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# Minimization of greenhouse gas emissions from extended aeration activated sludge process

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## Abstract

One of the greenhouse gas (GHG) emission resources is industrial wastewater treatment plants. In this study, on-site and off-site greenhouse gas emissions of an extended aeration activated sludge process in a meat processing wastewater treatment plant were estimated using a new developed approach based on the IPCC method. On-site emissions were regarded as the emissions related to the biochemical treatment process and microbial activity in the wastewater. On-site emissions were estimated from organic materials removal from wastewater and microbial mass activity. Biological oxygen demand (BOD) and chemical oxygen demand (COD) removal were considered as pollutant resources of carbon dioxide ($CO_2$) and methane ($CH_4$), respectively. Off-site emission was estimated from electricity consumption, chemical use and the sludge stabilization process. This paper aimed to determine and reduce on-site and off-site emissions for the extended aeration process in an industrial wastewater treatment plant. Modification of operating conditions was applied to reduce GHG emissions. The results revealed that electricity consumption was the major source of the greenhouse gas emissions for this process with a value of 6,002.77 kg $CO_2$e/d. The minimization of total GHG emissions reached up to 17.1% by modifying the treatment process conditions.

**Key words:** greenhouse gas emission, industrial wastewater treatment, minimization, off-site emission, on-site emission

## Highlights

- The originality of this paper is that the on-site and off-site emissions were investigated for the extended aeration process of a highly organic industrial wastewater plant using a new developed GHG estimation model. A new calculation term was adapted to the IPCC method for on-site and off-site emissions. The novelty of the study, process modification was applied to reduce GHG emissions from the extended aeration process.

## INTRODUCTION

Greenhouse gas (GHG) emissions have been increasing in the atmosphere due to industrial, agricultural and anthropogenic activities in recent years (Kyung *et al.* 2015). Wastewater treatment plants (WWTPs) have been considered as one of the greenhouse gas emissions resources in recent years (Yerushalmi *et al.* 2009; Corominas *et al.* 2012; Kyung *et al.* 2015; Yapıcıoğlu 2018a). According to the Intergovernmental Panel on Climate Change (IPCC) reports, greenhouse gas emission from the waste sector corresponds to approximately 3% of the anthropogenic emissions on a global scale, and wastewater treatment constitutes approximately 20% of the waste sector (IPCC 2014). Carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) are the main greenhouse gases which are emitted from wastewater treatment plants to the atmosphere due to the applied treatment process, sludge dewatering and disposal process, chemical use, energy consumption and maintenance and transport (Metcalf & Eddy 2014; Kyung *et al.* 2015; Yapıcoğlu 2018a).

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Greenhouse gas emissions can be classified as on-site emissions and off-site emissions (Paraviccini *et al.* 2016; Yapıcıoğlu 2018a). The on-site emissions in the plants are emitted emissions at the wastewater collection system, treatment units and discharge point of the treated water. The off-site GHG emissions come from the electricity consumption, air consumption, transportation, chemical use and sludge stabilization and disposal processes (Paraviccini *et al.* 2016; Yapıcıoğlu 2018a). Especially, industrial wastewater plants emit huge amounts of greenhouse gas emissions due to highly organic wastewater content and treatment processes. The meat processing industry is one of them.

The meat processing industry discharges large volumes of wastewater in many countries and needs considerable treatment if its release to the environment is to be sustainable (Yapıcıoğlu 2018b). The organic materials and total suspended solids concentrations are very high and it has a highly contaminating effect (Lecompte & Mehrvar 2014; Yapıcıoğlu 2018b). There are several methods to treat meat processing wastewater, with most focusing on biological processes such as activated sludge, stabilization ponds and aerobic reactors (Davarnejad & Nasiri 2017). The widespread treatment method is the extended aeration activated sludge process for meat processing wastewater. In this process, carbon and nitrogen removal can be ensured (Metcalf & Eddy 2014). Extended aeration activated sludge process consists of an aeration tank and a sedimentation tank. In the aeration tank, organic materials in the wastewater are stabilized by the living microbial mass. Blowers are used to pump the air to the tank. Air pumps leads to high energy consumption (Metcalf & Eddy 2014). The other energy consumption resource is sludge pumps which are used for the return of activated sludge into the aeration tank. Also, denitrification is applied to remove nitrogen from wastewater in this process. Methanol is used as an additional carbon resource in the denitrification process (Metcalf & Eddy 2014). Electricity consumption and chemical use in the aeration tank lead to off-site greenhouse gas emissions (Kyung *et al.* 2015). Some of the activated sludge was returned to the aeration tank to maintain a living microbial mass at certain concentrations (Metcalf & Eddy 2014). Waste activated sludge is an environmental challenge that leads to high costs of handling and dewatering processes and greenhouse gas emissions. The other source of off-site GHG emissions is the sludge handling process. On-site emissions have been regarded as GHG emissions due to wastewater treatment processes in the WWTPs (Paraviccini *et al.* 2016). In the result of the extended aeration process, $CO_2$ and $CH_4$ emissions have been released from the treatment units due to organic materials stabilization process by living microorganisms in the wastewater. From this point of view, biological oxygen demand (BOD) and chemical oxygen demand (COD) removal were regarded as pollutant sources of $CO_2$ and $CH_4$, respectively.

