity, chemicals, sludge transportation and disposal and equipment replacement.

3. Results and Discussion

3.1 Carbon Footprint

The CFPs of the three winery wastewater treatment alternatives ranged from 0.9 to 52.7 kg CO_2eq m_{water}^{-3} (Figure 1). As shown in Figure 1, constructed wetlands (scenario W2) had the lowest CFP (1.6 and 0.9 kg CO_2eq m_{water}^{-3} during the vintage season and the rest of the year, respectively), while the third-party management (scenario W1) had the highest CFP (around 50 kg CO_2eq m_{water}^{-3} during both seasons considered). The activated sludge system (scenario W3) had a CFP of 5.9 and 3.2 kg CO_2eq m_{water}^{-3} during the vintage season and the rest of the year, respectively. This means that constructed wetlands helped to reduce the CFP associated with winery wastewater management by 70-98% compared to the conventional solutions. This was in accordance with previous studies which highlighted that constructed wetlands had lower GHG emissions and less environmental impacts than conventional plants treating urban and industrial wastewater (Garfí et al., 2017; Ingrao et al., 2020).

The CFP for the third-party management (scenario W1) did not show significant fluctuations over the year, since in this solution wastewater is stored and transported by a third-party once per month. On the contrary, the CFPs generated during the vintage season were higher (around 2 times) than those generated during the rest of the year for the constructed wetland and activated sludge systems (scenarios W2 and W3). As mentioned above, winery wastewater is characterized by fluctuations in terms of quality and quantity over the year. In particular, flow rates and organic loadings generated during the vintage season were up to 10 times higher than those produced during the rest of the year, when winery effluents are comparable to urban wastewater (Flores et al., 2019a). For this reason, during the vintage season, direct GHG emissions, as well as electricity and chemicals consumption, were higher than those generated during the rest of the year (Table 3 and 4).

As shown in Figure 2, the CFP of the third-party management (scenario W1) was mostly associated with wastewater transportation and disposal (99% of the overall CFP). On the other hand, the CFP of the constructed wetland system (scenario W2) was mainly due to direct GHG emissions (5 and 30% of the overall CFP during the rest of the year and the vintage season respectively), the additional effluent treatment at the municipal wastewater treatment plant (56 and 35%, of the overall CFP during the rest of the year and the vintage season, respectively) and construction materials (30 and 19% of the overall CFP during the rest of the year and the vintage season, respectively). These results were in accordance with recent studies which stated that the environmental impact of constructed wetlands treating urban wastewater was mainly due to direct GHG emissions and construction materials (around 30% of the overall impacts for each of them) (Diaz-Elsayed et al., 2020; Resende et al., 2019).

In the case of the activated sludge system (scenario W3), the CFP was mainly influenced by chemicals and electricity consumption (around 45% and 12% of the overall CFP during both seasons, respectively), as well as sludge transportation and disposal (around 15% of the overall CFP for both seasons). This was in accordance with previous studies which observed that chemicals and electricity consumption, as well as wastewater and sludge transportation, generated the highest environmental impacts in conventional wastewater treatment plants (Flores et al., 2019a; Lehtoranta et al., 2014). In particular, electricity consumption and the transport of sludge to centralized treatment were found to be the major causes of the environmental impacts of different conventional municipal wastewater treatment options (e.g. dry toilets, greywater treatment, biofilters and sludge bed reactors) in Finland (Lehtoranta et al., 2014). This study also suggested that the footprints of the sludge management options could be reduced by not transporting the sludge to the centralized wastewater treatment plant but by composting it on-site or by applying it to farmlands. In this context, sludge treatment wetlands can be implemented to avoid sludge transportation and thus, reducing the environmental impacts associated with it (Flores et al., 2019a).

