

# Carbon Footprint Analyses of Wastewater Treatment Systems in Puducherry

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## Abstract

Carbon footprint analysis is a method to quantify the life cycle Greenhouse Gases (GHGs) emissions and identify the measure to reduce climate change impacts. The Intergovernmental Panel on Climate Change (IPCC) has identified that the global warming and climate change which is one of the most important issues in the domain of environment are caused by the excessive emission of Greenhouse Gases (GHG) mainly constituting Carbon dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>) and Nitrous oxide (N<sub>2</sub>O). The municipal wastewater treatment plant receives wastewater for treatment and finally discharges the treated effluent. The emissions of GHG during the treatment of wastewater as well as during the treatment process of sludge and also for energy generation are known to be on-site GHG emissions. Off-site GHG emissions are generated due to transportation and disposal of sludge, off-site energy and chemical production. In Puducherry, the municipal wastewater is being treated using oxidation ponds, Upflow Anaerobic Sludge Blanket (UASB) and Sequencing Batch Reactor (SBR). Wastewater treatment using Sequencing Batch Reactor (SBR) technology is one of the state-of-the art wastewater management systems. In this technology equalization, biological treatment and secondary clarification are performed in a single reactor in a time control sequence. The emissions of GHG from the Oxidation ponds of 12.5 MLD, UASB reactor of 2.5 MLD and SBR of 17 MLD were assessed based on the IPCC guidelines and the total emissions of GHG in terms of equivalent of CO<sub>2</sub> were compared. The performance of the SBR is more efficient and the emissions of GHG are less than the emissions in the UASB as well as in oxidation ponds. The emission of GHG in SBR is about 60% of the existing treatment systems of oxidation ponds and UASB thus a reduction of 40% GHG emission could be achieved.

## Keywords

Greenhouse Gas (GHG), Intergovernmental Panel on Climate Change (IPCC), Global Warming Potential (GWP), Sequencing Batch Reactor (SBR), Upflow Anaerobic Sludge Blanket (UASB)

## 1. Introduction

### 1.1. Definition of Carbon Footprint

Carbon footprint is defined as the total set of greenhouse gas emissions caused by an activity or product expressed as carbon dioxide equivalent. It is a measure of the total amount of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and Nitrous Oxide (N<sub>2</sub>O) emissions of a defined system or activity, considering all relevant sources and sinks within the system or activity. It is calculated as carbon dioxide equivalent using the relevant 100-year global warming potential (GWP100). The main constituents of the GHG are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). The accounted GHG emissions are indexed in terms of global warming potential (GWP) by converting in terms of CO<sub>2</sub> with a base value over a period of 100 years namely, 1 for CO<sub>2</sub>, 21 for CH<sub>4</sub> and 310 for N<sub>2</sub>O [1] [2]. Even though CO<sub>2</sub> emissions from biological wastewater treatment are not normally considered, some studies have pointed out that about 20% of the carbon present in the wastewaters can be of fossil origin and the emissions of fossil CO<sub>2</sub> from wastewater treatment were underestimated. The sources of GHG may be either natural or anthropogenic. Further the identification and quantification of all sources are essential for developing the strategy to control and reduce the rate of increase of the emissions of GHG. The wastewater treatment plants (WWTP) are considered as source of GHG emissions because of the generation of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O during the process of treatment and energy demand.

In a defined system boundary, the emissions of GHG from different scenarios can be estimated and evaluated. The GHG emissions include 1) direct emission of GHG from wastewater treatment comprising emission of CO<sub>2</sub> due to degradation of organic matters, emission of N<sub>2</sub>O during the process of nitrification and denitrification and emissions of CH<sub>4</sub> and N<sub>2</sub>O from anaerobic digestion during sludge treatment and 2) indirect emissions of GHG from sludge treatment, usage of electrical power and chemicals during the operation and maintenance of the treatment plant and disposal of sludge. Apart from these, the production and transportation of construction materials also cause indirect emissions of GHG [3].

### 1.2. Carbon Credit Scheme in Wastewater Treatment

Global warming and climatic change is being viewed as an international problem and several studies establish the significance of Greenhouse Gas (GHG) emissions from the wastewater process and the impact on the ecosystem. Wastewater treatment plants (WWTPs) are some of the sources of GHG emission. The wastewater treatment processes use biological and physio-chemical processes for the removal of contaminants and produce the three primary GHGs, *i.e.* carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) during the treatment operation and energy generation processes.

Aerobic treatment systems produce primarily CO<sub>2</sub>, whereas anaerobic systems produce a mixture of CH<sub>4</sub> and CO<sub>2</sub>. When the sludge generated from the wastewater treatment unit is digested on-site, then, there will be additional CO<sub>2</sub> and CH<sub>4</sub>

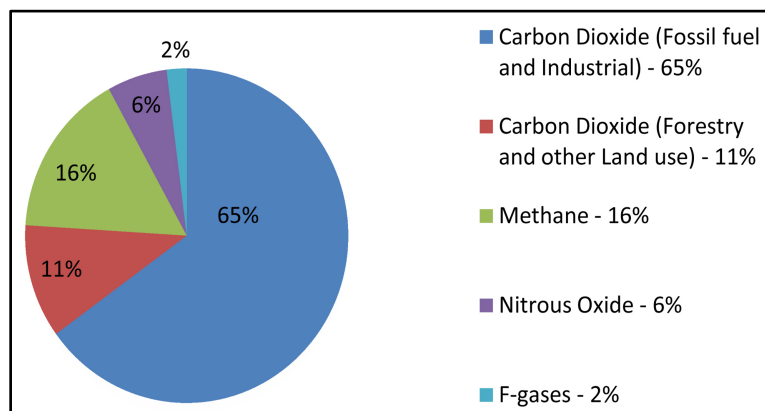
emissions.  $N_2O$  is produced during the processes denitrification, nitrification and during chemical reactions that take place in the WWTP. There is considerable interest to determine carbon footprints of Wastewater Treatment Plants (WWTPs) with respect to Greenhouse Gas (GHG) emissions, energy usage, energy production, and carbon credits.

The Global Warming Potential (GWP) of a GHG is the ratio of heat trapped by one unit mass of the gas compared to one unit mass of  $CO_2$  over a specified time period (typically 100 years). The GWP of  $N_2O$  is 310 kg equivalent  $CO_2$  and for  $CH_4$  it is 21. To model the GHGs of a WWTP it is therefore important to take the  $N_2O$  emissions into account. The GWP varies significantly, depending on the type of GHG. Therefore, a small quantity of GHG emitted with a high GWP has a greater effect on the atmosphere than a GHG with low GWP.

### 1.3. The Global Greenhouse Gas Emissions

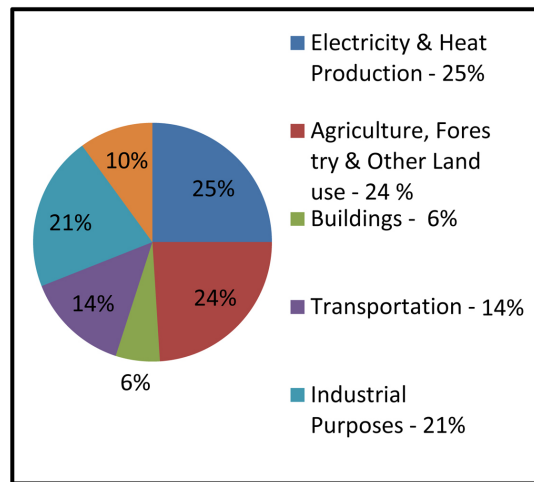
The IPCC has developed the concept of Global warming potential (GWP) for comparing the ability of each of the GHG to trap heat in the atmosphere relative to another gas. The GWP of a GHG is the ratio of heat trapped by one unit mass of the gas compared to one unit of  $CO_2$  over a time period of 100 years [4]. The key greenhouse gases emitted due to anthropogenic activities are  $CO_2$ ,  $CH_4$  and  $N_2O$ . As per IPCC (2014) based on global emissions from 2010, out of the total global GHG emissions,  $CO_2$  alone constitutes about 76% from fossil fuel, industries, forestry and land use. The  $CH_4$  constitute about 16%,  $N_2O$  constitute 6% and F-gases constitute about 2% as shown in **Figure 1**.