There are several studies in the literature related to this topic. Kyung *et al.* (2015) investigated off-site emissions resulting from electricity consumption and chemical use for a five-staged Bardenpho process. Also, they estimated on-site emissions from a hybrid process. Bani Shahabadi *et al.* (2009) performed a study estimating off-site greenhouse gas emissions for a combined anaerobic treatment and AO process. Masuda *et al.* (2015) investigated off-site emission from energy consumption for a classical activated sludge process. Barbu *et al.* (2017) observed greenhouse gas emissions from a classical activated sludge process in another study. The other study corresponded to Santín *et al.* (2018) which GHG emission was investigated for a classical activated sludge process. There are several GHG emissions reduction methods applied for industrial WWTPs. Innovative treatment techniques could be performed in order to reduce greenhouse gas emissions (Yapıcıoğlu 2018a). Microalgal treatment is regarded as one of the oldest GHG emissions reduction processes. $CO_2$ assimilation is applied due to photosynthesis of microalgae in this technology. Also, the nitrite-dependent anaerobic methane oxidation (n-damo) process is considered as one of the biological GHG emission minimization methods. Recently, biochar adsorption for wastewater treatment has become one of the GHG emission minimization technologies due to the $CO_2$ and $N_2O$ adsorption capacity (Yapıcıoğlu 2018a). Modification of operating conditions and wastewater treatment processes is another GHG emission

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minimization technique (Yapıcıoğlu 2018a). In this study, treatment process modification was applied to reduce GHG emissions. Operational conditions including hydraulic retention time (HRT) and solid retention time (SRT)) were modified to decrease GHG emissions.

The originality of this paper is that on-site and off-site emissions were investigated for extended aeration process of a highly organic industrial wastewater plant using a newly developed GHG estimation model. A new calculation term was developed based on the IPCC method for on-site and off-site emissions. The novelty of this study is that process modification was applied to reduce GHG emissions from an extended aeration activated sludge system. The operating conditions were varied to estimate GHG emissions formation.

## MATERIAL AND METHODS

In this study, on-site and off-site greenhouse gas emissions of an aeration tank for extended aeration activated sludge process applied in a meat processing wastewater treatment plant were estimated. Off-site emission was estimated from chemical (methanol for denitrification) consumption, the sludge stabilization process and electricity consumption using the IPCC approach. On-site emissions were determined using the approach of organic materials removal from wastewater. It was considered that $CO_2$ is formed resulting from BOD removal and microbial respiration in the wastewater. It was assumed that $CH_4$ is released when COD is removed from wastewater and microbial mass is dead during the endogen phase. $CH_4$ could be generated in the anaerobic sections of the aeration tank. Under aerobic conditions, $CH_4$ can also be partially biologically oxidized (Paraviccini *et al.* 2016). These sections could be formed as the result of inadequate or partial aeration at the aeration tank. At these units, methanogens have been grown. $CH_4$ is formed as the result of anaerobic stabilization of the organic substances in the wastewater. And COD is an indicator parameter of the wastewater pollution. Organic materials stabilization amount (organic materials removal efficiency) is defined with COD removal theoretically. So, they were correlated with each other. The main aim of this study was to minimize on-site and off-site emissions for an extended aeration tank in a meat processing industry wastewater treatment plant.

### Description of the industrial WWTP and treatment process

The meat industry is located at an organized industrial zone in Turkey. The organized industrial zone is in the west of Turkey. The wastewater treatment capacity of this industrial park is nearly 20,000 $m^3$/d. After pretreatment of meat processing wastewater in the plant, the wastewater is discharged to the organized industrial zone sewage collection system. The main wastewater generating points of the meat processing industry are the slaughterhouse, rendering unit, and intestinal washing process. The wastewater characterization of this plant is given in Table 1. The wastewater analysis results were performed using *Standard Methods* (APHA 1998).

**Table 1** | Wastewater characterization of the meat industry

| Parameter | Influent[a] | Effluent[a] |
|---|---|---|
| COD (mg/L) | 5,293 | 1,547 |
| BOD (mg/L) | 2,554 | 221 |
| TSS (mg/L) | 2,122 | 487 |
| FOG (mg/L) | 329 | 10 |
| pH | 7.29 | 6.9 |

[a]Influent and effluent values corresponded to the extended aeration process.