Although in the constructed wetland system (scenario W2) direct GHG emissions generated and measured in the plants had a high contribution, in the third-party management (scenario W1) and the activated sludge system (scenario W3) they accounted for less than 1% of the overall CFP (Figure 2). Indeed, in scenario W1 and W3 indirect GHG emissions due to wastewater and sludge transportation as well as electricity consumption had the highest contribution (Figure 2). This was in accordance with previous studies which analysed the CFP of different conventional wastewater treatment plants (Caivano et al., 2017; Chai et al., 2015). Moreover, it has to be mentioned that winery wastewater had a low content of nitrogen and thus, lower N_2O emissions were released in the treatment systems in comparison to municipal wastewater treatment plants (Flores et al., submitted). For this reason, the contribution of direct GHG emissions to the overall CFP in conventional systems treating urban wastewater found in literature was higher (up to 70%) than in the present study (Chetty and Pillay, 2015; Delre et al., 2019; Longo et al., 2017). This means that direct GHG emissions and CFP depend not only on the technology used, but also on the wastewater quality. Thus, the results of this study confirmed the importance of measuring direct GHG emissions on-site (Gallego-Schmid and Zepon-Tarpani, 2019; Flores et al., 2019; Maktabifard et al., 2020; Nguyen et al., 2020). Indeed, previous studies stated that real measurements and transparency in the calculation methods applied should be encouraged and that it is vital to create a complete and reliable database to improve the overall quality of the CFP (Gallego-Schmid and Zepon-Tarpani, 2019; Nguyen et al., 2020).

In summary, the annual average CFP of the constructed wetland system (scenario W2) was 1.2 kg CO_2eq m_{water}^{-3}. This value was around 42 and 4 times lower than the third-party (scenario W1) (52 kg CO_2eq m_{water}^{-3}) and the activated sludge scenarios (scenario W3) (4.5 kg CO_2eq m_{water}^{-3}), respectively. This was mainly due to the high GHG emissions generated by wastewater and sludge transportation, as well as chemicals and electricity consumption, in the third-party and activated sludge scenarios compared to the constructed wetlands. This is in accordance with previous studies which observed that constructed wetland systems helped to reduce environmental impacts associated with wastewater treatment compared with conventional technologies (Casas-Ledón et al,, 2017; Flores et al., 2019; Garfí et al., 2017; Yildirim and Topkaya, 2012).

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

3.2 Economic analysis

The results of the economic analysis are shown in Table 5. As expected, the capital cost of the third-party (scenario W1) appeared to be the lowest, due to the lower amount of materials required for the construction of the wastewater storage tank. On the other hand, the capital cost of constructed wetlands (scenario W2) and activated sludge system (scenario W3) was similar. It is due to the fact that the latter treated a flow which is around 3.5 times higher than that treated by the former (Table 1). Indeed, it was observed that the smaller the size of the wastewater treatment plant the higher the capital cost per cubic meter of treated water (Acampa et al., 2019). If the constructed wetlands (scenario W2) treated the same flow as the activated sludge system (scenario W3) considered in this study, the capital cost of the former would be reduced by 50% (around 1 € m^{-3}), which is in accordance with previous studies (Corbella et al., 2017).

Regarding operation and maintenance, the activated sludge system (scenario W3) had the highest cost followed by the third-party alternative (scenario W1). It was mainly due to the high cost associated with chemicals and electricity consumption, as well as wastewater and sludge transportation and disposal. The constructed wetlands system (scenario W2) presented a very low operation and maintenance cost (up to 60 times lower compared to the other scenarios) due to their small energy requirements.

In conclusion, the constructed wetland system was shown to be a low-cost technology which would reduce the capital, operation and maintenance costs associated with winery wastewater treatment up to 50 and 98%, respectively.

4. Conclusions

This study assessed the carbon footprint (CFP) of constructed wetlands for winery wastewater treatment. In particular, the constructed wetland scenario was compared to the previous scenario (third-party management) and to an activated sludge system. Moreover, an economic analysis was also addressed. The results showed that the constructed wetland scenario had the lowest CFP (1.2 kg CO_2eq m_{water}^{-3}), while the third-party management was the worst scenario followed by the activated sludge system. Specifically, the CFP of the constructed wetland scenario was 42 and 4 times lower than the third-party and the activated sludge scenarios, respectively. This was mainly due to the high GHG emissions generated by wastewater and sludge transportation, as well as chemicals and electricity consumption in the third-party and activated sludge scenarios compared to the constructed wetlands.

From an economic point of view, constructed wetland system was shown to be a low-cost technology which reduces the capital, operation and maintenance costs associated with winery wastewater treatment up to 50 and 98%, respectively.

In conclusion, constructed wetlands are low-cost and environmentally friendly technologies which constitute a sustainable alternative to conventional solutions for winery wastewater treatment.