The global greenhouse gas emissions by economic sector various sectors as per IPCC 2014 based on global emissions from 2010 are indicated in **Figure 2**. Out of the total GHG emissions, 25% is from Electricity & heat production, 24% is from agriculture, forestry & other land use, 6% from buildings, 14% is from transportation, 21% from industrial process and 10% from other energy. Generally, the  $CO_2$  emission from biological wastewater treatment is not considered while accounting the GHG emissions since it is biogenic origin. Out of the total emissions of  $CH_4$  and  $N_2O$  from various sources about 18.1% is from waste disposal



**Figure 1.** Global greenhouse gas emissions by gas.

Source: IPCC (2014) based on global emissions from 2010.



**Figure 2.** Global GHG emissions by economic sector.

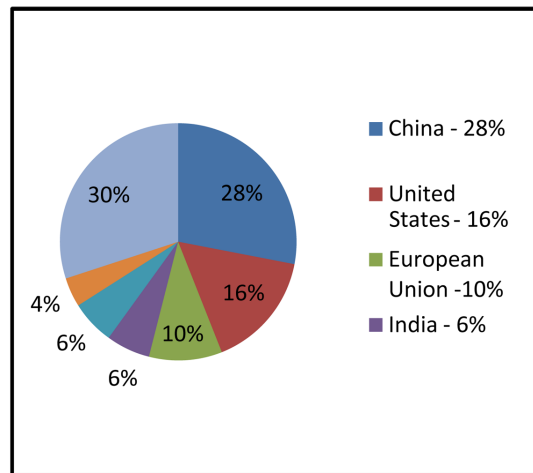
and treatment. Similarly, out of the total emissions of  $N_2O$ , 2.3% is from waste disposal and treatment.

#### 1.4. Trends in Global $CO_2$ Emissions: 2014 Report

Among the six largest  $CO_2$  emitting countries, remarkable trends were reported in the top 3  $CO_2$  emitting countries, which account for 55% of total global  $CO_2$  emissions in 2011 [5]. China is the largest  $CO_2$  emitting country, sharing about 28% of the total emissions of  $CO_2$  in 2011 which was much larger than the second-largest, the United States, with 16%, the European Union with 10%, India with 6%, The Russian Federation with 6% and Japan with 4% as shown in **Figure 3**. India is the fourth largest  $CO_2$  emissions country in 2011 with a  $CO_2$  emission of about 2.1 billion tonnes. The increase in emission level is partly because of increase in population and economy. The per capita  $CO_2$  emission of India is 1.7 tonnes of  $CO_2$ , which is much lower than those of most developed countries and China. The output of domestic wastewater in urban areas is influenced by multiple factors. The gross domestic product (GDP) is an important comprehensive indicator reflecting the economic development of a country. Economic development and improvement of people's living conditions promote an increase in domestic wastewater and COD discharge and removal. A study on the characteristic data and GDP data on domestic wastewater treatment showed that the quantity of domestic wastewater effluent grows annually with a stable GDP growth. The statistical calculation model for the quantity of domestic wastewater effluent showed a linear relationship with GDP. The relevant data of GDP and the characteristics of wastewater can be used to analyze the relationship between GDP and domestic wastewater discharge, and COD discharge and removal. The trends in share of national GDP and the  $CO_2$  emissions are shown in **Table 1**.

#### 1.5. Greenhouse Gas Emissions in India

Internationally, the Indian Government has voluntarily agreed to reduce the



**Figure 3.** National CO<sub>2</sub> emissions. Source: IPCC (2014) based on global emissions from 2010 and 2011.

**Table 1.** Trends in national GDP (%) and CO<sub>2</sub> emissions in during 2013.

Country	Shares of national GDP (%) on PPP basis	% CO <sub>2</sub> global emission	CO <sub>2</sub> emission in billion tonnes	Per capita CO <sub>2</sub> emissions in tonnes
China	15	29	10.3	7.40
USA	16	15	5.3	16.6
EU28	17	11	3.70	7.3
India	7	6	4.30	1.7
Russia	3	5	1.80	12.6
Japan	3	4	1.40	10.7

Source: Trends in global CO<sub>2</sub> emissions: 2014, PBL Netherlands Environmental Assessment Agency.

emissions intensity of its gross domestic product (GDP) by 20 - 25 percent from 2005 levels by 2020. Indian and international studies suggest that India is likely to meet or even exceed this pledge based on its existing policy package and macroeconomic trends. Nevertheless, significant uncertainty surrounds the effective implementation of these policies and changes in the GDP composition [6].

The emissions of GHG from wastewater are from domestic and disposal from the industries. The total CO<sub>2</sub> equivalent emissions from waste water generating sources in India in 2007 was 45 million tons, which is 82% of the total CO<sub>2</sub> equivalent emissions from the waste sector [7]. The total methane emitted in 2007 was 1.9 million tons and N<sub>2</sub>O emitted was 15.8 thousand tons as shown in **Table 2**.

In India, domestic wastewater has been categorized as urban high, urban low & rural, since the characteristics of the municipal wastewater vary from place to place depending on several factors such as economic status, food habits of the community, water supply status and climatic conditions of the area. In India, the wastewater treatment is provided only in Class I and II cities. Sewage contributes to 60% of the total pollution load in terms of biological oxygen demand which is beneficial if recovered through the anaerobic treatment process.

**Table 2.** GHG emission from waste water sector in India (Thousand tonnes).

Activity	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub> equivalent
Domestic	861	15.8	22,979
Industrial	1050	-	22,050
Total	1911	15.8	45,029

### 1.6. The GWP Values for the GHG

Determination of carbon footprints of Wastewater Treatment Plants (WWTPs) with respect to greenhouse gas emissions, energy usage, energy production, and carbon credits are gaining interest. For the estimation of GHG emissions in a WWTP, the inventory of all GHGs emitted has to be considered and the appropriate global warming potential (GWP) for each gas has to be determined. The Global Warming Potential (GWP) of a GHG is the ratio of heat trapped by one unit mass of the gas compared to one unit mass of CO<sub>2</sub> over a specified time period (typically 100 years). The GWP varies significantly based on the type of constituent GHG. A small quantity of gas emitted with a high GWP will have the same heat trapping potential as that of large quantity of gas emitted with low GWP [8].

The GWP varies significantly, depending on the type of gas. Therefore, a small quantity of gas emitted with a high GWP has a greater effect on the atmosphere than a gas with low GWP. For example one kilogram (kg) of N<sub>2</sub>O emitted will have the same heat trapping potential as 310 kg of CO<sub>2</sub>. The Global Warming Potential of GHGs produced in WWTPs as per IPCC, 2001, Research Triangle Institute, 2010 (USEPA) are shown in **Table 3**.

The emissions of GHG in WWTPs are associated with both on-site and off-site sources. The on-site sources of GHG emission include liquid and solid treatment processes as well as the combustion of fuels and biogas for energy generation. The off-site sources include the production and transmission of electricity, fuel and chemicals for off-site use, as well as solid waste transportation and disposal such as landfill, composting and degradation of remaining constituents in liquid effluent. The GHG emission by on-site and off-site processes in aerobic, anaerobic and hybrid system of biological wastewater treatment plants is shown in **Figure 4**.

**Table 3.** Global warming potential (GWP) of the GHGs.

GHGs	Chemical formula	Lifetime in years	Global warming potential for given time horizon (100 years)	
			IPCC 2006	RTI (USEPA) 2010
Carbon dioxide	CO <sub>2</sub>	100	1	1
Methane	CH <sub>4</sub>	12	23	21
Nitrous oxide	N <sub>2</sub> O	114	296	310

