

**ASSESSMENT OF METHANE EMISSIONS FROM ANAEROBIC AND  
FACULTATIVE PONDS FROM DOMESTIC AND INDUSTRIAL SOURCES  
AT DANDORA ESTATE SEWERAGE TREATMENT WORKS, NAIROBI  
CITY COUNTY, KENYA**

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## DECLARATION

This thesis is my original work and has not been presented for a degree award in any other University.

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## **DEDICATION**

I am sincerely thankful to Nairobi City Water and Sewerage Company, where this research was carried out. Many thanks to Dandora Estate Sewerage Treatment Works' chief chemist, Mr. Michael Kimenye and his entire team who guided me through data collection at the plant.

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## LIST OF ACRONYMS AND ABBREVIATIONS

<b>BOD</b>	Biochemical Oxygen Demand
<b>BOD<sub>5</sub></b>	Standard 5-day test measurement for Biochemical Oxygen Demand
<b>CH<sub>4</sub></b>	Methane Gas
<b>CO<sub>2</sub></b>	Carbon Dioxide
<b>COD</b>	Chemical Oxygen Demand
<b>DESTW</b>	Dandora Estate Sewerage Treatment Works
<b>GHG</b>	Greenhouse Gas
<b>GWP</b>	Global Warming Potential
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>KNBS</b>	Kenya National Bureau of Statistics
<b>MCF</b>	Methane Correction Factor/ Fraction
<b>NCWSC</b>	Nairobi City Water and Sewerage Company
<b>pH</b>	Measure of amount of hydrogen ion concentration
<b>UV</b>	Ultra Violet Radiation
<b>UASB</b>	Up-flow Anaerobic Sludge Blanket
<b>TS</b>	Total Solids

## DEFINITION OF TERMS

- BOD** According to IPCC (2006), BOD is the content of aerobically biodegradable carbon in the wastewater. A 5-day test is used in measuring BOD, denoted as BOD<sub>5</sub>. Frequently, the term BOD is used in wastewater from domestic sources.
- COD** Chemical Oxygen Demand is a measure of the total biodegradable and non-biodegradable material available for chemical oxidation (IPCC, 2006).
- TOW** TOW denotes total organics in the wastewater. It is calculated to measure organic matter content in the wastewater (IPCC, 2006).

## ABSTRACT

Methane gas is odorless and colorless, and causes greenhouse gas effect and is up to 100 times more potent than carbon dioxide in capturing energy at lower atmosphere in the first 5-year duration, and 72 times more in the next 20 years. The goal of this study was to quantify the amount of methane emission from anaerobic and facultative ponds at Dandora Estate Sewerage Treatment Works. Dandora Estate Sewerage Treatment Works is located 30 kilometers to the East of Nairobi City County. The treatment plant receives municipal wastewater of domestic and industrial composition for treatment mainly through wastewater stabilization ponds. This process, however, leads to production of three important greenhouse gases; methane, nitrous oxide and carbon dioxide. Due to the importance in reduction of greenhouse gases, it is critical to understand the processes responsible for these emissions. This study focused on the following objectives: i) to analyze how methane production is affected by typical wastewater quality parameters such as pH, Biological Oxygen Demand, Chemical Oxygen Demand, Total Organics in the Wastewater and temperature; ii) to assess how the performance of Dandora Estate Sewerage Treatment Works ponds affects methane emission; and iii) to assess the trend of methane emission from the anaerobic and facultative ponds at Dandora Estate Sewerage Treatment Works between the years 2007 to 2017. This study used the Intergovernmental Panel on Climate Change (IPCC) methodology of 2006 in assessment of methane emission. There were two anaerobic ponds, six primary facultative ponds, eight secondary facultative ponds and twenty-two maturation ponds making a total of 38 ponds. A laboratory research design was employed to measure the amount of biological oxygen demand, chemical oxygen demand, total solids, temperature, pH, dissolved oxygen, and wastewater inflow and outflow volumes. It was estimated that anaerobic ponds emitted into the atmosphere  $3.2641 \times 10^7$  kg CH<sub>4</sub>/yr from domestic wastewater sources and  $5.5053 \times 10^4$  kg CH<sub>4</sub>/yr from industrial sources. Facultative ponds emitted into the atmosphere  $1.5176 \times 10^7$  kg CH<sub>4</sub>/yr from domestic wastewater sources and  $3.9176 \times 10^4$  kg CH<sub>4</sub>/yr from industrial sources. Methane emission was significantly affected by typical wastewater parameters. The performance of the ponds in breaking down organic components in the wastewater was significantly proportional to methane emission. The trend of methane emission between the years 2007 and 2017 showed a correlation of 0.915 between anaerobic and facultative ponds methane emission from industrial wastewater sources. Mean methane emission from domestic wastewater from anaerobic and facultative ponds had a correlation of 0.67. Optimization of wastewater parameters such as temperature, pH, total solids, biological oxygen demand, chemical oxygen demand and dissolved oxygen significantly influenced methane emission and is important in effective biogas production system. It is therefore recommended that methane gas be captured for electricity production.