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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**
General data			
Location	-	Galicia (Spain)	Galicia (Spain)
Total wine production	L y^{-1}	368,000	3,850,000
Vintage season duration	d y^{-1}	26	15
Wastewater treatment and management			
Wastewater flows			
Total	m^{3} y^{-1}	1,400	4,832
Vintage season	m^{3} during the vintage season	620	2,416
Rest of the year	m^{3} during the rest of the year	780	2,416
Wastewater treatment/management alternatives	-	W1: third-party management (previous scenario) W2: constructed wetlands (current scenario)	Activated sludge system
Sludge management	-	W1: third-party management (previous scenario) W2: sludge treatment wetlands (current scenario)	Third-party management
Wastewater quality characteristics (vintage season)			
pH	-	5	7
COD	mg L^{-1}	1,031	11,957
BOD$_5$	mg L^{-1}	650	4,110
TSS	mg L^{-1}	706	2,190
TN	mg L^{-1}	9.7	-
TP	mg L^{-1}	1.5	-
Wastewater quality characteristics (rest of the year)			
pH	-	6.5-7.5	6.5-7.5
COD	mg L^{-1}	< 500	< 2,000
BOD$_5$	mg L^{-1}	< 250	< 1,000
TSS	mg L^{-1}	< 200	< 1,000
TN	mg L^{-1}	< 20	-
TP	mg L^{-1}	< 10	-

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**
Inputs				
Concrete	$m^3\ m^{-3}$	1.011E-03	1.339E-04	1.244E-03
Reinforcing steel	$kg\ m^{-3}$	6.943E-02	7.340E-03	1.244E-01
Steel	$kg\ m^{-3}$	2.336E-04	1.170E-03	6.766E-05
Copper	$kg\ m^{-3}$	3.507E-04	1.756E-03	1.016E-04
Cast iron	$kg\ m^{-3}$	7.014E-04	3.512E-03	2.032E-04
PVC	$kg\ m^{-3}$	-	6.385E-03	6.207E-04
Gravel	$m^3\ m^{-3}$	-	1.967E-03	-
Sand	$m^3\ m^{-3}$	-	2.145E-04	-
Geotextile	$kg\ m^{-3}$	-	2.989E-03	-
Geomembrane	$kg\ m^{-3}$	-	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: constructed wetland system; W3: activated sludge system.

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**
Inputs				
Electricity	kWh m^{-3}	0.000E+00	5.032E-01	2.000E+00
Flocculant	kg m^{-3}	-	-	1.242E-01
Sodium hydroxide	kg m^{-3}	-	-	4.139E-01
Urea	kg m^{-3}	-	-	6.623E-01
Phosphoric acid	kg m^{-3}	-	-	4.139E-01
Outputs				
Sludge	kg m^{-3}	-	-	9.934E+00
Sludge transportation	tkm m^{-3}	-	-	1.490E+00
Wastewater transportation	tkm m^{-3}	2.400E+02	-	-
Direct emissions to air (released by wastewater treatment systems)				
CO_2	g m^{-3}	1.034E+01	2.080E+03	2.394E+02
CH_4	g m^{-3}	1.893E-01	1.142E+01	4.477E-01
N_2O	g m^{-3}	6.553E-03	6.775E-01	8.532E-02
Direct emissions to air (due to fertilizer application to soil)				
CH_4	g m^{-3}	-	9.518E-01	-
N_2O	g m^{-3}	-	8.848E-02	-
Avoided products				
N as Fertiliser (from sludge reuse as fertilizer)	g m^{-3}	-	7.373E+00	-
P as Fertiliser (from sludge reuse as fertilizer)	g m^{-3}	-	4.074E+00	-

Scenarios: W1: third-party management; W2: constructed wetland system; W3: activated sludge system.

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**
Inputs				
Electricity	kWh m^{-3}	0.000E+00	1.743E-01	6.900E-01
Flocculant	kg m^{-3}	-	-	1.034E-01
Sodium hydroxide	kg m^{-3}	-	-	1.241E-01
Urea	kg m^{-3}	-	-	3.310E-01
Phosphoric acid	kg m^{-3}	-	-	2.069E-01
Outputs				
Sludge	kg m^{-3}	-	-	4.137E+00
Sludge transportation	tkm m^{-3}	-	-	6.206E-01
Wastewater transportation	tkm m^{-3}	2.400E+02	-	-
Direct emissions to air (released by wastewater treatment systems)				
CO_2	g m^{-3}	1.034E+01	1.230E+02	2.823E+02
CH_4	g m^{-3}	1.893E-01	1.969E+00	2.079E-01
N_2O	g m^{-3}	6.553E-03	1.160E-02	7.631E-02
Direct emissions to air (due to fertilizer application to soil)				
CH_4	g m^{-3}	-	9.518E-01	-
N_2O	g m^{-3}	-	8.848E-02	-
Avoided products				
N as Fertiliser (from sludge reuse as fertilizer)	g m^{-3}	-	7.373E+00	-
P as Fertiliser (from sludge reuse as fertilizer)	g m^{-3}	-	4.074E+00	-

Scenarios: W1: third-party management; W2: constructed wetland system; W3: activated sludge system.

