Chapter

Sustainability Assessment of Wastewater Treatment Plants

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Abstract

It is thought that this chapter will make a significant contribution to the literature or at least will fill the space on the wastewater treatment plant's effect on climate change. It demonstrates the potential climate change impact of a sequential batch reactor (SBR) and constructed wetland on treating domestic wastewater by giving methods for calculation of their greenhouse gas emissions in terms of N_2O and CH_4. Are wastewater treatment plants sustainable? What aspects determine sustainability? Do tertiary wastewater treatment plants and constructed wetlands (CWs) have less global warming potential (CO_2 emissions) and less energy use than conventional treatment? In accordance with the literature, greenhouse gas calculations of this study showed that CWs and SBR WWTPs do not contribute to global warming negatively.

Keywords: wastewater treatment, sequential batch reactor, greenhouse gas, constructed wetlands, methane, nitrous oxide, sustainability

1. Introduction

Wastewater treatment plants are generally capable of reaching hygienic and environmental standards; however, these were not designed for zero discharge principle in which nutrients, organic matter, and water are recycled and nutrient, organic and water cycles are closed. Are wastewater treatment plants (WWTPs) sustainable? What aspects determine sustainability? Do tertiary wastewater treatment plants and constructed wetlands (CWs) have less global warming potential (CO_2 emissions) and less energy use than conventional treatment?

Since sequential batch reactor (SBR) system sequentially removes carbon, nitrogen, and phosphorous in a single reactor by maintaining anoxic and aerobic stages, it recently has attracted a great deal of interest. High nitrogen and phosphorus removal are achieved by a series of steps, namely, fill, react, settle, draw, and idle steps, as shown in **Figure 1**. Denitrification occurs at the beginning of the fill step taking usually 25% of the total cycling time where raw wastewater is added to the reactor. The step taking up 35% of the total cycle time is called react step where the reactions were finalized. The main purpose of the third step (settle) is to allow solid separation and provide a supernatant ready to be discharged as effluent. The purpose of the fourth step (draw step) ranging from 5 to 30% of the total cycle time is to remove clarified treated water from the reactor. The purpose of last step, "idle," is to provide time for one reactor to complete its fill cycle before switching to another unit.

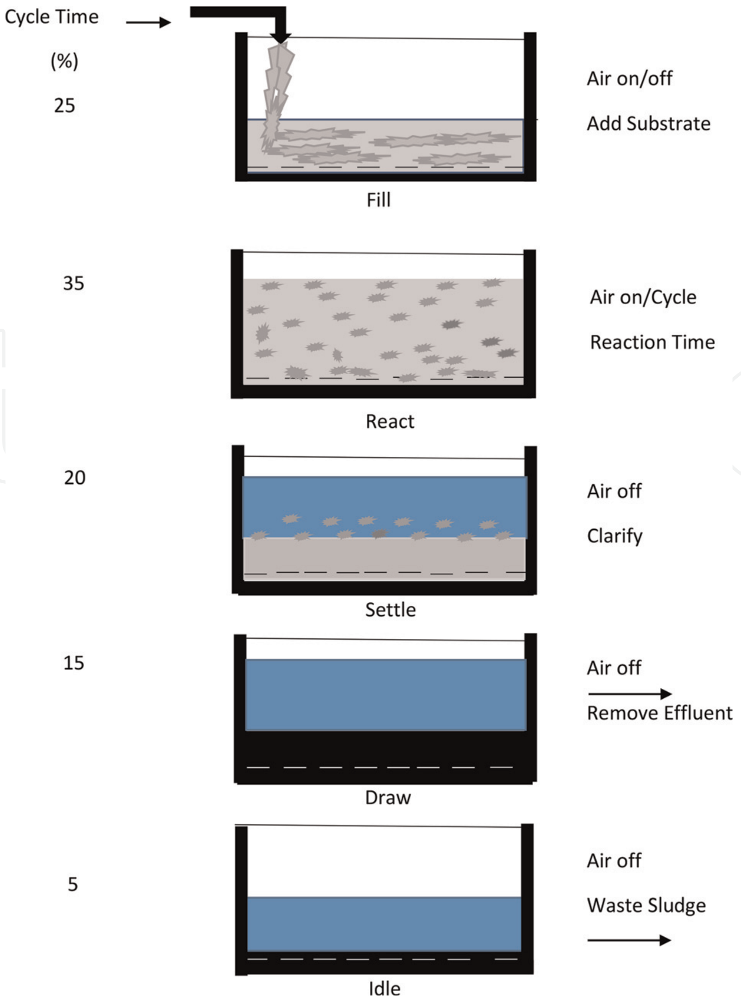

Figure 1.
Operation sequence for sequential batch reactor [1].