## CHAPTER ONE: INTRODUCTION

### 1.1 Background to the Study

The treatment of wastewater using stabilization ponds results in the generation of methane gas, which is a colorless and odorless element of natural gas. Methane ranks as the second-most important human-caused greenhouse gas after carbon dioxide, accounting for about 15% of the human-induced climate change impacts (Forster, 2007; IPCC, 2013). Although methane dissipates from the atmosphere within ten years, it is 34 times more effective than carbon dioxide at capturing heat in the lower atmosphere (Myre, 2013). Therefore, accurately assessing methane emissions from wastewater stabilization ponds is essential for understanding climate change.

Strategies for mitigation include enclosing anaerobic and facultative ponds to capture methane gas, thereby managing emissions to more controllable levels. An estimated 8 to 11% of global methane emissions stem from wastewater treatment plants (Fayez, 2011). However, the lack of adequate in situ measurements leads to uncertainty in the creation of precise greenhouse gas emission inventories (Wang, 2011). As a result, developing comprehensive inventories for methane emissions is crucial for combating climate change (UNEP, 2011).

The level of degradable organic matter, temperature, and the type of ponds used influences amount of methane produced in wastewater stabilization ponds. Higher temperatures contribute to an increase in methane generation (Gupta, 2012). Shallow lagoons, generally less than 1 meter deep, tend to maintain aerobic conditions, resulting in minimal methane production, while ponds with depths of 2-3 meters create anaerobic conditions that promote

significant methane production (IPCC, 2006). This study will focus on the anaerobic and facultative ponds at DESTW, which have depths of 4.7 meters and 2.7 meters, respectively (NCWSC, 2016).

Based on the IPCC (2006) guidelines, the essential parameters for evaluating methane emission potential include Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD). Elevated levels of BOD or COD in wastewater are associated with higher methane production when compared to wastewater with lower BOD or COD under similar conditions. Methane possesses a Global Warming Potential (GWP) value of 21 and classified as a greenhouse gas, emphasizing its considerable impact over a specific timeframe in comparison to CO<sub>2</sub> (IPCC, 2006). Temperature is also a crucial factor, as rising temperatures are likely to increase methane emissions, potentially surpassing carbon dioxide emissions.

## **1.2 Statement of the Problem**

Few scientific studies have been carried out on methane emission into the atmosphere from municipal wastewater management. The handful studies done concentrated on marshes, agricultural and domestic biogas production. Wastewater treatment works are estimated to generate between 8 - 11% of the total emission of methane gas. There is also lack of quantitative onsite methane gas emission data, and variability and uncertainty of methane emission estimations using default factors (Bousquet, 2006).

Despite state agencies/the ministry of health stressing the need for quality parameters in treating sewage water, the situation in DESTW has not adhered to the standards. For the past 15 years, the operation of the physical treatment unit has been challenging thus putting pressure on the facultative ponds on biological breakdown of the organic composition. This

has led to conversion of six primary facultative ponds to serve as anaerobic ponds thereby increase organic load to DESTW system; and this leads to methane production into the atmosphere causing greenhouse gas effect. Anthropogenic emissions accounts for 50% - 65% of the total methane emissions (IPCC, 2013).

