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Original Articles

Life-cycle greenhouse gas emissions assessment and extended exergy accounting of a horizontal-flow constructed wetland for municipal wastewater treatment: A case study in Chile

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ABSTRACT

The life-cycle greenhouse gaseous emissions and primary exergy resources consumption associated with a horizontal subsurface flow constructed wetland (HSSF) were investigated. The subject of study was a wetland for municipal wastewater treatment with a 700-person-equivalent capacity. The effects of two types of emergent aquatic macrophytes (*Phragmites australis* and *Schoenoplectus californicus)* and seasonality on greenhouse gas (GHG) gas emissions, the environmental remediation cost (ERC) and the specific environmental remediation cost (SERC) were assessed. The results indicate that GHG emissions per capita (12–22 kgCO2eq/p.e/yr) and primary exergy resources consumed (24–27 MJ/m^3) for the HSSF are lower than those of a conventional wastewater treatment plant (67.9 kgCO2eq/p.e/yr and 96 MJ/m^3). The SERC varied between 176 and 216 MJ/kg biological oxygen demand (BOD_5) removal, which should be further reduced by 20% for an improved BOD_5 removal efficiency above 90%. The low organic matter removal efficiency is associated with a high organic load and low bacterial development. Seasonality has a marked effect on the organic removal efficiency and the SERC, but the macrophyte species does not.

1. Introduction

The generation of wastewater is increasing considerably because of population growth and improved living standards in many countries. Consequently, there is an increasing demand for more sustainable wastewater treatment systems. In particular, constructed wetlands (CWs) are regarded as an attractive contamination abatement solution for small communities (Vera et al., 2013, 2011; Vymazal, 2011), mainly due to their simple operation and maintenance, minimal secondary pollution, favorable environmental appearance and other ecosystem benefits (Chen et al., 2011a,b; Chen et al. 2009a,b; EPA, 2000). Nevertheless, several researchers have highlighted the effect of CWs on current global warming potential (GWP) due to direct greenhouse gas emissions (CO_2, CH_4 and N_2O) during their lifetime (De la Varga et al., 2015; Gao et al., 2012; Mander et al., 2014a). Net gas emissions from CWs are strongly influenced by design and operation parameters such as the length of the wetland, flow direction, hydrology, fluctuating water table, type of vegetation, season, and organic load (De la Varga et al., 2015; García et al., 2005; Inamori et al., 2007; Mander et al., 2014a; Sehar et al., 2014).

Accordingly, researchers have measured greenhouse gases emissions from various types of CWs such as those characterized by a free water surface (FWS) (Mander et al., 2014b; Søvik and Kløve, 2007), horizontal subsurface flow (HSSF) (García et al., 2005; Inamori et al., 2008; López et al., 2015; Picek et al., 2007; Sciubba et al., 2008; Teiter and Mander, 2005; Vymazal and Kröpfelova, 2008), and vertical subsurface flow (VSSF) (Shao et al., 2013; Teiter and Mander, 2005) as well as hybrid constructed wetlands (De la Varga et al., 2015). Several studies have focused on measurements of direct gas emissions from CWs; however, few studies have examined their life-cycle greenhouse gas emissions. Chen et al. (2011a,b) assessed the direct and indirect greenhouse gas (GHG) emissions from a constructed wetland and a cyclic activated sludge system. In parallel, Pan et al. (2011) compared the estimated greenhouse gas emissions from a vertical subsurface flow (VSSF) constructed wetland with those from conventional wastewater treatment plants (WWTPs). The findings from both studies suggested that constructed wetlands are an effective option for mitigation of GHG emissions in the wastewater sector. Gao et al. (2012) quantified the total GHG emissions associated with the construction and operation stages of a pilot CW, specifically the Longdao

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Nomenclature

BOD_5	Biologic oxygen demand at 5 days (g/L)
C	Capital flow (US$)
C_{env}	Environmental cost (US$)
CEeq	Capital equivalent exergy (MJ)
CExC	Cumulative exergy consumption (kJ/kg)
COD	Chemical oxygen demand (g/L)
CWs	Constructed wetland
EEA	Extended exergy accounting
eec	Exergetic equivalence of capital (MJ/US$)
EEC	Extended exergy of capital (MJ)
EEeq	Environmental remediation exergy (MJ)
eel	Exergetic equivalence of labor (MJ/Labor)
EEL	Extended exergy of labor (MJ)
$\mathrm{E}_{\mathrm{In\text{-}Society}}$	Global exergy fluxes into Society (MJ/year)
$\mathrm{E}_{\mathrm{Used}}$	Global exergy used by Society (MJ/year)
ERC	Environmental remediation cost (MJ/m)
e_{surv}	Exergy use for survival (MJ/persons/days)
ex_{ch}	Standard chemical exergy (kJ/kg)
FEeq	Feedstock exergy (MJ)
GHG	Greenhouse gas emission
GWP	Global warming potential (kg $CO_{2\text{-eq}}$/kg)
HDI	Human Development Index of current society
HDIo	Human Development Index of primitive society
HSSF	Horizontal subsurface flow constructed wetland
L	Labor (hours)
LEeq	Labor equivalent exergy (MJ)
M2	Money + quasi-money indicator (US$/year)
Nh	Number of inhabitants (Persons)
Nw	Number of workers (Persons)
S	Global monetary salaries (US$/year)
SERC	Specific environmental remediation cost (MJ/kg BOD_5 removal)
SIC	Central interconnected system
TEeq	Total exergetic equivalents (MJ)
VSSF	Vertical subsurface flow constructed wetland
wh	Number of work-hours (hours)
WWTP	Conventional wastewater treatment plant
yr	Years

