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Trade-off between carbon emission and effluent quality of activated sludge processes under seasonal variations of wastewater temperature and mean cell retention time

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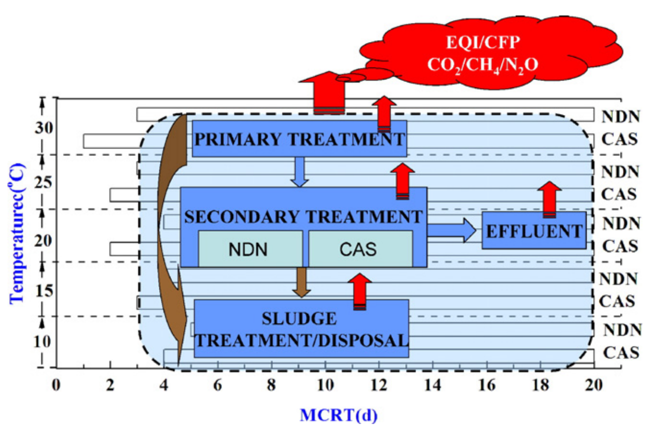
HIGHLIGHTS

- There is a trade-off between the carbon emission and the effluent quality.
- EQI was not necessarily improved with the increasing MCRT.
- NDN process was preferable to CAS process from effluent quality consideration.
- $\gamma_{NDNprocess}$ is less than $\gamma_{CASprocess}$ if N_2O emitted from NDN was limited.
- γ derived from CFP and EQI provides a quantitative tool for decision makers.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the seasonal cycles, the mean cell retention time (MCRT) of the activated sludge process is varied to compensate the wastewater temperature variations. The effects of these variations on the carbon footprint (CFP) and effluent quality index (EQI) of a conventional activated sludge (CAS) process and a nitrification/denitrification (NDN) process were quantified. The carbon emission included both biogenic and non-biogenic carbon. Carbon emissions of wasted biosolids management were also addressed. Our results confirmed that the effluent quality indicated by EQI was not necessarily improved by increasing MCRT. Higher MCRT increased the carbon emission and reduced excess sludge production, which decreased the potential for biogas energy recovery. The NDN process was preferable to the CAS process from the perspective of effluent quality. This consideration extended to the whole plant CFP if the N_2O emitted during NDN was limited ($[N_2O] < 1\% [NH_4^+]_{removed}$) as the carbon emission per unit effluent quality achieved by NDN process is less than that of the CAS process. By putting forward carbon emission intensity (γ) derived from CFP and EQI, our work provides a quantitative tool for decision makers evaluating process alternatives when there is a trade-off between carbon emission and effluent quality.

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1. Introduction

Advances in wastewater treatment over the past two centuries have made great contributions to the mitigation of environmental pollutions. Recently, particular attention has been paid to the broader environmental implications of these improvements. Neethling et al. (2011) and Shao and Chen (2013) indicated that the environmental impacts associated with achieving lower levels of effluent nutrients might counter the local benefits arising from improved water quality. The concept that wastewater treatment could result in direct emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as indirect emissions resulting from power generation, chemicals manufacturing and sludge disposal, is recognized and of global interest (Fine and Hadas 2012; Flores-Alsina et al. 2014; Préndez and Lara-González 2008). According to Gupta and Singh (2012), wastewater was a relevant source of GHGs in 2000, and was expected to grow in the coming century following population growth. The challenge of reducing overall GHGs emissions from wastewater treatment necessarily involves including GHGs emissions in addition to effluent quality and operational costs when evaluating design alternatives (Cakir and Stenstrom 2005; Keller and Hartley 2003; Neethling et al. 2011; Pan et al. 2011; Préndez and Lara-González 2008; Shahabadi et al. 2010).

Wastewater treatment plants (WWTPs) are operated under constantly changing conditions and compensations are made to reduce the impacts of the seasonal changes of temperature, wastewater composition and flow rate on the microbial ecology, dynamic loading and energy consumption (Gori et al. 2011; Hu et al. 2013; WEF 2002, 2007). Nevertheless, some generally accepted wastewater treatment process operations might conflict with the strategies used to reduce process GHGs emissions. For example, the tendency of WWTPs to decrease their energy consumption (and thus its GHGs emissions) by decreasing aeration could have adverse effects on the stability of the process and its ability to meet target effluent limits (Cristea et al. 2011; Holenda et al. 2008; Liu et al. 2008). Furthermore, although the indirect CO_2 emission reduction from power importation may be expected, this reduction could be counteracted by the increase in N_2O emission under low dissolved oxygen (DO) concentration (Flores-Alsina et al. 2014; Kampschreur et al. 2009). Extended mean cell retention time (MCRT) and higher DO concentration would increase the total energy input for aeration, however it would decrease the energy usage per air delivered due to the increased oxygen transfer efficiency (Rosso and Stenstrom 2007). Concomitantly, at longer MCRTs and higher DO concentrations the accumulation of nitrite during nitrification is minimized and N_2O emission is reduced (Lotito et al. 2012; van Loosdrecht and Salem 2006). Therefore, investigating the dynamics of process carbon footprint (CFP) and the effluent quality under the fluctuations of key operational parameters appears to be a key tool in support of decision-making.