This study assesses methane gas emission from anaerobic and facultative ponds at DESTW using the proposed methodology by IPCC (2006) and quantifies how much methane gas is emitted into the atmosphere. In filling the above knowledge gaps, this research also added methane emission from DESTW to the body of knowledge in Kenya.

### **1.3 Research Questions**

The following research questions were sought to be answered by research study:

1. How much methane is emitted from anaerobic and facultative ponds at DESTW?
2. How is methane emission affected by wastewater quality parameters such as pH, BOD, COD, TOW and temperature at DESTW?
3. How does the performance of anaerobic and facultative ponds in breaking down organic matter affect methane production at DESTW?
4. How has the trend in methane emission from anaerobic and facultative ponds been from the year 2007 to 2017 at DESTW?

### **1.4 Specific Objectives**

The main goal of this research was to assess methane emission from anaerobic and facultative ponds at DESTW. To achieve the goal, the following specific objectives guided the research:

1. To quantify the amount of methane emission from anaerobic and facultative ponds at DESTW.
2. To determine water quality parameters such as pH, BOD, COD, TOW and temperature and analyze their effect on methane emission.
3. To determine how the performance of anaerobic and facultative ponds in breaking down organic matter affects methane emission.
4. To assess the trend of methane emission from the anaerobic and facultative ponds at DESTW between the year 2007 to 2017.

### **1.5 Hypotheses**

The research was guided by the following hypotheses:

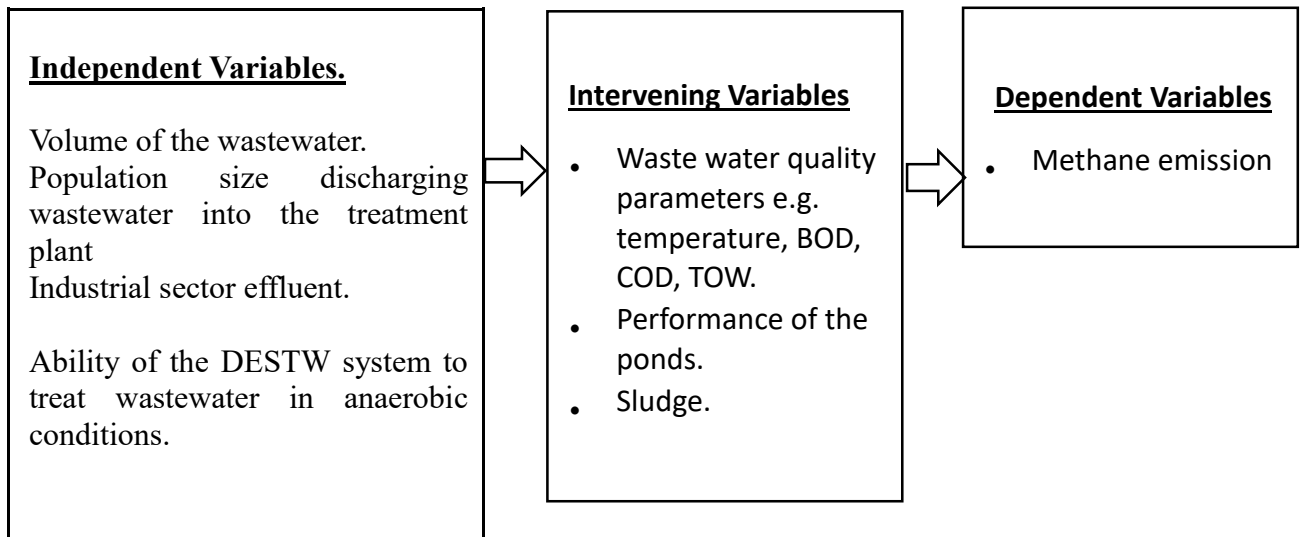
1. Methane emissions from anaerobic and facultative ponds at DESTW are significantly influenced by pH, BOD, COD, and temperature.
2. The conversion of primary facultative ponds to anaerobic ponds at DESTW has resulted in a significant increase in methane emissions.
3. A measurable trend in methane emissions from anaerobic and facultative ponds at DESTW from 2007 to 2017 is associated with changes in pond management and environmental conditions.