In wastewater treatment technologies like activated sludge, membrane methods are not feasible enough for widespread application in rural areas [2]. Constructed wetlands however are attracting great concern due to lower cost, easy operation, and less maintenance requirements as a reasonable option for treating wastewater in rural areas. They are designed and constructed to mimic natural wetland systems for removing contaminants which are basically composed of vegetation, substrates, soils, microorganisms, and water, utilizing complex processes involving physical, chemical, and biological mechanisms (e.g., sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and various microbial processes) [3].

While the treatment performance of CWs is critically dependent on the optimal operating parameters (water depth, hydraulic retention time and load, feeding mode and design of setups, etc.) which could result in variations in the removal efficiency of contaminants, plant species and media types are crucial influencing factors for the treatment in CWs as they are considered to be the main biological component of CWs. Emergent, submerged, floating-leaved, and free-floating plants are commonly planted among 150 macrophyte species. The most common used emergent species reported are *Phragmites* spp. (Poaceae), *Typha* spp. (Typhaceae), *Scirpus* spp. (Cyperaceae), *Iris* spp. (Iridaceae), *Juncus* spp. (Juncaceae), and *Eleocharis* spp. (Spikerush) [3].

The greenhouse effect of major greenhouse gases, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) all produced in wastewater treatment operations, is weighted by their global warming potentials (GWP). Over a period of 100 years, 1 ton of methane and nitrous oxide will have a warming effect equivalent to 25 and 298 ton of CO_2, respectively [4]. In the same direction, it is stated that nitrous oxide is a significant greenhouse gas with a lifetime of 114 years with a 298-fold stronger effect of global warming than carbon dioxide and is also responsible for ozone depletion in the stratosphere [5].

In SBR processes, ammonium is transformed into N_2 gas via nitrification and denitrification. N_2O is generated as a by-product or an intermediate due to insufficient oxygen during nitrification in the aeration step and due to insufficient carbon during denitrification in settling and decanting steps [6]. Wastewater treatment facilities are anthropogenic sources of N_2O to the atmosphere, taking account of 3.2–10% of the total emission [7]. Practically, only methane and nitrous oxide are calculated since carbon that is present in wastewater is biogenic and it is assumed that it is returning the carbon to the atmosphere as CO_2 representing no net flux to the system [8].

Based on field measurements, the maximum methane flux occurred in sludge screw conveyor with 823 $g/m^2/d$, and CH_4 emission occurred in every processing unit [9]. Methane is produced by methanogens due to low O_2 and nitrate/nitrite concentration during the anaerobic and anoxic processes. In the same direction, more than 50% of global methane emissions are related to human-related activities like landfill, wastewater treatment, agriculture, and certain industrial process [10].

Are constructed wetlands sustainable? It is reported that constructed wetlands have less global warming potential (CO_2 emissions) and less energy use than conventional treatment [11]. Wetlands also reduced aquatic toxicity and eutrophication compared to conventional activated sludge wastewater treatment [12]. A sustainable solution means minimized costs; minimized energy use; minimized land area required; minimized loss of nutrients; minimized waste production; maximized products like clean water, biogas, biomass, fertilizers, and compost; and maximized qualitative sustainability indicators like social acceptance, institutional requirements, etc. But it is not always possible to design a wastewater treatment that minimizes cost, energy use, and land area, while maximizing performance.

The greenhouse gas emissions measured in N_2O, CO_2, and CH_4 for horizontal flow constructed wetlands (HFCWs) were 3, 1400 and 5 $mg/m^2/d$, respectively [13]. Moreover, vertical flow constructed wetlands (VFCWs) had significantly higher areal gaseous emissions than HFCWs, and gas emissions were correlated to temperature, substrate supply (influent N and C concentrations), and degree of oxidation in the wetland [14]. The quantity and impact of CH_4 and N_2O are important since CH_4 has 25 times and N_2O has 298 times the global warming potential of CO_2 [4].

The CO_2, CH_4, N_2, and N_2O fluxes in both horizontal and vertical subsurface flow constructed wetlands in Estonia were measured and reported that the global influence of constructed wetlands is not significant, that is, even if all global domestic wastewater were treated by constructed wetlands, the emitted GHG would be <1% of total anthropogenic emissions [15]. They also reported the averaged experimental data of 788.33 mg CO_2/m^2 h, 4 mg CH_4/m^2 h, and 0.79 mg N_2O/m^2 h.