Table 5. Capital and operation and maintenance costs of the considered scenarios expressed in terms of euros per cubic meter of treated water

	Unit	Scenarios		
		W1	W2	W3
Capital cost	€ m^{-3}	0.20	2.30	2.58
Operation and maintenance cost	€ m^{-3}	1.76	0.04	2.49

Scenarios: W1: third-party management; W2: constructed wetland system; W3: activated sludge system.

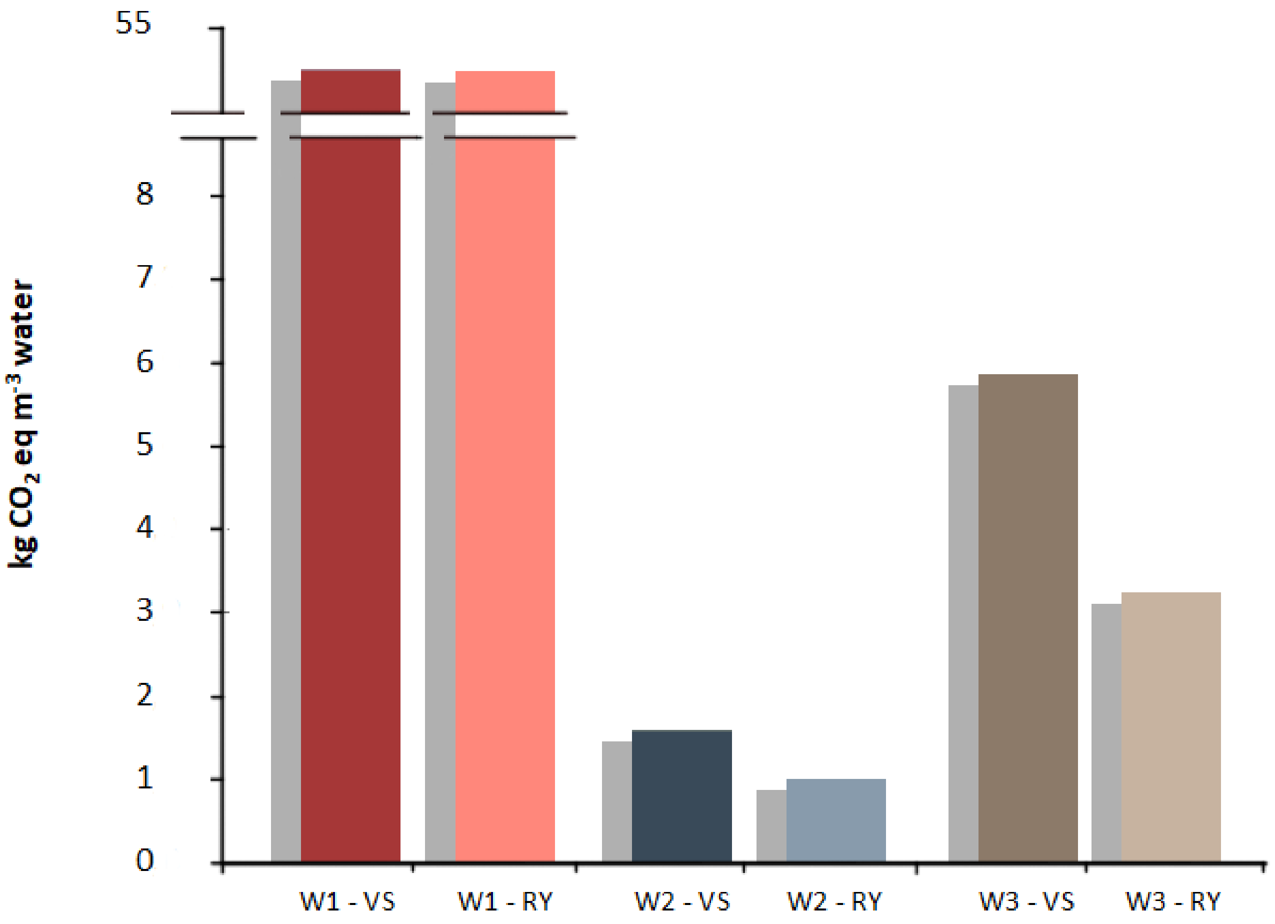

Figure 1. Carbon footprint of the three scenarios considered during the vintage season (VS) and the rest of the year (RY). Values are referred to the functional unit (1 m^3 of treated water). Scenarios: W1: third-party management; W2: constructed wetland system; W3: activated sludge system.