### **1.6 Conceptual Framework**

This research examines methane emissions produced from anaerobic and facultative ponds at Dandora Estate Sewage Treatment Works (DESTW). Emphasis is on understanding the various factors that lead to methane production, utilizing a structured framework. Key independent factors consist of the amount of wastewater treated, the population size

contributing to the plant, industrial discharges, and the system's capability to treat wastewater anaerobically (Figure 1.1). The quantity of wastewater influences the capacity and efficiency of methane production processes. The size of the population has a direct effect on the organic matter being processed, while industrial discharges add more pollutants that may affect methane production (Gerardi, 2003). The effectiveness of the DESTW system in sustaining anaerobic conditions is critical for methanogenesis (IPCC, 2006).

Intervening factors play an essential role in moderating these interactions. These include wastewater quality indicators such as temperature, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Total Organic Carbon (TOC). These indicators significantly affect methanogenic activity (Henze et al., 2008). The performance of the ponds, particularly their capacity to decompose organic matter, directly influences the rates of methane production (Global Methane Initiative, 2021). Furthermore, the build-up and management of sludge, which contains high levels of organic material, impact the overall functioning of the system and methane emissions (Myhre et al., 2013). The main dependent variable is methane emissions, measured by the levels of methane gas expelled from the ponds. This measurement acts as a crucial indicator of both the environmental effects and the efficiency of the wastewater treatment process (Forster et al., 2007; Gupta, 2012).



**Figure 1.1: Conceptual framework. Source: IPCC, 2006**

### 1.7 Research Justification

Recognizing methane emissions from wastewater treatment facilities like DESTW is vital because of its much higher global warming potential in comparison to carbon dioxide (Myhre et al., 2013). Given the scarcity of studies focusing on municipal wastewater treatment plants in developing nations, this research contributes significantly by offering comprehensive empirical data on methane emissions from DESTW (Bousquet, 2006).

The results from this investigation will aid in policy formulation by providing solid data that can guide local and national regulations, thereby supporting Kenya's commitments to international climate accords such as the Paris Agreement (UNFCCC, 2015). Having accurate methane emission inventories is crucial for crafting effective climate change mitigation strategies (UNEP, 2011).

By pinpointing critical factors that affect methane generation—such as wastewater quality indicators (temperature, BOD, COD, TOC) and pond efficiency—this study seeks to improve treatment processes at DESTW (Gerardi, 2003). This could result in better

operational effectiveness and lower greenhouse gas emissions, yielding both environmental and economic advantages (Henze et al., 2008).

Additionally, harnessing methane for energy production not only lessens environmental repercussions but also enhances energy security and stimulates economic growth (Global Methane Initiative, 2021). Effective wastewater management carries substantial public health benefits, mitigating health risks linked to untreated or inadequately treated wastewater (Government of Kenya, 2013).

### **1.8 Significance of the Research**

The results of this research would offer a concrete framework within which policymakers could devise better legislation and policy to cut the methane emissions within the wastewater treatment facilities. Second, it can help the makers of policy understand the correlation between the environmental factors and methane production and promote adaptation of appropriate measures that go beyond mere compliance, but contribute toward sustainability. It can lead to greater integration with renewable energy via capture and usage of biogas.

This study could provide practical insights for the optimization of the treatment processes in wastewater treatment plants to their managers and operators. Identifying the key environmental parameters controlling methane production, it allows for informed decision-making on operational conditions. Insights such as in the effective control of factors like temperature and organic loading which can increase energy recovery at the facilities while minimizing the greenhouse gas emissions.