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Figure 1 demonstrates the existing wastewater treatment process in the plant. An extended aeration activated sludge system is carried out in order to remove organic and suspended materials from the wastewater. The extended aeration activated sludge system is used as the biological treatment technology and requires air in order to keep the microorganisms alive that are responsible for wastewater stabilization. A blower is used to generate air to operate the treatment system. Air is pumped into the aeration tank for the respiration of the microbial mass in the activated sludge process. This system, combined with blower and air pumps, leads to the high energy consumption in the plant. Furthermore, a sedimentation tank is operated to remove the waste activated sludge. Some of the activated sludge was returned to the aeration tank to ensure living microorganisms at a determined biomass concentration. Sludge pumps, which consume a huge amount of electricity, are used for the return sludge process. Also, denitrification and nitrification processes are applied for removal of nitrogen from wastewater. Methanol is used as an added carbon source for the denitrification process. Energy consumption resulting from operating the blower and sludge pumps and chemical use, as methanol addition to sustain the process and lime addition for the sludge stabilization process, have led to off-site greenhouse gases emissions in the plant.

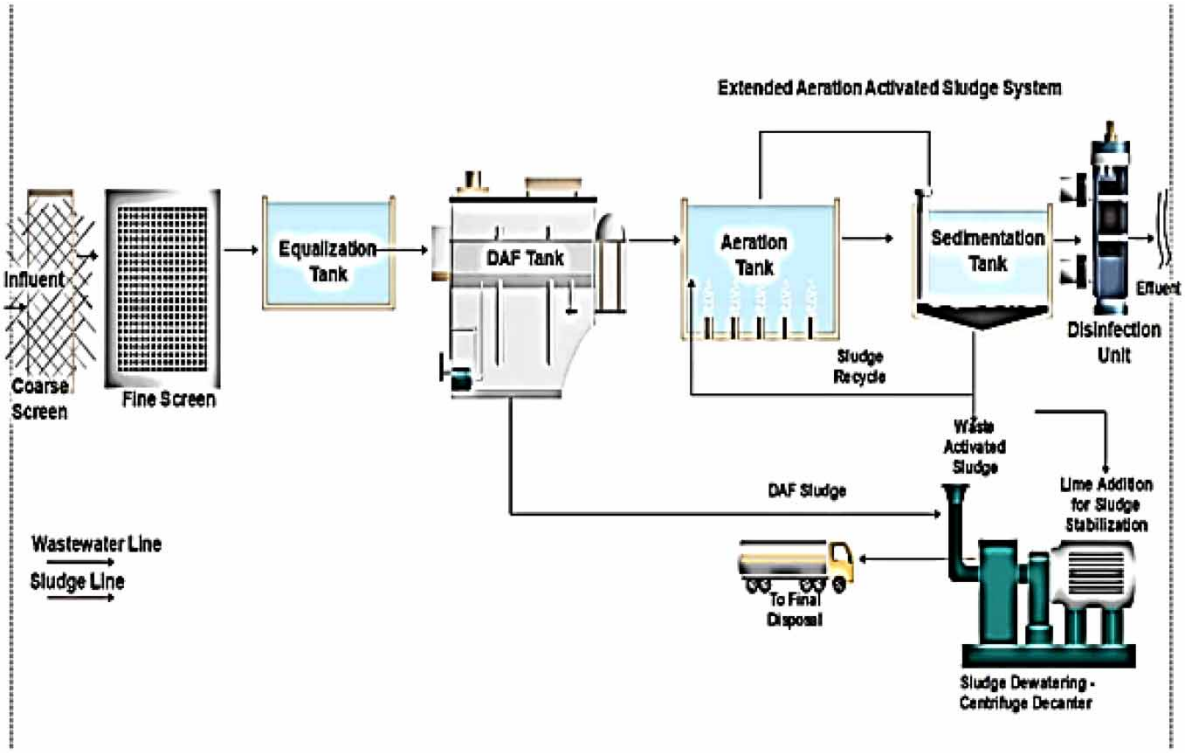


**Figure 1** | Wastewater treatment process flow scheme of the meat industry.

The extended aeration activated sludge process is a type of biological treatment. It consists of an aeration tank and sedimentation tank. Hydraulic retention time (HRT) is in the range of 18–36 hours. Organic material is removed with the help of microorganisms in the aeration tank. Air is pumped into the aeration tank for the respiration of the microbial mass (Metcalf & Eddy 2014).

In this study, the HRT in the aeration tank is approximately 24 hours. Solids retention time (SRT) is 22 days. Both carbon and nitrogen removal can be ensured as a result of the extended aeration process. For the denitrification process, methanol is added to the aeration tank as a carbon source. Table 2 presents the data used to estimate greenhouse gas emissions corresponding to the aeration tank, which emits GHG emissions as the major unit in the WWTP. Methanol dose is the meaning

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**Table 2** | Data set for the estimation of on-site GHG emission

| Parameter | Value |
|---|---|
| Q ($m^3$/d) | 2,800 |
| BOD removed (B) (kg/$m^3$) | 2.333 |
| COD removed (C) (kg/$m^3$) | 3.746 |
| MLVSS (kg/$m^3$) | 2.4 |
| $MLSS_d$ (kg/$m^3$) | 1.6 |
| $k_d$ | 0.40 |

of the amount of methanol required for the denitrification process. Electricity consumption comprises the electricity used by the blower, air and sludge pumps. Lime is used for the sludge stabilization process.