The following section will represent CH_4, N_2O, and CO_2 emission calculating principles for both SBR and CW WWTPs.

2. Emission calculating principles for wastewater treatment plants

2.1 Methane (CH_4) emission calculating principles

Estimation of organically degradable material in domestic wastewater, estimation of methane emission factor (EF) for domestic wastewater, and estimation of CH_4 emissions from domestic wastewater are steps for calculating CH_4 emissions.

The direct methane emissions are a function of the amount of degradable carbon in the wastewater and sludge and an emission factor. As can be seen from Eq. (1) (Eq. (1): Eq. 6.2 of IPCC, 2006:CH_4 emission factor for each domestic wastewater treatment/discharge pathway or system), the emission factor is a function of the maximum CH_4 producing potential (B_o) and the methane correction factor (MCF). The B_o value of 0.6 kg CH_4/kg BOD removal, the uncertainty range of ±30%, and the MCF value of 0.05 are recommended [4].

Total organics in wastewater (TOW) (in inventory year, kg BOD/year) is a function of human population and BOD generation per person, and it is expressed in terms of biochemical oxygen demand (kg BOD/year). TOW was calculated by using Eq. (2) (Eq. (2): Eq. 6.3 of IPCC, 2006: total organically degradable material in domestic wastewater) [4].

$$\begin{gathered}\text{CH}_4\text{ emission factor for each domestic wastewater treatment/}\\ \text{discharge pathway or system }\left(\text{EF}_\text{j}\right)=\text{B}_0\bullet\text{MCF}_\text{j}\end{gathered}\tag{1}$$

where F_j emission factor, kg CH_4/kg BOD; j each treatment/discharge pathway or system; B_0 maximum CH_4 producing capacity, kg CH_4/kg BOD; MCF_j methane correction factor (fraction).

$$\begin{gathered}\text{Total organically degradable material in domestic wastewater}\\ (\text{TOW})=\text{P}\bullet\text{BOD}\bullet0.001\bullet\text{I}\bullet365\end{gathered}\tag{2}$$

where TOW, total organics in wastewater in inventory year, kg BOD/year; P, country population in inventory year (person); BOD, country-specific per capita BOD in inventory year, g/person/day; 0.001, conversion from gram BOD to kg BOD, I, correction factor for additional industrial BOD discharged into sewers (for collected the default is 1.25; for uncollected the default is 1.00).

The general equation for estimating CH_4 emissions from domestic wastewater was calculated by using Eq. (3) (Eq. (3): Eq. 6.1 of IPCC, 2006: total CH_4 emissions from domestic wastewater).

$$\begin{gathered}\text{Total CH}_4\text{ emissions from domestic wastewater}\\ (\text{CH}_4\text{ emissions})=\left[\sum_{ij}\left(U_i\cdot T_{ij}\cdot EF_j\right)\bullet(\text{TOW}-\text{S})-\text{R}\right.\end{gathered}\tag{3}$$

where CH_4 emissions, CH_4 emissions in inventory year, kg CH_4/year; TOW, total organic wastewater in inventory year, kg BOD/year; EF_j, emission factor, kg CH_4/kg BOD; S, organic component removed as sludge in inventory year, kg BOD/year; U_i, fraction of population in income group i in inventory year; $T_{i,j}$, degree of utilization of treatment/discharge pathway or system, j, for each income group fraction i in inventory year; i, income group: rural, urban high income and urban low income; j, each treatment/discharge pathway or system; R, amount of CH_4 recovered in inventory year, kg CH_4/year.

2.2 Nitrous oxide (N_2O) emission calculating principles

Estimation of nitrogen in effluent, estimation of emission factor, and emissions of indirect N_2O emissions from wastewater are steps for calculating N_2O emissions. It is associated with the microbial conversion of nitrogen compound in the wastewater. It occurs as emissions from treatment plants or from wastewater after disposal of effluent into waterways, lakes, or the sea. The emission factor (0.005) is taken for domestic wastewater nitrogen effluent, referring to the default value recommended by IPCC [4]. The factor 44/28 is the conversion of kg N_2O-N into kg N_2O. A simplified equation is given in Eq. (5). Emission factors of N_2O were evaluated by incorporating N loads in influent of the SBR WWTP.