Greek letters

β	Amplification factor for financial activities
α	Primary exergy fraction of labor

River constructed wetland, and compared the emissions with those from a typical conventional wastewater treatment system (cyclic activated sludge system). Shao et al. (2014) developed a set of ecological indicators for comparing the Longdao River constructed wetland with a cyclic activated sludge system and analyzed the impacts on climate change and resource utilization.

In contrast, Fuchs et al. (2011) compared the complete environmental profile of vertical flow CWs and horizontal flow by way of life cycle assessment (LCA). The results indicated that the vertical subsurface flow constructed wetland (VSSF) is a lower-impact alternative to the HSSF.

As explained above, constructed wetlands play an important role in mitigating greenhouse gas emissions. However, they also involve consumption of resources such as material, energy, and capital and are an additional source of waste generation. Several methods have been developed for estimating the economic value of the environmental benefits of the process. Exergy analysis has been promoted as a thermodynamic tool for evaluating processes based on their resource use efficiency and energy consumption (Dincer and Cengel, 2001; Szargut, 2004; Wall and Gong, 2001). Exergy offers a good way to understand natural processes. It makes clear how sustainable present and future industrial processes can be (Granovskiiet al., 2007). In addition, exergy is also a measure of technology sustainability by means of the renewability index and cumulative exergy consumption (CExC), thereby allowing for assessments of virgin resources and their transformation quality (Dewulf et al., 2005, 2000; Szargut, 2004). Furthermore, exergy offers a measure of environmental pollution costs in terms of waste exergy; thus, it provides a quantitative comparison of environment impacts (Seager and Theis, 2002). These facts make exergy a good measure of damage and make it a useful ecological index in that high exergy efficiency means that less exergy is dumped to the environment or less environmental damage occurs. Furthermore, integration of the exergy concept with economics, environmental and ecological principles has been developed in the form of exergo-economic, exergo-environmental and cosmic exergy analyses, respectively (Chen and Chen, 2006; Jørgensen and Nors Nielsen, 2007; Meyer et al., 2009; Shao et al., 2014; Tsatsaronis, 2011a,b); thus, exergy can be used to identify and quantify the locations, causes, costs, and environmental impacts associated with thermodynamic inefficiencies. Ecological assessments of constructed wetlands have been (Chen et al., 2009a,b). Chen et al. (2011a,b) assessed a wetland ecosystem based on cosmic exergy. The results indicated that the wetland ecosystem was more dependent on local and renewable resources and achieved a larger ecological sustainability index than did activated sludge and cyclic activated sludge systems, respectively. These findings imply that wetlands are more environmentally friendly and sustainable than these other water treatment alternatives.

Sciubba (2011, 2003, 2001) proposed a holistic ecological indicator based on extended exergy accounting (EEA) derived from an integration of exergy analysis with economic and environmental issues. The advantage of performance indicators based on an EEA is that they can be used as exergetic and monetary metrics for all stages of systems. These indicators can be used to compare physical flows (matter and energy) and non-energetic quantities (capital, human labor and environmental impact) and are expressed in terms of a metric unit (exergetic terms, Joule/unit). Labor and capital costs are quantified based on the exergy expenditures necessary to generate them, and environmental impact is measured based on the total primary exergy resource "used up" in the environmental remediation (Sciubba et al., 2008).

The potentiality of the EEA method was demonstrated by Sciubba (2003) though an evaluation of a technical alternative between a non-integrated waste recycling and an integrated waste recycling and incineration facility. More recently, EEA has gained the interest of the scientific community due to its usefulness for describing the degree of sustainability in various national contexts, where the emphasis is on destruction and efficiency of primary exergy resources within each societal sector. Societal EEA analyses have been performed in Norway (Ertesvag, 2005), Italy (Milia and Sciubba, 2006), Siena province in Italy (Sciubba et al., 2008), China (Chen and Chen, 2009, 2007) and Turkey (Seckin et al., 2012). Exhaustive analyses of the energy (Ptasinski et al., 2006) and transportation (Seckin et al., 2013) sectors have also been performed from an EEA point of view.

EEA was applied by Talens et al. (2010) to account for and compare the exergy resource consumption in biodiesel production from various feedstocks (cooking oil and rapeseed crop), and the production of biodiesel from cooking oil was found to be less resource intensive than that from rapeseed. In contrast, few studies have focused on the wastewater sector. Accordingly, Seckin and Bayulken (2013) determined the environmental remediation cost for conventional municipal wastewater treatment by means of EEA. Those authors also assessed sludge treatment by means of anaer-