### Determination of on-site GHG emissions

On-site emission is regarded as the GHG emissions due to the biochemical treatment process of the extended aeration activated sludge system. It was considered that $CO_2$ is the GHG resulting from BOD removal in the wastewater. It is assumed that $CH_4$ occurs when COD is removed from wastewater and microbial mass is dead during the endogen phase. From this point of view, an estimation tool was developed based on the IPCC approach. On-site $CO_2$ emission ($GHGE_{on\text{-}site,CO_2}$) is figured out by multiplying BOD removal (B) (kg/$m^3$) and wastewater flow (Q) ($m^3$/d) and global warming potential (GWP) of carbon dioxide ($GWPCO_2$), whose value is '1'. Also, it is considered that $CO_2$ is formed as the result of microbial mass respiration. Partial $CO_2$ emission was figured out by multiplying MLVSS (living microbial mass), flow rate (Q) and GWP of $CO_2$. Similarly, on-site $CH_4$ emission ($GHGE_{on\text{-}site,CH_4}$) is estimated by multiplying COD removal (C) and wastewater flow (Q) and global warming potential of $CH_4$ ($GWPCH_4$). The other resource of $CH_4$ emission is the microbial death ($MLSS_d$). It is figured out from $MLSS_d$ and wastewater flow rate and the GWP of $CH_4$. The GWP of methane is 28 (IPCC 2014). The calculation terms of on-site emissions developed in this study are given in Equations (1) and (2). The data used for estimation of on-site emission are given in Table 2. On-site GHG emission is the sum of $CO_2$ and $CH_4$ emissions (Equation (3)). When these calculations were applied, the endogenous respiration rate ($k_d$) was considered. It was assumed as 0.40 (Metcalf & Eddy 2014). $k_d$ means the endogenous respiration indicator constant, which describes the self-destruction of the cells in the microbial culture. 40% of $k_d$ corresponded to 40% of microbial mass under the endogenous phase (Metcalf & Eddy 2014). While COD and BOD have been removed from wastewater, some removed materials transformed into waste sludge and GHG emissions in the wastewater systems. Also, the gases, apart from $CO_2$ and $CH_4$, were ignored in the result of the treatment process from COD and BOD removal.

$$GHGE_{on-site,CO_2} = [(B \times Q \times GWPCO_2)(1 - k_d)] + (MLVSS \times Q \times GWP_{CO_2}) \quad (1)$$

$$GHGE_{on-site,CH_4} = [(C \times Q \times GWP_{CH_4})(1 - k_d)] + (MLSS_d \times Q \times GWP_{CH_4}) \quad (2)$$

$$GHGE_{on-site} = GHGE_{on-site,CO_2} + GHGE_{on-site,CH_4} \quad (3)$$

Total GHG emission (GHGE) is the sum of the on-site and off-site emissions.

### Estimation of off-site GHG emissions

There are three constituents of off-site greenhouse gas emissions were considered in this study. Electricity consumption for the operation of extended aeration process in the plant was used to estimate

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the off-site emissions. The second constituent is the off-site emission from methanol (chemical) use for denitrification for the removal of nitrogen in the extended aeration process. The other constituent of off-site emission is the sludge stabilization process. An adaptive model was developed in this study.

The off-site emission related to the electricity consumption was figured out by multiplying the electricity consumption ($EC_{total}$) (kWh) of the extended aeration process and the specific emission factor ($EF_{electricity}$) of the electricity consumption related to Turkey (kg $CO_2$e/kWh). Electricity consumption of the extended aeration process was obtained from the electricity bills and the electricity meters in the treatment plant. Electricity consumption of the plant contains the energy demand of the blower and air pumps ($EC_{blower\&air\ pumps)}$ for the aeration process and the energy depletion of the sludge pumps ($EC_{sludge\ pumps)}$. $EF_{electricity}$ is 0.497 kg $CO_2$e/kWh (IEA 2016). The estimation model based on the IPCC method is given in Equation (4) for total off-site emissions from electricity (Kyung *et al.* 2015).

$$GHGE_{electricity} = EC_{total} \times EF_{electricity} \quad (4)$$

Methanol addition as an added carbon source for denitrification to achieve nitrogen removal leads to the other off-site emission in the aeration tank. It can be estimated by means of multiplying daily methanol consumption ($L_{methanol}$) (kg/d) and the emission factor of methanol ($EF_{methanol}$) (Kyung *et al.* 2015). The emission factor of methanol is 1.54 kg$CO_2$e/kg methanol (Yerushalmi *et al.* 2009; Ashrafi 2012; Kyung *et al.* 2015). The off-site emission of the chemical use could be estimated using the equation below (Equation (5)) (Kyung *et al.* 2015).