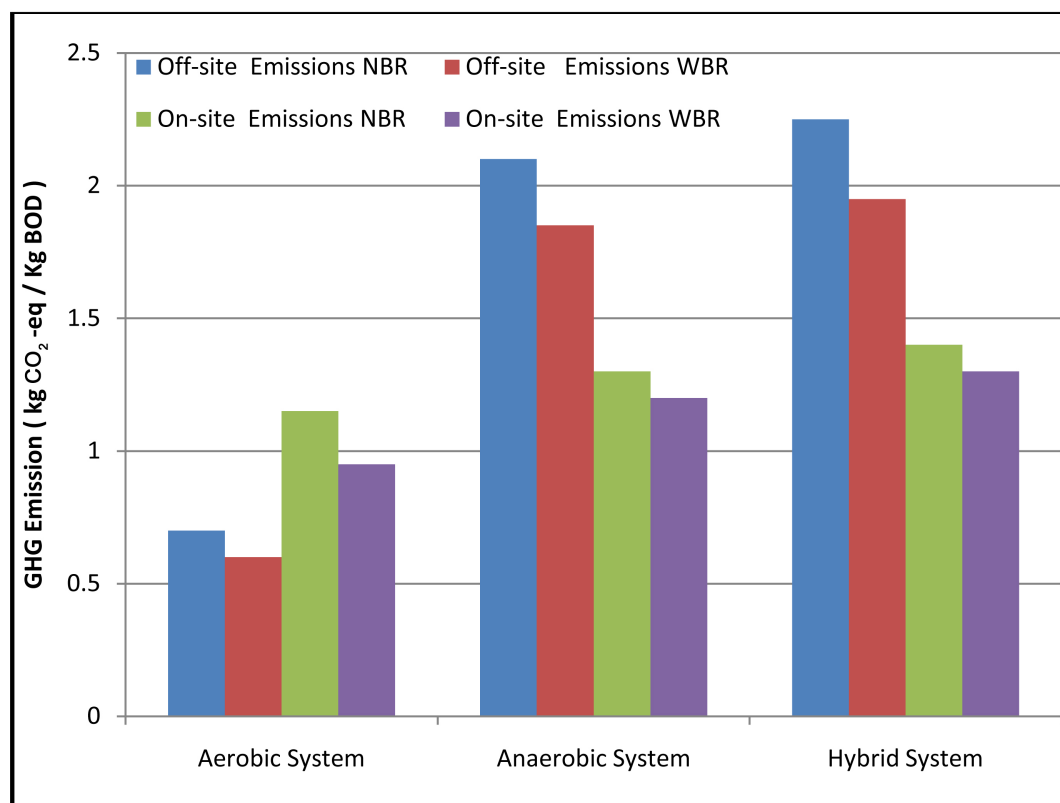
Source: RTI (USEPA)-Research Triangle Institutes International, United States Environmental Protection Agency.

### 1.7. Objective of the Study

The objective of this study is to examine the emission of the greenhouse gases and the global warming potential due to the treatment of wastewater in Puducherry, India and to assess the possible reduction potential of GHG emissions to obtain carbon credit.

### 2. Study Area and Present Scenario

Puducherry, the erstwhile French Colony is a coastal city, located at 11°58'12"N, 79°48'40"E and it is located at 162 km south of Chennai, India. The urban population of Puducherry as per 2011 census is 6.54 lakhs. Puducherry town has been provided with underground sewerage facilities partially as early as 1980 and the municipal wastewater has been treated with an oxidation pond of 2.9 MLD capacity at Karuvadikuppam, in the north western part of the Puducherry. Later on, three more oxidation ponds with treatment capacities of 2.9, 2.2, 4.8 MLD and two Upflow Anaerobic Sludge Blanket (UASB) reactors each having a capacity of 2.5 MLD were added. The installed capacity of all the existing STPs is 17.8 MLD. The BOD removal efficiency of the oxidation ponds and UASBs are about 60% only. Rapid urbanization and limitation of available space have necessitated adopting modern treatment methods. Accordingly, three Sequencing Batch Reactors (SBRs), each having a capacity of 17 MLD have been provided at



**Figure 4.** GHG emission by on-site and off-site processes in the biological wastewater treatment plants (NBR = no biogas recovery, WBR = with biogas recovery).

Source: Water Science & Technology 2013, 67.5, p. 1163.

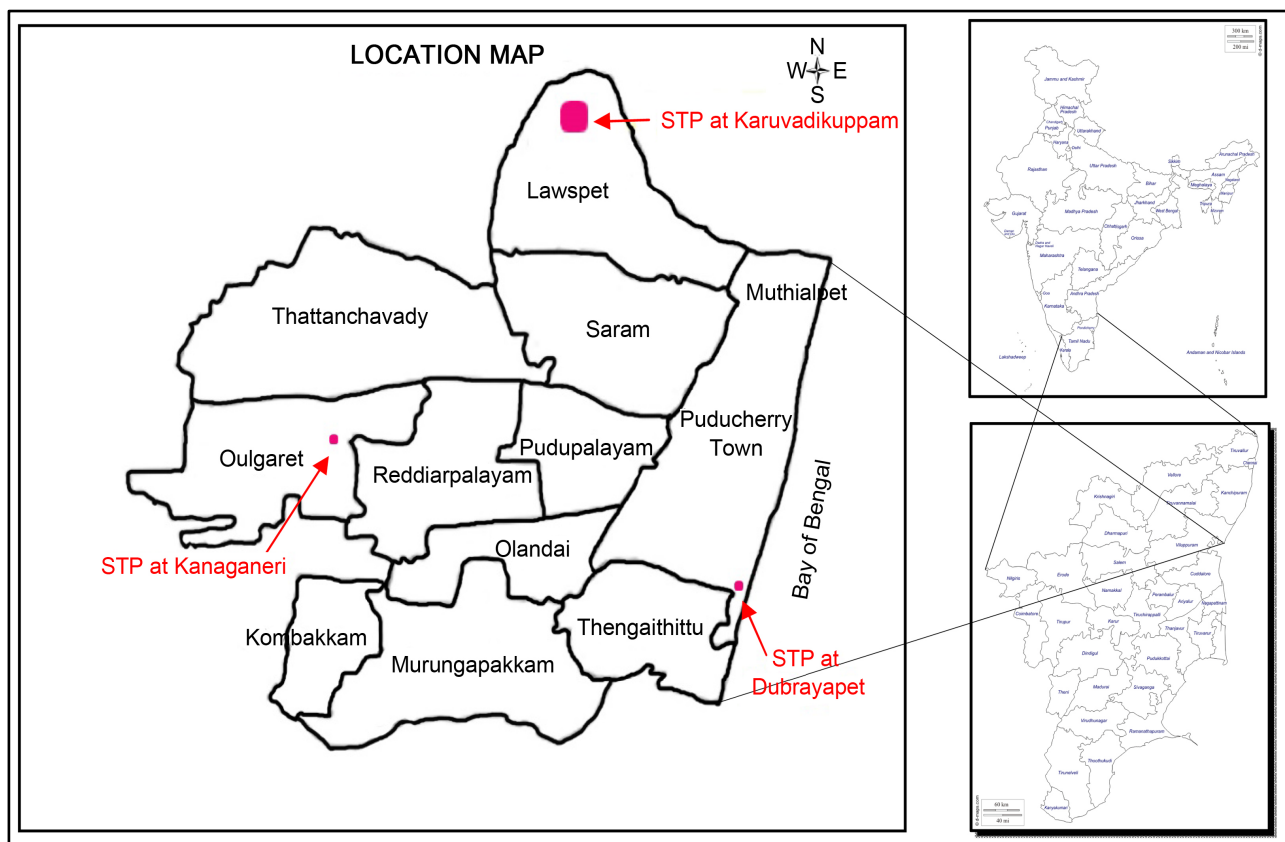
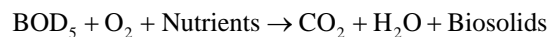
Karuvadikuppam, Dubrayapet and Kanakaneri. All these sewage treatment plants are small scale WWTPs with low carbon footprint. The sludge treatment and disposal not only concern environmental pollution problems, but also play a critical role in reducing the carbon footprint of the whole process. In other words, the energy content in organic matters in the wastewater is either converted to CO<sub>2</sub> (or CH<sub>4</sub>) or wasted as sludge through the biological process. The sludge from all these processes are treated by aerobic composting in sludge drying yard and the digested sludge are used for land application. The location of the study area and the STP sites is shown in **Figure 5**.

### 3. Methodology

#### 3.1. GHG Emissions

Both aerobic and anaerobic wastewater treatment processes remove BOD<sub>5</sub> and the bacteria in both processes also generate CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O [9]. The methodology used to estimate GHG emissions is based on the Intergovernmental Panel on Climate Change (IPCC, 1996) Revised Guidelines for National Greenhouse Gases Inventory and the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.

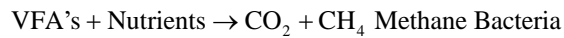
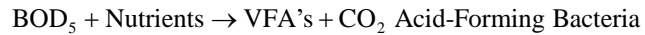
Aerobic:



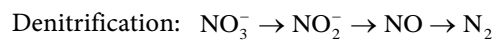
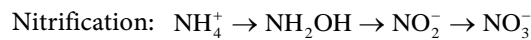
**Figure 5.** Location map of the study area.