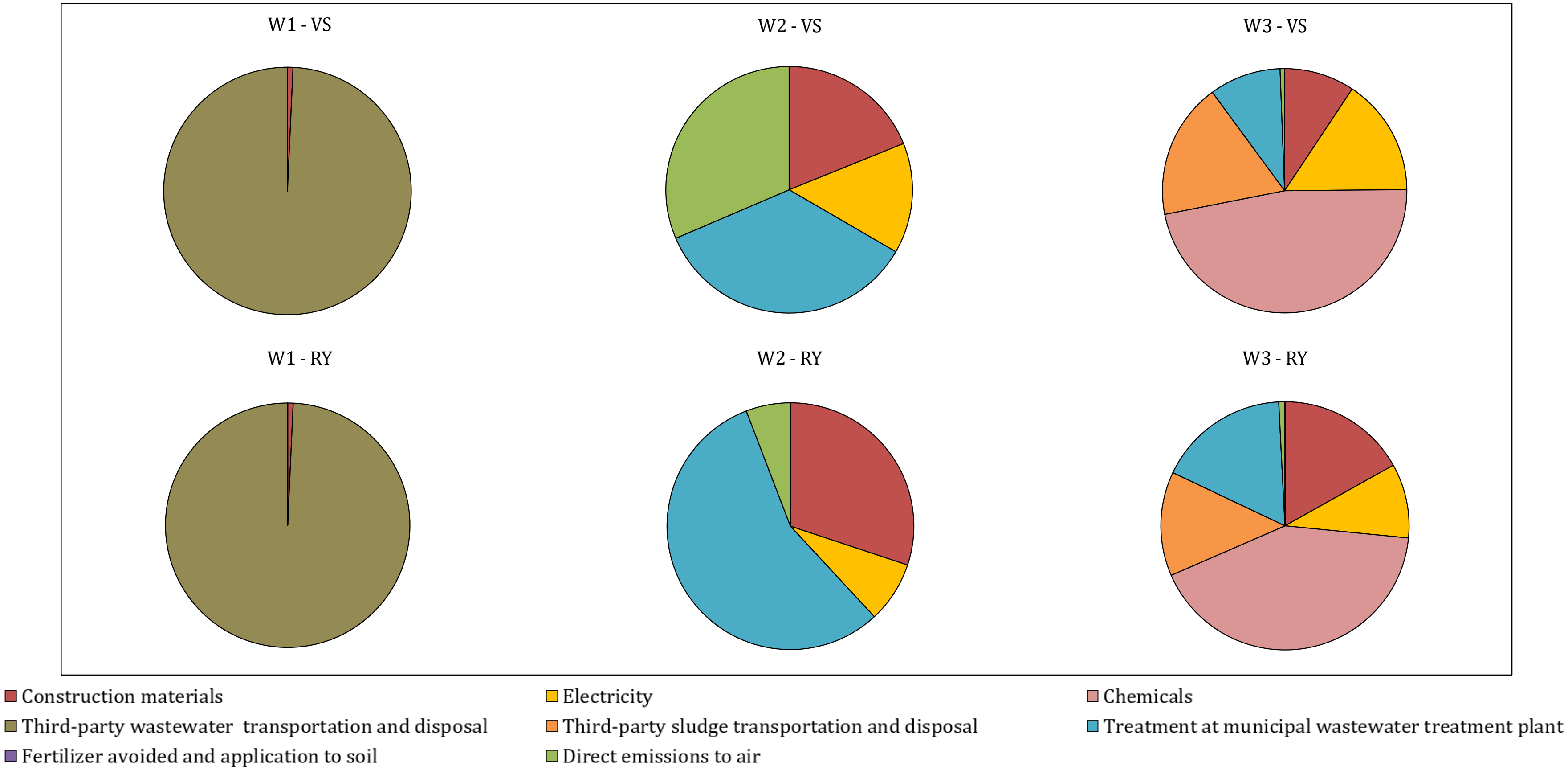

Figure 2. Contribution analysis for the three scenarios considered during the vintage season (VS) and the rest of the year (RY). Scenarios: W1: third-party management; W2: constructed wetland system; W3: activated sludge system.