$$GHGE_{chemical} = L_{methanol} \times EF_{methanol} \quad (5)$$

The other resource of off-site GHG emissions is the sludge stabilization process. Lime is used for the stabilization of waste activated sludge. It can be figured out by means of multiplying daily lime consumption ($L_{sludge}$) (kg/d) and the emission factor of lime ($EF_{lime}$) (IPCC 2006). The emission factor of lime is 0.43971 kg$CO_2$e/kg lime. $CaCO_3$ is used as the chemical. A new calculation tool developed to estimate the GHG emission from sludge stabilization is given in Equation (6).

$$GHGE_{sludge} = L_{sludge} \times L_{lime} \times EF_{lime} \quad (6)$$

The data used for the estimation of off-site GHG emissions are given in Table 3. The off-site emission is the total of the emissions from electricity and chemical consumption and sludge stabilization

**Table 3** | Data set for the estimation of off-site GHG emission

| Parameter | Value |
|---|---|
| $L_{methanol}$ (methanol dose for denitrification) (kg/d) | 65.5 |
| Total electricity consumption ($EC_{total}$, kWh) | 12,078 |
| $EC_{blower\&air\ pumps}$ (kWh) | 9,467 |
| $EC_{sludge\ pumps}$ (kWh) | 2,611 |
| $L_{lime}$ (lime for stabilization of sludge) ($CaCO_3$ dose) (kglime/kgsludge) | 1.31 |
| $L_{sludge}$ (kg sludge/d) | 6,808.48 |
| $EF_{methanol}$ (kg$CO_2$/kg methanol) | 1.54 |
| $EF_{lime}$ (kg$CO_2$/kglime) | 0.43971 |
| $EF_{electricity}$ (kg $CO_2$e/kWh) | 0.497 |

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process. It is shown in Equation (7).

$$GHGE_{off-site} = GHGE_{electricity} + GHGE_{chemical} + GHGE_{sludge} \quad (7)$$

### Minimization of GHG emissions

There are several techniques for the reduction of GHG emission releasing from WWTPs. One of them is modifications to treatment processes and configurations. In this study, treatment process modification was carried out to reduce the GHG emission. Operational conditions (hydraulic retention time (HRT) and solid retention time (SRT)) were modified to decrease the GHG emissions. HRT means the wastewater retention time in the aeration tank and SRT means the duration of retention time of microbial mass in the aeration tank. Altering the durations of the operation, on-site emissions were figured out. HRT and SRT were minimized to 18 hours and 20 days, respectively. The values were considered without deterioration of the effluent quality. The GHG emissions minimization was figured out by benchmarking the previous emission at an HRT of 24 h and an SRT of 22 days and the last emission at an HRT of 18 hours and SRT of 20 days. The same estimation tools were used for both operational conditions.

## RESULTS AND DISCUSSION

### On-site GHG emissions

On-site emissions were considered as the emissions as a result of BOD and COD removal and microbial activity. The results revealed that on-site $CH_4$ emission was higher than $CO_2$ emission. The values of $CH_4$ and $CO_2$ emissions were 3,016.5 and 1,063.9 kg $CO_2$e/d, respectively. Total on-site GHG emission is 4,080.4 kg $CO_2$e/d. Table 4 shows the comparison of on-site GHG emissions.

Kyung *et al.* (2015) calculated that on-site greenhouse gas emission for a municipal wastewater (influent BOD = 200 mg/L) that was treated with a five-stage Bardenpho process as 3,701 ± 269 kg $CO_2$e/d They reported lower emissions than this study. It can be said that the Bardenpho process emits GHG emission lower than the extended aeration activated sludge process due to better influent characterization. Masuda *et al.* (2015) similarly reported that the aeration tanks released methane emissions. The other study is related to Rodriguez-Caballero *et al.* (2014). They reported that the highest GHG emission was observed in the aeration tank. If we compare the values of emissions, off-site GHG emissions were higher than on-site greenhouse gas emissions. Qiao *et al.* (2020) investigated greenhouse gas emission from the wastewater treatment process by integrating activated sludge and microalgae processes. They

**Table 4** | Total, off-site and on-site GHG emissions

| Emission | Value (kg $CO_2$e/d) |
|---|---|
| $GHGE_{on\text{-}site,CH_4}$ | 3,016.5 |
| $GHGE_{on\text{-}site,CO_2}$ | 1,063.9 |
| $GHGE_{on\text{-}site}$ | 4,080.4 |
| $GHGE_{electricity}$ | 6,002.77 |
| $GHGE_{chemical}$ | 100.87 |
| $GHGE_{sludge}$ | 3,921.82 |
| $GHGE_{off\text{-}site}$ | 10,025.46 |
| GHGE | 14,105.86 |