The anaerobic process is actually performed by heterotrophic bacteria in a 2-step process as follows:



During aerobic treatment, ammonia ( $\text{NH}_4^+$ ) or organic nitrogen is biologically oxidized to nitrites ( $\text{NO}_2^-$ ) and nitrates ( $\text{NO}_3^-$ ) by autotrophic bacteria through a process called nitrification.  $\text{NO}_2^-$  and  $\text{NO}_3^-$  can then be converted to nitrogen gas ( $\text{N}_2$ ) under anoxic conditions (*i.e.*, where dissolved oxygen is absent) by heterotrophic bacteria through a process called denitrification.  $\text{N}_2\text{O}$  is a by-product of the nitrification process and an intermediate product of the denitrification process.



### 3.1.1. Aerobic Treatment

The aerobic treatment is the process in which the complex organic matter present in the wastewater is synthesized by the aerobic bacteria and converted into  $\text{CO}_2$ . In aerobic treatment aeration is carried out either by diffused or submerged aerators in order to maintain adequate quantity of microorganism to oxidize the organic matters. Equalization, biochemical reactions and flocculation take place during aeration. The mixed liquor suspended solids shall be controlled to have sufficient concentration of aerobic bacteria or biomass. The aerated and well mixed liquor is subjected for sedimentation in the settling tank or clarifier. The excess sludge is removed from the setting tank. The activated sludge process is one of the most commonly used biological wastewater treatment system for treatment of both municipal and industrial wastewater. Sequencing batch Reactor system is known to be the pioneer of all activated sludge system and the SBR system operates in time rather than in space [10]-[15].

### 3.1.2. Anaerobic Treatment

The organic matters are metabolized by methanogenic bacteria and synthesized in to new biomass or converted to  $\text{CO}_2$  or  $\text{CH}_4$  under anaerobic environment. Even though the growth of anaerobic bacteria is slower than the aerobic bacteria, the degradation of certain types of wastes by the anaerobic bacteria is more rapid than by the aerobic bacteria. During anaerobic digestion the acid- and  $\text{CH}_4$ -forming (methanogenic) bacteria convert organic matter into a biogas consisting of approximately 60% - 70%  $\text{CH}_4$ , 30% - 40%  $\text{CO}_2$ , and trace amounts of  $\text{N}_2$ , hydrogen ( $\text{H}_2$ ), hydrogen sulphide ( $\text{H}_2\text{S}$ ), and  $\text{O}_2$  [2]. The Upflow Anaerobic Sludge Blanket (UASB) is one of the efficient anaerobic treatment processes for treating both domestic and industrial wastewater.

Anaerobic wastewater treatment system is a more advantageous than the aerobic processes because of its low energy consumption and sludge production [16]. When methane is used as an energy source, GHGs emissions in anaerobic treatment are lower than that of the aerobic technologies and this process has

the advantages of energy saving, biogas recovery and lower sludge production. Earlier it was viewed that anaerobic process was suitable for high-strength, high temperature wastewaters only, and that it required rigorous pH control and protection from toxic shocks. But recent researches have shown that anaerobic processes could also be applied to low strength wastewaters at low temperatures successfully.

### **3.1.3. Oxidation Ponds**

Oxidation ponds or lagoons may be aerobic (shallow), anaerobic (deep) or facultative (medium depth) depending on the depth of the lagoons. In facultative lagoons aerobic condition will prevail due to aeration by the wind action and at the bottom of the lagoon anaerobic condition will prevail. Within the lagoon the generation of biomass occurs and accumulates at the bottom of the lagoon which is always in anaerobic condition. The  $\text{CH}_4$  is generated at the bottom of the lagoon and it travels upwards through the aerobic zone near the surface it is oxidized. The oxidation ponds are of different categories namely, aerobic, facultative and anaerobic ponds. In Puducherry there are four oxidation ponds having an area of 52,392 Sqm and an average depth of 1.2 m and the capacity of all the 4 oxidation ponds is 12.5 Mld. The average BOD removal efficiency in the oxidation ponds is from 50% to 60%. The emission of Greenhouse gases from the Oxidation ponds include  $\text{CO}_2$  and  $\text{CH}_4$  as the top surface of the oxidation pond is in aerobic zone and the bottom of the pond is in anaerobic zone. The stabilization ponds typically emit 85  $\text{g/m}^2$  day of  $\text{CO}_2$  and 86  $\text{g/m}^2$  day of  $\text{CH}_4$ , with nitrous oxide levels significantly lower [17] [18].

### **3.1.4. Upflow Anaerobic Sludge Blanket (UASB)**

In an UASB reactor approximately 60% - 65% of the influent COD is converted to  $\text{CH}_4$ , depending on the temperature and the characteristics of the sewage. The advantages of conversion of COD to  $\text{CH}_4$  are the reduction of the oxygen demand in the aerobic post-treatment unit and the  $\text{CH}_4$  can be utilized for the generation of heat and electricity. Though the UASB reactor has the advantage of having energy self-sufficient sewage treatment plant (STP) about (20% - 40%) of the  $\text{CH}_4$  produced in UASB reactors remains dissolved in the effluent. In most of the USABs the  $\text{CH}_4$  is emitted into the atmosphere instead of recovery and this leads to the reduction of the potential energy generation from the utilization of the produced biogas and emission of potent greenhouse gas (GHG) in to atmosphere [19]. The uncontrolled greenhouse gas emissions shall be avoided and non-flaring of captured  $\text{CH}_4$  shall be prohibited. If instead, all the energy is used, with the increasing energy prices and tradable  $\text{CO}_2$  credits, anaerobic sewage treatment will become an affordable investment for many developing countries.

### **3.1.5. Sequencing Batch Reactor (SBR)**

The sequencing batch reactor technology is one of the most commonly used biological wastewater treatment processes at both municipal and industrial wastewater treatment plants. Even though there are many variations of activated sludge biological wastewater treatment processes, all the reactions take place in

the same reactor and the reactor serves as aeration and sedimentation tank [20]. In SBR, primary sedimentation, biodegradation and biomass separation take place within a single reactor. SBR is a time-oriented technology instead of space-oriented, which can be operated with great flexibility. Ease of operation of SBR could be realized by controlling bacterial species which cause filamentous bulking, remove nutrient or hazardous organics.

### 3.1.6. Greenhouse Gases (GHG)

**Carbon dioxide (CO<sub>2</sub>):** The main source of CO<sub>2</sub> in wastewater is from treatment process and electricity consumption. During aerobic process in activated sludge process, the emission of CO<sub>2</sub> is from the breakdown of organic matter in the aeration tank. During anaerobic process the organic matter is converted into biomass and again into CO<sub>2</sub> and CH<sub>4</sub> through endogenous respiration. The other source of CO<sub>2</sub> is from sludge digestion and combustion of digester combustion gas [21].

**Methane (CH<sub>4</sub>):** The main source of CH<sub>4</sub> is during the anaerobic treatment of wastewater as well as from its sludge. The extent of emission of CH<sub>4</sub> depends on the quantity of degradable organic material in the wastewater, the temperature, and the type of treatment system. The rate of CH<sub>4</sub> emission increases with the increase in temperature. When the temperature is below 15°C the methanogens are not active and there is almost no production of CH<sub>4</sub>.

The Total CH<sub>4</sub> emissions from domestic wastewater can be calculated as follows:

$$\text{CH}_4\text{Emission} = (\text{BOD}_i \times \text{EF}) - \text{R}$$

where,

BOD<sub>i</sub> is the total organic content in domestic wastewater in the calculation year (TPY);

EF is the emission factor (kg CH<sub>4</sub> (kg BOD));

R is the amount of recycled CH<sub>4</sub> in the calculation year (CH<sub>4</sub>).

$$\text{EF} = \text{Bo} \times \text{M}$$

where,

Bo, is the maximum CH<sub>4</sub> generation capacity.

M is the CH<sub>4</sub> correction for domestic wastewater.

**Nitrous Oxide (N<sub>2</sub>O):** The main source of N<sub>2</sub>O is from the degradation of nitrogen components in the wastewater. Direct emissions of N<sub>2</sub>O may be generated during both nitrification and denitrification process. Nitrification is an aerobic process during which the ammonia and other nitrogen compounds are converted into nitrates (NO<sub>3</sub>) and. Denitrification is the process which occurs under anoxic conditions in which the nitrate is converted into nitrites NO<sub>2</sub> and again into nitrogen gas N<sub>2</sub>. Both processes can occur in the plant and in the water body that is receiving the effluent [21].