$$\begin{gathered}\text{Total nitrogen in the effluent}\\ (N_{EFFLUENT}) = (P\bullet \text{Protein}\bullet F_{NPR}\bullet F_{NON-CON}\bullet F_{IND-COM}) - N_{SLUDGE}\end{gathered} \tag{4}$$

where $N_{EFFLUENT}$, total annual amount of nitrogen in the wastewater effluent, kg N/year; P, human population; Protein, annual per capita protein consumption, kg/person/year; F_{NPR}, fraction of nitrogen in protein, default = 0.16, kg N/kg protein; $F_{NON\text{-}CON}$, factor for non-consumed protein added to the wastewater; $F_{IND\text{-}COM}$, factor for industrial and commercial co-discharged protein into the sewer system; N_{SLUDGE}, nitrogen removed with sludge (default = zero), kg N/year.

$$\begin{gathered}N_2O\text{ emissions from wastewater effluent}\\ (N_2O\text{ emissions}) = N_{EFFLUENT}\bullet EF_{EFFLUENT}\bullet 44/28\end{gathered} \tag{5}$$

where N_2O emissions, N_2O emissions in inventory year, kg N_2O/year; $N_{EFFLUENT}$, nitrogen in the effluent discharged to aquatic environments, kg N/year, $EF_{EFFLUENT}$, emission factor for N_2O emissions from discharged to wastewater, kg N_2O-N/kg N; 44/28, the factor 44/28 is the conversion kg N_2O-N into kg N_2O.

2.3 Carbon dioxide (CO_2) emission calculating principles

The two main factors causing CO_2 production from wastewater treatment plants are the type of treatment process and electricity consumption. During anaerobic treatment, the BOD_5 in the wastewater is either converted to CO_2 or CH_4, or some of it enters the biomass and is also converted to CO_2 and CH_4 by endogenous respiration. Other sources of carbon dioxide emissions are caused by sludge digesters and digestion gas combustion. In aerobic process, CO_2 is produced by decomposition of organic substances. Since CO_2 emissions from the wastewater treatment plant are biogenic, they are not included in the national total emissions and are not considered in the IPCC Guidelines. Biogenic origin means that it is part of the natural carbon cycle and the food chain passing from plants to animals and humans, or natural atmospheric CO_2 source.

3. Emission calculating principles for constructed wetlands

3.1 Methane (CH_4) emission calculating principles

The direct methane emissions are the function of the amount of degradable carbon in the wastewater and sludge, and an emission factor. The emission factor is a function of the maximum CH_4 producing potential (B_o) and the methane correction factor (MCF) for the wastewater treatment and discharge system. The B_o value of 0.6 kg CH_4/kg BOD removal and the uncertainty range of ±30% is recommended by IPCC [16]. The MCF indicates that the extent to which the CH_4 producing capacity is realized in each type of treatment and discharge pathway and system. The CH_4 emissions from constructed wetlands and CH_4 emission factors for constructed wetlands are given in Eq. (6) (Eq. (6): Eq. 6.1 of IPCC, 2014: CH_4

emissions from constructed wetlands) and Eq. (7) (Eq. (7): Eq. 6.2 of IPCC, 2014: CH_4 emission factor for constructed wetlands), respectively.

$$\begin{aligned}&CH_4 \text{ emissions from constructed wetlands}\\&(CH_4 \text{ emissions}) = \sum_j \left(TOW_j \cdot EF_j\right) + \sum_{ij} \left(TOW_{ij} \cdot EF_j\right)\end{aligned} \tag{6}$$

where CH_4 emissions, CH_4 emissions in inventory year, kg CH_4/year; TOW_j, total organics in wastewater entering CW in inventory year, kg BOD/year or kg COD/year; EF_j, emission factor, kg CH_4/kg BOD (for domestic wastewater only) or kg CH_4/kg COD (for domestic and industrial wastewater). If more than one type of CW is used in an industrial sector, this factor would need to be a TOW_{ij} weighted average: i, industrial sector; j, type of CW.

$$CH_4 \text{ emission factor for constructed wetlands } \left(EF_j\right) = B_0 \bullet MCF_j \tag{7}$$

where EF_j, emission factor, kg CH_4/kg BOD or kg CH_4/kg COD; j, type of CWs; B_0, maximum CH_4 producing capacity, kg CH_4/kg BOD or kg CH_4/kg COD; MCF_j, methane correction factor (fraction).