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reported COD, $NH_4^+$, and total phosphorus removals above 95%. No $CH_4$ emissions during the operation of the study. Emitted $CO_2$ only accounted for a small proportion of the total GHG in the influent. Nayeb *et al.* (2019) reported wastewater collection systems, wastewater treatment plants and discharging wastewater to the environment led to direct greenhouse gas (carbon dioxide, nitrous oxide, and methane) emission from biological processes (activated sludge process) and indirect emissions due to energy consumption, similarly. They used a similar method for estimation of on-site emissions. They similarly estimated $CH_4$ emissions from degradable organic materials. Sweetapple *et al.* (2014) investigated the potential of control strategy optimization for the reduction of operational greenhouse gas emissions from wastewater treatment for which the activated sludge process was carried out. They reported that multi-objective optimization of WWTP operational parameters and controller tuning parameters enables a significant reduction in GHG emissions. They estimated similar to this study and optimized GHG emissions using the BSM2G model in terms of COD and BOD removal. Flores-Alsina *et al.* (2011) investigated greenhouse gas emissions during benchmarking of wastewater treatment plant control strategies and modelling of the activated sludge process. They used the BSM2G method considering the dissolved oxygen, the solids retention time (SRT) and the organic carbon/nitrogen ratio (COD/N) as promoters of GHG emissions similar to this study.

### Off-site GHG emissions

In this study, off-site GHG emissions resulted from electricity consumption, methanol addition as the chemical use and the sludge stabilization process. The results revealed that the emission from electricity consumption was the major source of GHG emissions in the WWTP with a value of 6,002.77 kg $CO_2$e/d. The distribution of the emission from electricity consumption is given in Figure 2. It can be said that the electricity consumption of the blower and air pumps led to the highest emission. GHG emission from the sludge stabilization process with lime led to off-site emission to the value of 3,921.82 kg $CO_2$e/d. The minor source of off-site GHG emission is methanol addition for denitrification. The value of GHG emission from chemical consumption was 100.87 kg $CO_2$e/d. Total off-site GHG emission was 10,025.46 kg $CO_2$e/d. Figure 2 also shows the distribution of off-site GHG emissions.

Kyung *et al.* (2015) carried out a similar study for a municipal plant. On the contrary, Kyung *et al.* (2015) reported that chemical use is the major source of off-site emissions in the hybrid plant ($2.698 \pm 336$ kg $CO_2$e/d), and that this amounts to 58.8% of total off-site emissions ($4{,}591 \pm 576$ kg $CO_2$e/d). In this study, off-site GHG emission from chemical use was 39% of total GHG emissions. The major off-site emission source was GHG from electricity consumption with the value of 60% in this study. In another study, Bani Shahabadi *et al.* (2009) achieved similar results with the value for the aerobic system of 1,313 kg $CO_2$e/d. Chemical use was the main source of their study. Masuda *et al.* (2015) reported that off-site GHG emission from electricity consumption was 43.4% of the total emissions. In this study, GHG emission resulting from electricity consumption was 60% of total off-site GHG emissions. In a study by Nayeb *et al.* (2019), they reported that off-site $CO_2$ emission attributed to energy consumption in wastewater treatment plants depends on the population covered by wastewater treatment plants and energy efficiency. Flores-Alsina *et al.* (2011) reported similarly that increasing the carbon source addition increases the GHG emissions due to increased sludge production, which results in increased endogenous respiration, sludge treatment and disposal and both chemicals and energy use.

### Total GHG emissions

Total greenhouse gas (GHGE) emissions refer to the sum of the on-site emissions from the treatment process and the off-site greenhouse gas emissions from electricity and chemical consumption and