## 3.2. Estimation of GHG Emissions from Wastewater and Sludge Treatment Units

The Research Triangle Institute International (RTI) has submitted a report to

the U.S. Environmental Protection Agency, in which the method of estimating CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions from biological wastewater treatment systems based on IPCC has been recommended. The equations provide a general means of estimating the CO<sub>2</sub> and CH<sub>4</sub> emissions directly from any type of wastewater treatment process assuming all organic carbon removed from the wastewater is converted to either CO<sub>2</sub>, CH<sub>4</sub> or new biomass. There are different methods to quantify the life cycle greenhouse gases emissions. However the method adopted in this study is as per report of RTI International, submitted to the USEPA based on IPCC.

### 3.2.1. Estimation of CH<sub>4</sub> and CO<sub>2</sub> Emissions from Wastewater

In wastewater treatment process all organic carbon removed from the wastewater is converted to CO<sub>2</sub>, CH<sub>4</sub>, or new biomass. Aerobic wastewater treatment systems produce primarily CO<sub>2</sub> during the process of wastewater treatment, whereas in anaerobic systems a mixture of CH<sub>4</sub> and CO<sub>2</sub> is produced. The estimation of direct emission of CO<sub>2</sub> and CH<sub>4</sub> can be done by the following equations [2].

$$\text{CO}_2 = 10^{-6} \times Q_{\text{ww}} \times \text{OD} \times \text{Eff}_{\text{OD}} \times \text{CF}_{\text{CO}_2} \times \left[ (1 - \text{MCF}_{\text{ww}} \times \text{BG}_{\text{CH}_4}) (1 - \lambda) \right] \quad (3.1)$$

$$\text{CH}_4 = 10^{-6} \times Q_{\text{ww}} \times \text{OD} \times \text{Eff}_{\text{OD}} \times \text{CF}_{\text{CH}_4} \times \left[ (\text{MCF}_{\text{ww}} \times \text{BG}_{\text{CH}_4}) (1 - \lambda) \right] \quad (3.2)$$

The biomass yield  $\lambda$  can be determined from the following equation and when the biomass generation rate cannot be assessed, default values for the biomass yield provided in **Table 4** and **Table 5** can also be used.

$$\lambda = \frac{Q_{\text{s}} * \text{MLVSSs} * \text{CF}_{\text{s}}}{Q_{\text{ww}} * \text{OD} * \text{Eff}_{\text{od}} * \text{CF}_{\text{c}}} \quad (3.3)$$

### 3.2.2. Estimation of CH<sub>4</sub> and CO<sub>2</sub> Emissions from Sludge

1) When the sludge is digested on-site, then there will be additional CO<sub>2</sub> and CH<sub>4</sub> and this is applicable for all sludge digesters. The estimation of GHG can be done by the following equations, when:

- a) The sludge digester is the only biological treatment process at the facility.
- b) Additional waste streams are fed to the sludge digester.
- c) Other physical/chemical treatment process are conducted on the sludge prior to the digester that alter the mass of carbon entering the digester.

$$\text{CO}_2 = 10^{-6} \times Q_{\text{s}} \times \text{MLVSS} \times \text{CF}_{\text{s}} \times \left( \frac{44}{12} \right) \times (1 - \text{MCF}_{\text{s}} \times \text{BG}_{\text{CH}_4}) \quad (3.4)$$

$$\text{CH}_4 = 10^{-6} \times Q_{\text{s}} \times \text{MLVSS} \times \text{CF}_{\text{s}} \times \left( \frac{16}{12} \right) \times (1 - \text{MCF}_{\text{s}} \times \text{BG}_{\text{CH}_4}) \quad (3.5)$$

2) For most sludge digesters, the only solids entering the unit are those generated in the wastewater treatment system and for these cases, the following equations can be used to determine the sludge digester's emissions based on the feed to the wastewater treatment process.

$$\text{CO}_2 = 10^{-6} \times Q_{\text{ww}} \times \text{OD} \times \text{Eff}_{\text{OD}} \times \text{CF}_{\text{CO}_2} \times \left[ \lambda (1 - \text{MCF}_{\text{s}} \times \text{BG}_{\text{CH}_4}) \right] \quad (3.6)$$

$$\text{CH}_4 = 10^{-6} \times \text{Qww} \times \text{OD} \times \text{Eff}_{\text{OD}} \times \text{CF}_{\text{CH}_4} \times \left[ \lambda \left( \text{MCFs} \times \text{BG}_{\text{CH}_4} \right) \right] \quad (3.7)$$

where,

$\text{CO}_2$  =  $\text{CO}_2$  emission rate (Mg  $\text{CO}_2$ /hr);

$\text{CH}_4$  =  $\text{CH}_4$  emission rate (Mg  $\text{CH}_4$ /hr);

Qww = Wastewater influent flow rate ( $\text{m}^3$ /hr);

OD = Oxygen demand of influent wastewater to the biological treatment unit determined as either;  $\text{BOD}_5$  or COD ( $\text{mg/L} = \text{g/m}^3$ );

$\text{Eff}_{\text{OD}}$  = Oxygen demand removal efficiency of the biological treatment unit;

$\text{CF}_{\text{CO}_2}$  = Conversion factor for maximum  $\text{CO}_2$  generation per unit of oxygen demand;

$\text{CF}_{\text{CH}_4}$  = Conversion factor for maximum  $\text{CH}_4$  generation per unit of oxygen demand;

$\text{MCF}_{\text{WW}}$  = methane correction factor for wastewater treatment unit;

$\text{BG}_{\text{CH}_4}$  = Fraction of carbon as  $\text{CH}_4$  in generated biogas (default is 0.65);

$Q_s$  = Waste sludge stream flow rate ( $\text{m}^3$ /hr);

Qww = Wastewater influent flow rate ( $\text{m}^3$ /hr);

MLVSSs = Mixed liquor volatile suspended solids concentration of the waste sludge stream ( $\text{mg/L}$ );

$\lambda$  = Biomass yield (g C converted to biomass/g C consumed in the wastewater treatment process).

### 3.2.3. Estimation of $\text{N}_2\text{O}$ Emissions

The amount of nitrogen present in the influent wastewater will determine the  $\text{N}_2\text{O}$  generation potential. The treatment process will also affect the magnitude of the  $\text{N}_2\text{O}$  emissions.  $\text{N}_2\text{O}$  emissions for both aerobic and anaerobic processes using an average value for the percent of influent TKN emitted as  $\text{N}_2\text{O}$ .

**Table 4.** Default values for methane correction factor (MCF) and biomass yield ( $\lambda$ ).

Treatment system	MCF	$\lambda$
<b>Wastewater treatment processes</b>		
Aerated treatment process (activated sludge system), well managed	0	0.65
Aerated treatment process, overloaded (anoxic areas)	0.3	0.45
Anaerobic treatment process (anaerobic reactor)	0.8	0.1
Facultative lagoon, shallow (<2 m deep)	0.2	0
Facultative lagoon, shallow (>2 m deep)	0.8	0
<b>Sludge treatment</b>		
Aerobic sludge digestion	0	$\lambda$ from wastewater treatment process
Anaerobic sludge digestion	0.8	

Source: IPCC (2006).

**Table 5.** Correction factors for different measurement method.

Correction factor term	Correction factor (CF) for designated measurement method	
	BOD5 or COD	TOC as methane
CF <sub>CO<sub>2</sub></sub>	1.375	3.667
CF <sub>CH<sub>4</sub></sub>	0.5	1.333
CFs	0.53	0.53
CFc	0.375	1

Source: IPCC (2006).

$$N_2O_{\text{wwtp}} = Q_i \times \text{TKN} \times \text{EF}_{N_2O} \times \left(\frac{44}{28}\right) \times 10^{-6} \quad (3.8)$$

where,

$N_2O_{\text{WWTP}}$  =  $N_2O$  emissions generated from WWTP process (Mg  $N_2O$ /hr);

$Q_i$  = Wastewater influent flow rate ( $m^3$ /hr);

$\text{TKN}_i$  = Amount of TKN in the influent (mg/L = g/ $m^3$ );

$\text{EF}_{N_2O}$  =  $N_2O$  emission factor (g N emitted as  $N_2O$  per g TKN in influent),  
= 0.0050 g N emitted as  $N_2O$ /g TKN [22].

Source: Research Triangle Institute report to USEPA.

### 3.3. Emissions of GHG from Industries

In respect of emissions of an industrial plant there Scopes have been defined by the United Nations. As per the GHG Protocol Initiative 2004, the Scope 1 is the direct GHG emissions which includes GHG emissions that occur from the own sources of the company. The Scope 2 includes the emissions that occur from the use of electricity and the generation of purchased electricity bought and consumed and the emissions from Scope 1. Due to the use of electricity of the plant the emissions during the production of electricity are to be included to the emissions of the plant. Scope 3 includes the emissions from Scopes 1 and 2 and the emissions that occur during the production of the chemicals that are used in the plants [8].