3.2 Nitrous oxide (N_2O) emission calculating principles

Nitrogen oxides are associated with microbial conversion of nitrogen compound in wastewater and emerge as emissions from wastewater discharge to waterways, lakes, or seas and treatment plants or wastewater. The emission factor (0.005) is taken for domestic wastewater nitrogen effluent, referring to the default value recommended by IPCC [16]. The factor 44/28 is the conversion of kg N_2O-N into kg N_2O. A simplified equation is given in Eq. (8).

$$\begin{aligned}&N_2O \text{ emissions from constructed wetlands}\\&(N_2O \text{ emissions}) = \sum_j \left(N_j \cdot EF_j \cdot 44/28\right) + \sum_{i,j} \left(N_{i,j} \cdot EF_j \cdot 44/28\right)\end{aligned} \tag{8}$$

where N_2O emissions, N_2O emissions in inventory year, kg N_2O/year; N_j, total nitrogen in domestic wastewater entering CWs in the inventory year, kgN/year; $N_{i,j}$, total nitrogen in industrial wastewater entering CWs in the inventory year, kgN/year; EF_j, emission factor, kg N_2O-N/kg N. If more than one type of CW is used in an industrial sector, this factor would need to be a $N_{i,j}$ weighted average: i, industrial sector; j, type of CW; 44/28, the factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

4. Results

4.1 SBR wastewater treatment plant's GHG emissions

Eqs. (1)–(3) and default maximum CH_4 producing capacity for domestic wastewater of 0.6 kg CH_4/kg BOD and 0.25 kg CH_4/kg COD and ($T_{i,j}$) values given in Table 6.5 of IPCC, "Suggested values for urbanization and degree of utilization of treatment discharge pathway or method ($T_{i,j}$) for each income group for selected countries," are used for the calculation of methane emissions from SBR WWTP [4].

Eqs. (4) and (5) and the values given in **Table 1** are used for N_2O emission calculations. Finally, indirect GHG emissions from the consumption of electricity are calculated by the use of emission factor of 0.91 $tCO_2e\ Mwh^{-1}$ [4]. Total emissions of full-scale SBR WWTP operated from 2012 to 2015 are given in **Table 2** [17].

4.2 Horizontal subsurface constructed wetland's GHG emissions

Eight-month average (April–December) methane and nitrous oxide emissions at the outlet of full-scale constructed wetland were calculated by using Eqs. (6)–(8). **Table 3** gives the calculated GHG emissions in terms of CH_4 and N_2O [18].

	Definition	Default value	Range
$EF_{EFFLUENT}$	Emission factor (kg N_2O-N/kg-N)	0.005	0.0005–0.25
P	Number of people in country	Country specific	±10%
Protein	Annual per capita protein consumption	Country specific	±10%
F_{NPR}	Fraction of nitrogen in protein	0.16	0.15–0.17
$F_{NON\text{-}CON}$	Non-consumed protein adjustment factor	1.1 for countries with no garbage disposals1.4 for countries with garbage disposals	1.0–1.5
$F_{IND\text{-}COM}$	Co-discharge factor for industrial nitrogen into sewers. Higher for countries with significant fish processing plants	1.25	1.0–1.5

Table 1.
N_2O methodology default data [4].

Year	CH_4 (tCO_2e)	N_2O (tCO_2e)	Electricity usage ($tCO_2e\ Mwh^{-1}$)	Total (tCO_2e)
2012	74.87	0.0143	69.34	144.22
2013	248.99	0.0143	69.34	318.34
2014	87.68	0.0143	387.1	474.79
2015	68.41	0.0143	928.2	996.62

Table 2.
Total emissions of the SBR wastewater treatment plant.

Parameter (kg/d)	2012	2013	2014	2015
BOD	312	406	292	224
TN	45	67	23	346
CH_4 emission	18.72	24.36	17.52	13.44
N_2O emission	0.56	0.83	0.29	4.30

Table 3.
Horizontal subsurface constructed wetland's GHG emissions.

5. Conclusions

This review chapter demonstrates the potential climate change impact of a sequential batch reactor and constructed wetland treating domestic wastewater by giving methods for calculation of their greenhouse gas emissions in terms of N_2O and CH_4.

If methane is to be recovered for energy use, the net emission of methane should be calculated by subtracting the recovered and flared amount of methane from the gross methane emission. In other words, methane that is not released is calculated as the amount used for biogas (and is thus included in CO_2 emissions from energy production).

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