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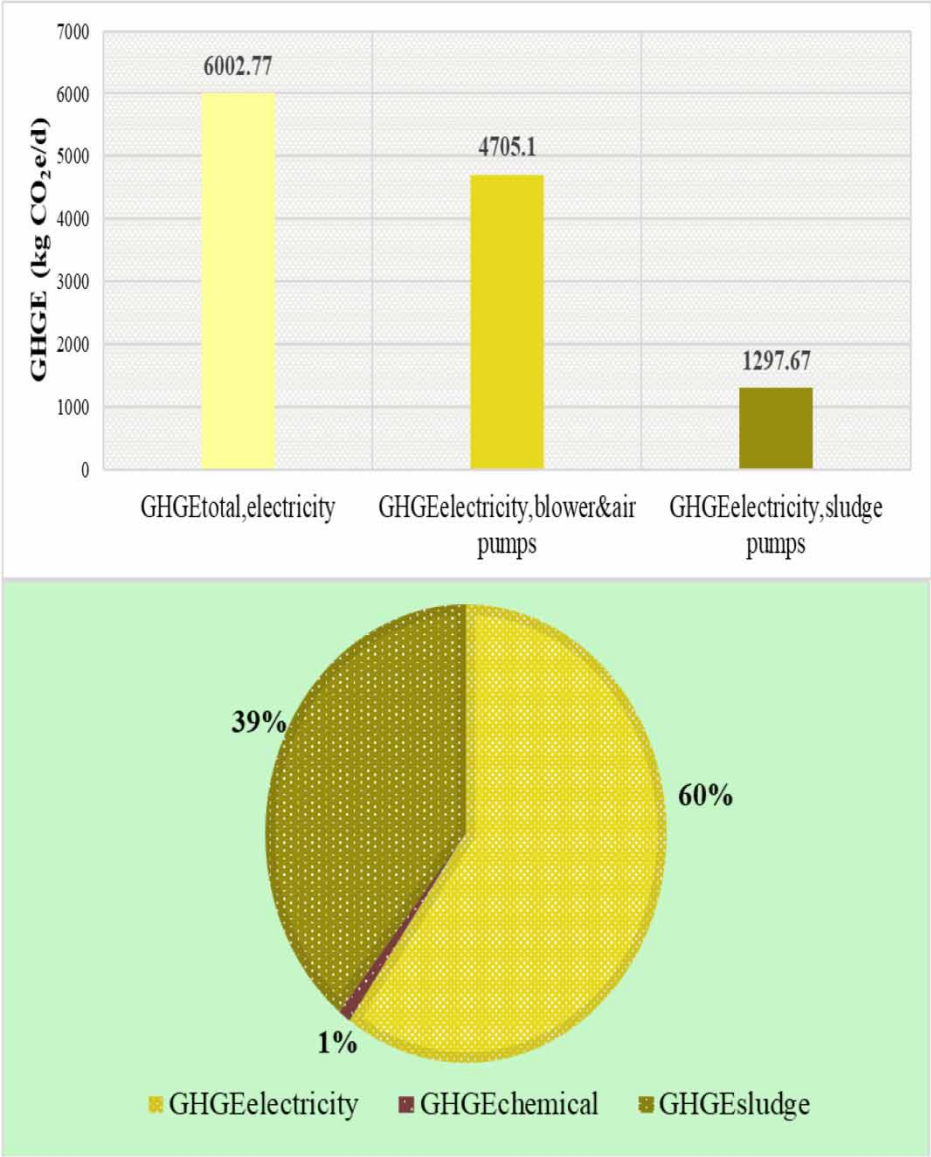


**Figure 2** | Off-site GHG emissions.

sludge stabilization process. Figure 3 demonstrates the distribution of total greenhouse gas emissions, in a detailed form. In Table 4, the values of off-site and on-site were presented.

The results show that off-site emission is higher than on-site emission. Electricity consumption was the major source of GHG emission. Total GHG emission was 14,105.86 kg $CO_2$e/d. Compared to other studies in the literature, Kyung *et al.* (2015) reported the total greenhouse gas emission value as 12.855 kg $CO_2$e/d. Bani Shahabadi *et al.* (2009) achieved similar results to this study. In their study for a hybrid system, they reported that most of the total greenhouse gas emissions were caused by off-site emissions. Barbu *et al.* (2017) reported the GHG emission from the activated sludge process at the value of 17.961 kg $CO_2$e/d. In the study of Santín *et al.* (2018), the GHG emission from the classical activated sludge process was 17.851 kg $CO_2$e/d. It could be said that the extended aeration process is a more environmentally friendly process than the classical activated sludge process considering GHG emission and effluent water quality. It could originate from $CH_4$ emissions. For activated sludge systems, air consumption is lower so some unaerated zones could be formed, and these conditions lead to $CH_4$ emissions.

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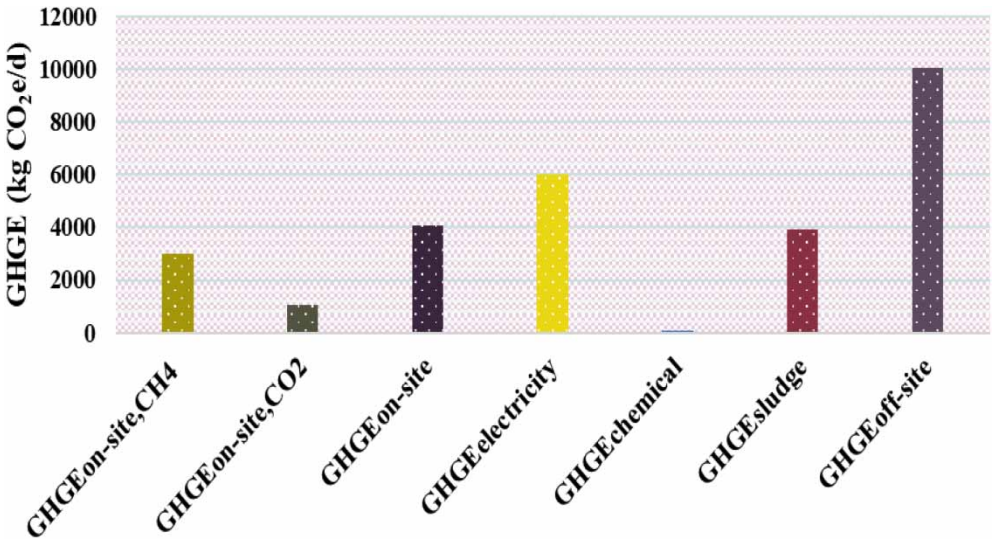