To estimate the GHG emissions of the wastewater treatment plants (WWTP) in a comparable way the considered emissions have to be listed. The selected boundaries are from Scope 3 and are listed below (Bridle Consulting, 2007):

- 1)  $CO_2$  and  $N_2O$  emissions at biotreatment, endogenous respiration, BOD oxidation nitrification  $CO_2$  credit and nitrogen removal;
- 2) Energy use of plant, for aeration, mixing and pumping which leads to  $CO_2$  emissions;
- 3) Sludge digestion, biogas  $CH_4$  and  $CO_2$ ;
- 4) Sludge disposal, truck emissions trip to reuse/disposal site,  $CO_2$  emissions mineralization;
- 5) Power credit by use of biogas;
- 6) GHG emissions from chemical use.

### 3.4. Treatment and Discharge Systems and CH<sub>4</sub> and N<sub>2</sub>O Generation Potential

The treatment systems that provide anaerobic environments will generally produce CH<sub>4</sub> whereas systems that provide aerobic environments will normally produce little or no CH<sub>4</sub> [1]. In lagoons without mixing or aeration, their depth is a critical factor in CH<sub>4</sub> production. Shallow lagoons, less than 1 meter in depth, generally provide aerobic conditions and little or no CH<sub>4</sub> is likely to be produced. Lagoons deeper than about 2 - 3 meters will generally provide anaerobic environments and significant CH<sub>4</sub> production can be expected.

#### Maximum CH<sub>4</sub> Producing Capacity for Domestic Wastewater

The potential of CH<sub>4</sub> that could be generated from the domestic wastewater can be determined based on BOD or COD as recommended by the Intergovernmental Panel on Climate Change (IPCC). The annual methane emissions from domestic wastewater can be expressed as (IPCC, 2002): [1].

$$\text{CH}_4 \text{Emissions} = \left\{ \sum_i^j (U_i * T_{ij} * EF_j) \right\} (TOW - S) - R$$

where:

CH<sub>4</sub> Emissions = CH<sub>4</sub> emissions in inventory year, kg CH<sub>4</sub>/yr;

TOW = total organics in wastewater in inventory year, kg BOD/yr;

S = organic component removed as sludge in inventory year, kg BOD/yr;

U<sub>i</sub> = fraction of population in income group i in inventory year;

T<sub>i,j</sub> = degree of utilization of treatment/discharge pathway or system, j, for each income group fractioning inventory year;

i = income group: rural, urban high income and urban low income;

j = each treatment/discharge pathway or system;

EF<sub>j</sub> = emission factor, kg CH<sub>4</sub>/kg BOD;

R = amount of CH<sub>4</sub> recovered in inventory year, kg CH<sub>4</sub>/yr.

The emission factor is a function of the maximum CH<sub>4</sub> producing potential (Bo) and the methane correction factor (MCF).

$$EF_i = B_o \times MCF_i,$$

where,

EF<sub>j</sub> = emission factor, kg CH<sub>4</sub>/kg BOD;

j = each treatment/discharge pathway or system;

B<sub>o</sub> = maximum CH<sub>4</sub> producing capacity, kg CH<sub>4</sub>/kg BOD;

MCF<sub>j</sub> = methane correction factor (fraction).

Generally, the country specific data may be used to determine the emission factor. In the case of non-availability of country specific data, default values may also be used. Accordingly, default maximum CH<sub>4</sub> producing capacity for domestic wastewater can be determined [23].

The maximum CH<sub>4</sub> producing capacity for domestic wastewater

= 0.60 kg CH<sub>4</sub>/kg BOD;

= 0.25 kg CH<sub>4</sub>/kg COD.

### 3.5. Control Measures for Reduction of GHG

#### 3.5.1. GHG Emissions and Reduction Strategies

In order to control the emission of GHG in domestic wastewater the  $\text{CH}_4$  may be recycled and reused during the process. In anaerobic treatment system, the  $\text{CH}_4$  may be recycled to replace the wastewater or sludge oxidation treatment system. The COD discharge is the oxygen required for the chemical oxidant to oxidize the organic pollutants in the water. Generally the amount of  $\text{CH}_4$  generated from treated wastewater with high COD or BOD concentration is more than that generated from that with lower concentrations. COD/N ratio in the reactor seems to have an effect on  $\text{N}_2\text{O}$  emission. During denitrification, in the activated sludge process a relatively low COD/N ratio is the main parameter leading to  $\text{N}_2\text{O}$  production. The  $\text{N}_2\text{O}$  increase with the decrease of  $\text{NH}_3$  and thus during aerobic digestion the nitrification plays an important role in  $\text{N}_2\text{O}$  emissions [24].

Research with the objective of reducing the GHGs emissions in the wastewater and waste treatment and disposal field was a hot topic in line with the commencement of Kyoto Protocol in 2008 until 2012. The reduced GHGs emission either from the wastewater treatment process improvement or effluent and biomass recycling will generate Certified Emission Reduction (CER) for sale or export. Generally, measurements intended to reduce GHGs emissions in the wastewater treatment section could be achieved through the following aspects.

#### 3.5.2. Proper Wastewater Treatment

The emission of GHG depends on the selection of wastewater treatment process based on the wastewater composition, organic loading rate, and the anticipated effluent quality. Normally anaerobic wastewater treatment processes are preferred as they could reduce GHGs emission by energy recycling in the form of  $\text{CH}_4$ . A study showed that the anaerobic wastewater treatments are applicable when level of the biochemical oxygen demand (BOD) concentrations of the wastewater is more than 300 mg/L [25] [26]. In a particular situation, various anaerobic treatment processes have different GHGs reduction potential. During the treatment of low strength wastewater the  $\text{CH}_4$  may be dissolved in the effluent leading to significant loss of  $\text{CH}_4$ . The  $\text{CO}_2$  and  $\text{CH}_4$  generated due to improper wastewater treatment reduced the possibility of carbon sequestration and energy recovery [27] [28] and the GHG emissions can be reduced by the regulation and control of process and operational parameters such as oxidation reduction potential, DO and COD/N ratio.

#### 3.5.3. Control of Wastewater Treatment Plants

Performance of control strategies with adjusted flow of different combinations of  $Q_w$  values can enable a reduction of GHG emissions. The predominant source of reduction in operating costs is the reduction of sludge produced for disposal, not reduction in pumping costs. The energy cost actually increase due to increased aeration requirements to maintain the desired level. But the reduction of GHG emissions due to the reduction in energy required for pumping is negligible. A high SRT increases direct non- $\text{N}_2\text{O}$  emissions from the bioreactor



and indirect emissions resulting from electricity use [16].

DO control strategy offers superior performance with regard to GHG emissions, operational costs and effluent quality. Increasing the SRT, can result in reduction of emission and cost but direct non-N<sub>2</sub>O emissions are increased. Developing control strategies to provide the greatest possible energy recovery may not always be preferable with regard to reducing GHG emissions and operational costs, since the effects of reduced energy recovery can be offset by the reduction in cost and emissions associated with sludge disposal, and a greater effluent quality may be achieved.

#### **3.5.4. Recycling of Treated Wastewater and Excess Sludge**

The reduction in the total emission of CH<sub>4</sub> could be achieved by the biogas reuse. The CH<sub>4</sub> can also be used as a source of renewable energy for the generation of electricity. It may be utilized as raw material to produce organic acids or biodegradable plastic. Further the aerobically treated sludge could be used as manure or organic fertilizer and for soil reclamation.

#### **3.5.5. Systematic Strategies for the Future Wastewater Treatment**

The cost-effective and energy-saving technology with low solid waste and GHGs emission shall be preferred. The excess sludge is rich in carbon, nitrogen and phosphorus, and micronutrients which could be used as raw material for industrial production. The excess sludge could be reduced for further treatment by recycling, for reducing the emission of GHG and for cost reduction. The goal intended to reduce the GHGs emissions from wastewater and excess sludge disposal could be achieved through the proper treatment of wastewater, choices for rational wastewater treatment process and recycling of treated wastewater and excess sludge.

### **3.6. Sample Collection and Testing**

The samples of both the influent and effluent were collected at regular interval and were tested as per the standard testing methods. The physiochemical and biological parameters like pH, temperature, TDS, TSS, BOD, COD, N as NO<sub>3</sub> and P as PO<sub>4</sub> were tested for both the influent and effluent. However in this study the average values of the influent and effluent BOD from the SBR, oxidation pond and UASB were adopted for the estimation of the emissions of GHG. Similarly, samples were collected from the SBR and tested for the BOD, MLVSS, TKN and other parameters to study the variation of the biomass yield coefficient in the estimation of GHG emissions.