There are geographical and seasonal variations for wastewater temperature, which influence biochemical reactions, oxygen transfer rates, and heat flow to and from digesters, thereby creating differences in energy demand and carbon emission (Garfí et al. 2012; Johansson et al. 2004; Lv et al. 2010). MCRT is one of the commanding operational parameters for biological wastewater treatment processes. MCRT controls the extent of carbon (C) and nitrogen (N) removal, the production of excess sludge and the energy demand for aeration (Babcock et al. 2001; Gillot and Héduit 2008; Majewsky et al. 2011; Racz et al. 2012; Rosso et al. 2008; Rosso and Stenstrom 2005; Sponza and Gok 2011; Tan et al. 2008). Hence, each site is characterized by a range of MCRT values that allow treatment with a certain layout (e.g., carbon oxidation only, carbon oxidation with nitrification and nitrification/denitrification, etc.) under the local wastewater temperatures. It is a routine practice to increase the MCRT during the cold season to compensate for the seasonal decline in wastewater temperature.

Effluent quality can be measured in absolute terms (i.e., using the effluent concentrations) or in relative terms (i.e., calculating the removal efficiency of influent constituents). When different facilities are compared across geographical areas, especially when their processes are different (e.g., one removing nutrients vs. another only reducing carbonaceous constituents) and their discharge/reuse permits are different, an effluent quality index (EQI) becomes useful. EQI, which is the weighted sum of all pollutants in the effluent, is defined as the total amount of pollutants discharged per unit time and condenses the large output of effluent quality dataset into a manageable number for easier comparison (Jeppsson et al. 2007; Nopens et al. 2010). The use of such indices allows us to normalize the process CFP per unit treatment achieved.

To the best of our knowledge, no study has yet reported the quantitative assessments of the effects of the seasonal variations in wastewater temperature and the compensated MCRT on the CFP and EQI of a WWTP. Consequently, the objectives of this study are: (1) to quantify the effects of MCRT and wastewater temperature on the CFP and EQI of the WWTPs not currently described by the standardized protocol-based methodologies (e.g., IPCC 2006; LGOP, 2010); (2) to propose feasible GHGs mitigation strategies when a trade-off between CFP and EQI can be highlighted. The results obtained from this study are promising and will help to support decision-makers and plant managers to design, operate, and manage WWTPs more sustainably while still meeting regulatory compliance.

2. Methods

2.1. Process descriptions

Wastewater quality values for the influent were collected at a full-scale facility in the United States (with average flow rate ~60 000 $m^3\ d^{-1}$). Over the past two decades, two widely applied activated sludge processes were operated at this facility, i.e., conventional activated sludge (CAS) process and nitrification/denitrification (NDN) process operated in the modified Ludzack–Ettinger configuration (shown in Fig. 1), while the CAS process also performed nitrification when the MCRT was sufficient. Table 1 summarizes the modeled scenarios and average influent quality conditions.

Wastewater temperatures were set at 10 °C, 15 °C, 20 °C, 25 °C and 30 °C to extend our modeling to scenarios in cold, mild and hot climates. The minimum MCRT for nitrification was calculated by methods described in Henze et al. (2008) with a safety factor of 1.5 (i.e., 4 d, 3 d, 2 d, 2 d and 1 d for wastewater temperatures of 10 °C, 15 °C, 20 °C, 25 °C and 30 °C, respectively). The BOD_5 effluent values were calculated for each scenario, and always respected the discharge criteria enforced in the United States (i.e., 30 mg $BOD_5\ l^{-1}$). The effluent TSS quality was set to meet the discharge criteria for the United States (i.e., 30 mg TSS l^{-1}). To access and compare the performance of the wastewater treatment process under different scenarios, evaluation criteria that condense the simulation output into a few indices and/or key variables were necessary. In this study, Effluent Quality Index (EQI; Jeppsson et al. 2007; Nopens et al. 2010) was applied to evaluate the performance of the processes by condensing a variety of water quality indices into a single index. The definition of the Effluent Quality Index (EQI; Jeppsson et al. 2007; Nopens et al. 2010) is a weighted sum of the pollutants emitted per unit time ($mass_{pollutant,emitted}$/time):

$$EQI = \frac{1}{\Delta t \cdot 1000} \int_{t_1}^{t_2} \begin{pmatrix} \beta_{TSS} \cdot TSS_e(t) + \beta_{COD} \cdot COD_e(t) + \beta_{TKN} \cdot TKN_e(t) \\ +\beta_{NO_3^-} \cdot NO_{3,e}^-(t) + \beta_{BOD_5} \cdot BOD_{5,e}(t) \end{pmatrix} Q_e(t) dt \tag{1}$$

in which Δt is the total evaluation period, $Q_e(t)$ is instantaneous flow rate during the evaluation period and the subscript e denotes the effluent. The weighting factors for different wastewater constituents