**Figure 3** | GHG emission from the industrial WWTP.

## GHG emission minimization results

Operational conditions (hydraulic retention time (HRT) and solids retention time (SRT)) were modified to decrease the GHG emissions. For the result of an HRT of 18 hours and SRT of 20 days, it is possible to decrease the GHG emissions deteriorating the effluent quality. With decreasing HRT and SRT, it was observed that the electricity consumption, methanol use and waste activated sludge amount were reduced, in parallel. Hence, the GHG emission was minimized as the result of this reduction. Also, it was obvious that on-site $CO_2$ and $CH_4$ emission reduced at these operating conditions. BOD and COD removal were decreased as the result of shortening the operating parameters. So, on-site GHG emissions were lower due to low BOD and COD removal. If HRT and SRT are long, GHG emission is higher. The results and comparison of the GHG emission minimization are given in Table 5.

As seen from Table 5, a significant reduction of GHG emission was achieved with a simple process modification technique. At 18 h of HRT and 20 d of SRT for extended aeration activated sludge

**Table 5** | GHG emission minimization results

| Parameter | HRT (24 h) + SRT (22 d) | HRT (18 h) + SRT (20 d) | GHG emission minimization result (%) |
|---|---|---|---|
| B ($kg/m^3$) | 2.333 | 2.267 | |
| C ($kg/m^3$) | 3.746 | 3.406 | |
| $L_{methanol}$ (kg/d) | 65.5 | 60.5 | |
| $EC_{total}$, (kWh) | 12,078 | 8,078 | |
| $EC_{blower\&airpumps}$ (kWh) | 9,467 | 5,989 | |
| $EC_{sludge\ pumps}$ (kWh) | 2,611 | 2,089 | |
| $L_{lime}$ (kg lime/kgsludge) | 1.31 | 1.31 | |
| $L_{sludge}$ (kg sludge/d) | 6,808.48 | 6,353.76 | |
| $GHGE_{on\text{-}site}$ | 4,080.4 | 3,928.2 | 3 |
| $GHGE_{on\text{-}site,CH_4}$ | 3,016.5 | 2,875.4 | 4 |
| $GHGE_{on\text{-}site,CO_2}$ | 1,063.9 | 1,052.8 | 1 |
| $GHGE_{off\text{-}site}$ | 10,025.46 | 7,767.83 | 22 |
| GHGE | 14,105.86 | 11,696.03 | 17.1 |

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process, total GHG emission reduction was up to 17.1%. The minimization of off-site emission was 22%. The reduction of on-site emission was 3%. It is possible to decrease GHG emission by modifying the process conditions. Rodriguez-Caballero *et al.* (2014) evaluated the effect of process conditions on GHG emission formation. They reported that process variations leading to peak $CH_4$ emissions were identified. Sweetapple *et al.* (2014) reported that greenhouse gas emission could be minimized with the optimization of operational parameters, in parallel. Flores-Alsina *et al.* (2011) reported similarly that a rather low SRT should be favored because it reduces GHG emissions.

## CONCLUSIONS

- This paper revealed that the extended aeration process emits GHG emission in terms of on-site and off-site GHG emissions. $CO_2$ and $CH_4$ emissions were released from this process.
- A new calculation model based on the IPCC approach was developed for the wastewater treatment plants, in this study. This term could be applied for all the biological aerobic wastewater treatment plants.
- The results revealed that off-site emission is higher than on-site emission. Electricity consumption was the major source of GHG emission. Total GHG emission was 14,105.86 kg $CO_2$e/d.
- The results revealed that on-site $CH_4$ emission was higher than $CO_2$ emission. The values of $CH_4$ and $CO_2$ emissions were 3,016.5 and 1,063.9 kg $CO_2$e/d, respectively. Total on-site GHG emission is 4,080.4 kg $CO_2$e/d.
- According to the findings, the off-site emission from electricity consumption was the major source of GHG emissions in WWTP with the value of 6,002.77 kg $CO_2$e/d. It was obvious that the electricity consumption of the blower and air pumps led to the maximum emission. GHG emission from the sludge stabilization process formed the off-site emission to the value of 3,921.82 kg $CO_2$e/d. The lowest off-site GHG emission results from methanol addition for the denitrification. The value of GHG emission from chemical consumption was 100.87 kg $CO_2$e/d. Total off-site GHG emission was 10,025.46 kg $CO_2$e/d.
- It is possible to decrease GHG emission by modifying the process conditions. An important minimization of GHG emission was ensured with a simple process modification technique. At 18 h of HRT and 20 d of SRT for the extended aeration activated sludge process, reduction of total GHG emission was up to 17.1%. The reductions of off-site emission and on-site emission were 22 and 3%, respectively.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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