## **4. Results and Discussion**

In this study, the emissions of GHG in Puducherry from the oxidation ponds of 12.5 Mld, UASB of 2.5 Mld (2 Nos) and one SBR of 17 Mld were determined. Only the on-site sources for the emissions were considered in this study. The emissions of GHGs in wastewater and sludge in SBR, UASB and Oxidation ponds in Puducherry were determined based on the IPCC guidelines.

### Estimation of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from the SBR, UASB and Oxidation Ponds

The estimation of CO<sub>2</sub> in the aerobic treatment of wastewater in SBR was calculated using the Equation (3.1). There is no emission of CH<sub>4</sub> during aerobic process. The emissions of CO<sub>2</sub> and CH<sub>4</sub> during on site sludge digestion in the sludge drying bed due to the sludge digester's emissions based on the feed to the wastewater treatment process by using the Equations (3.6) and (3.7) and the same is designated as SBR (A1). Similarly the emissions of CO<sub>2</sub> and CH<sub>4</sub> during on site sludge digestion were calculated based on the MLVSS and the volume of the sludge wasted by considering the Equations (3.4) and (3.5), since chemical treatment process are carried out on the sludge prior to the digester that alter the mass of carbon entering the digester and the same is designated as SBR (A2). The emission of N<sub>2</sub>O from the sludge digestion was also calculated using the Equation (3.8).

The emissions of CO<sub>2</sub> and CH<sub>4</sub> during the anaerobic treatment of wastewater in the UASB and additional emissions of CO<sub>2</sub> and CH<sub>4</sub> during on site sludge digestion in the sludge drying bed were calculated. In the case of oxidation ponds the emissions of CO<sub>2</sub> and CH<sub>4</sub> from the aerobic zone and the additional emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from the sludge digestion in the anaerobic zone were calculated and the details of estimation of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O. The estimation of GHG in UASB, Oxidation Ponds and SBR (A1) are shown in **Table 6**.

The emissions of CO<sub>2</sub> and CH<sub>4</sub> in SBR are influenced by the biomass yield coefficient  $\lambda$  and the efficiency of the BOD removal. The biomass yield coefficient is the ratio of the g C converted to biomass to the g C consumed in the wastewater treatment process. It is influenced by the volume of the sludge and the mixed liquor volatile suspended solids (MLVSS) concentration of the waste sludge stream (mg/L). The variation of CO<sub>2</sub> emission from the wastewater is shown in **Figure 6** and the variation of CO<sub>2</sub> from the sludge is shown in **Figure 7**.

The emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O for different values of biomass yield coefficient ( $\lambda$ ) were calculated as given in **Table 7**. The variation of biomass yield coefficient and the emissions CO<sub>2</sub> from wastewater (CO<sub>2</sub>-WW) and CO<sub>2</sub> (CO<sub>2</sub>-Sludge), CH<sub>4</sub> (CH<sub>4</sub>-Equ CO<sub>2</sub>), N<sub>2</sub>O (N<sub>2</sub>O-Equ CO<sub>2</sub>) and total equivalent CO<sub>2</sub> from sludge in terms of equivalent CO<sub>2</sub> are shown in **Figure 8**. It may be seen that as the biomass yield coefficient increases the emission of CO<sub>2</sub> from wastewater decreases. But the total equivalent CO<sub>2</sub>, CO<sub>2</sub> from sludge, CH<sub>4</sub>-Equ CO<sub>2</sub>, and N<sub>2</sub>O-Equ CO<sub>2</sub> increase as the biomass yield coefficient increases.

The total emissions of CO<sub>2</sub> and equivalent CO<sub>2</sub> of CH<sub>4</sub> and N<sub>2</sub>O for the biomass yield coefficients of 0.1 to 0.65 are shown in **Figure 9**.

The emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from various treatment plants and the equivalent CO<sub>2</sub> of GHG and the total equivalent CO<sub>2</sub> are shown in **Table 8**. The total emissions of equivalent CO<sub>2</sub> from the UASB and Oxidation ponds are 9532 tons per year, whereas the total emissions of equivalent CO<sub>2</sub> from the SBR is 7649 tons per year, which is only 80% of the total CO<sub>2</sub> emissions. However,

**Table 6.** Estimation of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from UASB, oxidation ponds and SBR.

Emission of greenhouse gases from wastewater and sludge		UASB 2.5 MLD			Oxidation ponds 12.5 MLD			SBR 17 MLD (A1)		
		CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O
<b>Emission of CO<sub>2</sub> &amp; CH<sub>4</sub> &amp; from wastewater</b>		Mg/day	Mg/day	Mg/day	Mg/day	Mg/day	Mg/day	Mg/day	Mg/day	Mg/day
3.1	$CO_2 = 10^{-6} \times Q_{ww} \times OD \times Eff_{od} \times CF_{CO_2} \times [(1 - MCF_{ww} \times BG_{CH_4})(1 - \lambda)]$	0.01300			0.1122			0.092		
3.2	$CH_4 = 10^{-6} \times Q_{ww} \times OD \times Eff_{od} \times CF_{CH_4} \times [(MCF_{ww} \times BG_{CH_4})(1 - \lambda)]$		0.0051		0.0061			0.00		
3.3	$\lambda = (Q_s \times MLVSS_s \times CF_s) / (Q_{ww} \times OD \times Eff_{od} \times CF_c)$									
<b>Emission of CO<sub>2</sub> &amp; CH<sub>4</sub> &amp; from sludge</b>										
3.4	$CO_2 = 10^{-6} \times Q_s \times MLVSS_s \times CF_s \times (44/12) \times (1 - MCF_s \times BG_{CH_4})$									
3.5	$CH_4 = 10^{-6} \times Q_s \times MLVSS_s \times CF_s \times (16/12) \times (1 - MCF_s \times BG_{CH_4})$									
3.6	$CO_2 = 10^{-6} \times Q_{ww} \times OD \times Eff_{od} \times CF_{CO_2} \times [\lambda (1 - MCF_s \times BG_{CH_4})]$	0.0074			0.0371			0.0729		
3.7	$CH_4 = 10^{-6} \times Q_{ww} \times OD \times Eff_{od} \times CF_{CH_4} \times [\lambda (MCF_s \times BG_{CH_4})]$		0.0029		0.0146			0.0287		
3.8	$N_2O_{wmp} = 10^{-6} \times Q_{ww} \times TKN \times EF_{N_2O} \times (44/28)$			0.00001			0.00006			0.00008
	CHG Mg per Hr	0.0204	0.0080	0.00001	0.1493	0.0207	0.00006	0.1649	0.0287	0.00008
	Equivalent CO <sub>2</sub> Mg per Hr	0.0204	0.1686	0.0038	0.1493	0.4352	0.0190	0.1649	0.6030	0.0259
	Total equivalent CO <sub>2</sub> Mg/day			4.628			14.486			19.051
	Total equivalent CO <sub>2</sub> Tonnes per year (Tpy)			1858			5816			7649
	Equivalent CO <sub>2</sub> per kg BOD			6.17			3.86			3.74
	Equivalent CO <sub>2</sub> per MLD Mg/MLD			1.85			1.16			1.12

**Table 7.** Emissions of GHG for various biomass yield coefficient.

GHG emissions Mg/hr	Biomass yield coefficient ( $\lambda$ )							
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.65
CO <sub>2</sub> -wastewater	0.0814	0.0733	0.0652	0.0570	0.0489	0.0407	0.0326	0.0285
CO <sub>2</sub> -sludge	0.0000	0.0081	0.0163	0.0244	0.0326	0.0407	0.0489	0.0529
CH <sub>4</sub> -equivalent CO <sub>2</sub>	0.0000	0.0323	0.0647	0.0970	0.1294	0.1617	0.1940	0.2102
N <sub>2</sub> O equivalent CO <sub>2</sub>	0.0133	0.0133	0.0133	0.0133	0.0133	0.0133	0.0133	0.0133
Total equivalent CO <sub>2</sub>	0.0947	0.1271	0.1594	0.1918	0.2241	0.2564	0.2888	0.3050

further study in the determination of CO<sub>2</sub> emissions showed that when other physical/chemical treatment process are conducted on the sludge prior to the digester, the emissions of CO<sub>2</sub> could be reduced to 5793 tons per year, which is only 60% of the total equivalent CO<sub>2</sub> emissions. The emissions of equivalent CO<sub>2</sub> per unit of organic load *i.e.*, per kg of BOD for each plant were also compared. The equivalent emissions of CO<sub>2</sub> per for the SBR were 2.83 kg per kg of BOD, whereas the CO<sub>2</sub> emissions for the UASB and oxidation ponds were 6.17 and 3.86 kg per kg of BOD respectively. From these, it can be seen that the

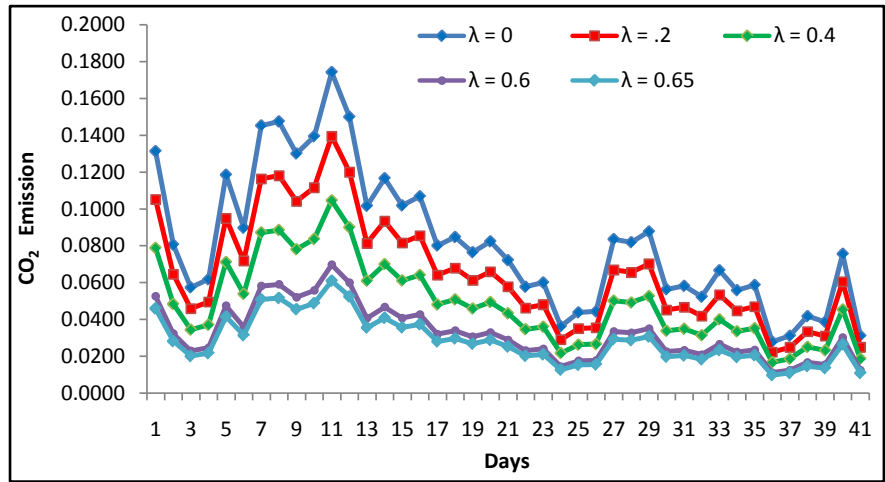


Figure 6. Variation of CO<sub>2</sub> emission (Mg/Hr) from wastewater in SBR.

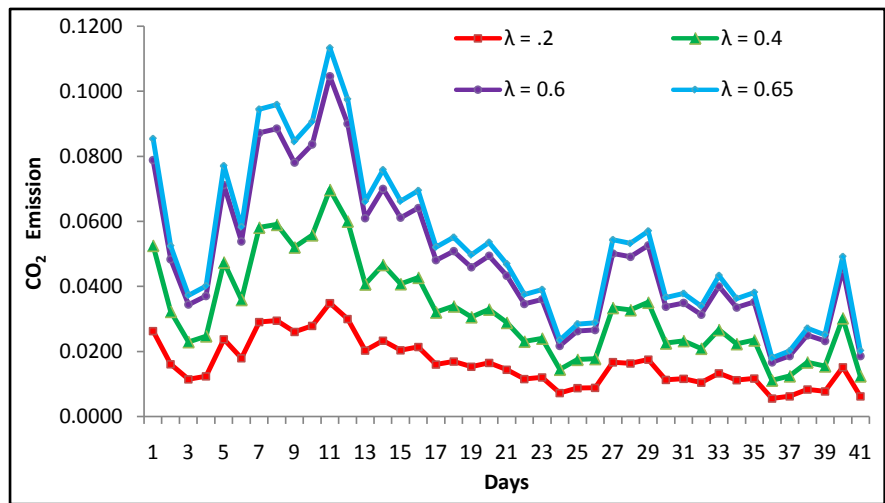


Figure 7. Variation of CO<sub>2</sub> emission (Mg/Hr) from sludge in SBR.

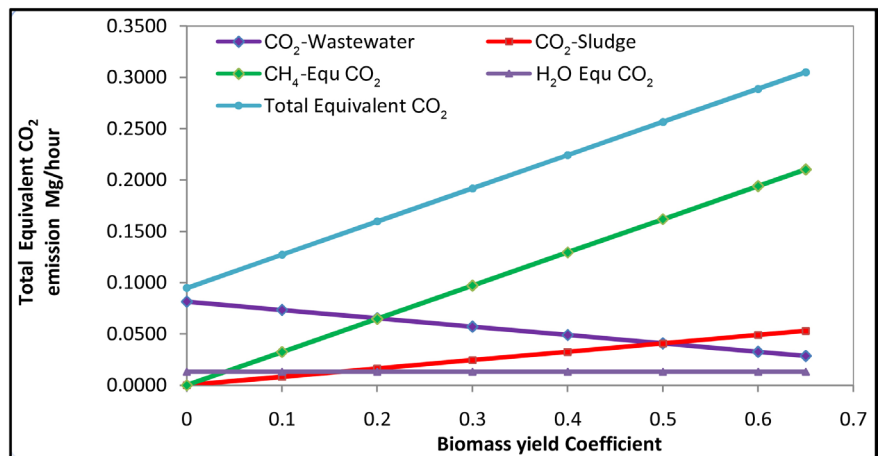
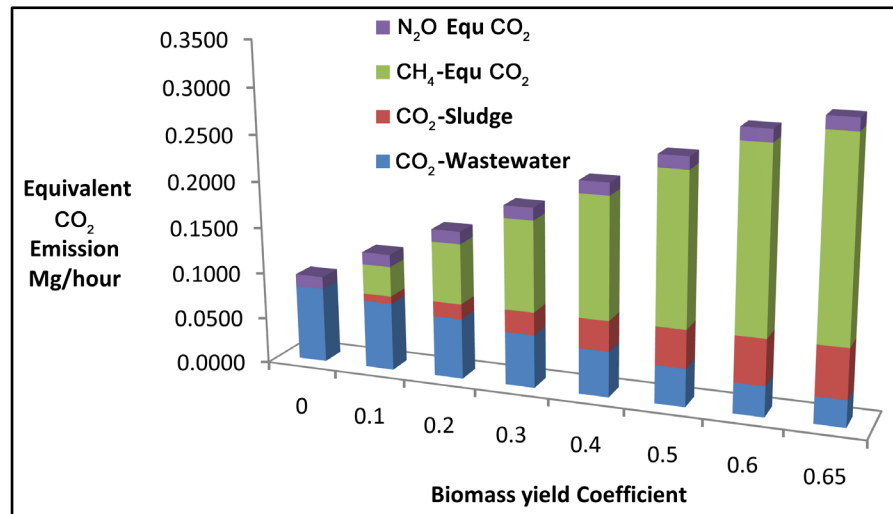


Figure 8. Emission of GHG (Mg/Hr) vs. biomass yield (λ).

performance of the SBR is better than the performance of the UASB and oxidation ponds in the emission of GHG.



**Figure 9.** Total emission of GHG-equivalent of kg CO<sub>2</sub>.

**Table 8.** Emissions of GHG in UASB, SBR and oxidation ponds.

Sewage treatment plants	Emission of GHG (Tons per year)			Emission of GHG equivalent CO <sub>2</sub> (Tons per year)			Total equivalent CO <sub>2</sub>		
	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	(Tons per year)	Mg per day	per Kg BOD
UASB2.5 MLD (2 Nos)	196	77	0.12	196	1625	37	3716	4.63	6.17
Oxidation ponds 12.5 MLD	1439	200	0.59	1439	4194	183	5816	14.49	3.86
SBR17 MLD (A1)	1589	277	0.80	1589	5811	249	7649	19.05	3.74
SBR 17 MLD (A2)	1426	196	0.80	1426	4118	249	5793	14.42	2.83

## 5. Conclusion

The emissions of GHG from the UASB, oxidation ponds and SBR in Puducherry were estimated. The emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from all these treatment plants were also estimated based on the guidelines of IPCC and RTI-USEPA and the total equivalent CO<sub>2</sub> was computed and analyzed. The impact of biomass yield coefficient on the emissions of GHG was also examined and their variations were also studied. The total emissions of equivalent CO<sub>2</sub> from the SBR of 17 Mld capacity are less than 20% of the total CO<sub>2</sub> emissions of CO<sub>2</sub> from the UASB and oxidation ponds of 17.5 Mld capacity. Further study revealed that by modifying the treatment process of the sludge from the SBR, by altering the waste sludge flow rate and the MLSS, the total emissions of equivalent CO<sub>2</sub> could be reduced and it is possible to achieve a reduction of about 40% of total equivalent CO<sub>2</sub> emissions. The study also established that the emissions of CO<sub>2</sub> from the SBR are the least and that the SBR performs well and more efficient in terms of reduction of GHG emissions when compared to that of the UASB and oxidation ponds.

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