The results reported in this study are also expected to be useful to the researchers and academics for further explorations in the field of wastewater treatment studies as a part of environmental science. Detailed methane emissions provide insight into certain critical interactions between wastewater characteristics and efficiency of treatments, acting thus as a basis for more advanced studies necessary for improving management practices.

Moreover, the local communities and the general public would benefit from the research through better and more environmentally responsible methods of wastewater treatment. This could, in turn, mean reduced methane production, leading to better air quality and environmental health as a step toward better public health and a quality lifestyle. Overall, the research intends to influence stakeholders, encouraging collaborative efforts toward sustainable wastewater management and climate change mitigation.

## **CHAPTER TWO: LITERATURE REVIEW**

### **2.1 Introduction to Methane Emissions from Wastewater Treatment**

While waste stabilization ponds offer numerous benefits to modern society, they are also associated with the emission of greenhouse gases (GHGs) such as methane, carbon dioxide, and nitrous oxide (Hernandez-Paniagua, 2014). With the increasing emphasis on GHG reduction, it is crucial to identify and improve on the most important emissions' activities. Particularly, 5% of the total anthropogenic emissions is attributed to anaerobic wastewater treatment operations (Cakir, 2005).

#### **2.1.1 Significance of Methane as a Greenhouse Gas**

Methane (CH<sub>4</sub>) is a potent greenhouse gas that contributes significantly to global warming. Its radiative forcing, or the ability to trap heat in the atmosphere, is approximately 25-34 times greater than that of carbon dioxide (CO<sub>2</sub>) over a 100-year period (IPCC, 2021). This makes methane a critical factor in climate change mitigation efforts.

#### **2.1.2 Methane Emissions from Wastewater Treatment**

When wastewater is disposed or treated anaerobically, it can become a source of methane production (IPCC, 2006). More uncertainty exists about methane emission during wastewater treatment (CH<sub>2</sub>MHill, 2008). Methane is emitted at several stages of wastewater treatment process (Daelman, 2012). As methane can already be produced in the sewerage system, it also gets in the treatment plant with wastewater influent (Guisasola, 2008).

Over the past decade, anaerobic process has become a mature wastewater treatment technology (Daelman, 2012). Anaerobic process not only saves anaerobic energy, but also

produces methane gas. In addition, it produces approximately 10% of the waste sludge in comparison to aerobic processes. Methane produced during anaerobic process can be utilized as a source of energy. Recovery of energy is one of the most effective methods to control gas emission from wastewater treatment works. Thereby reducing the greenhouse effect of methane (Daelman, 2012)

### **2.1.3 Anaerobic and Facultative Ponds: Key Sources of Methane**

Anaerobic and facultative ponds are two common types of wastewater treatment systems that can be significant contributors to methane emissions. Anaerobic ponds operate under anoxic conditions, promoting the growth of methanogenic bacteria (Daelman, 2012). Facultative ponds, while designed for both aerobic and anaerobic conditions, can also contribute to methane production, especially in the deeper, anoxic zones (Guisasola, 2008).

### **2.1.4 Relevance of Methane Emissions in the Kenyan Context**

Kenya, like many developing countries, faces increasing challenges related to rapid urbanization and industrialization leading to a growing demand for wastewater treatment services. As WWTPs expand in Kenya, it is crucial to address the associated methane emissions to mitigate their environmental impact and contribute to national climate change goals (Kenya Ministry of Environment and Forestry, 2018).

## **2.2 Methane Emissions from Anaerobic and Facultative Ponds**

### **2.2.1 Overview of Anaerobic and Facultative Ponds**

**Anaerobic Ponds:** They are based on anaerobic conditions which favor the development of methanogenic bacteria and the production of methane as a byproduct of organic content

breakdown. They are generally deeper and contain a reduced oxygen content relative to facultative ponds (Hernandez-Paniagua et al., 2014).

Facultative Ponds: Ponds with both aerobic and anaerobic regions. Although surface layers can be aerobic, the deeper layers can generate anoxic conditions that can support methane production. Facultative ponds usually have a shallower dimension than anaerobic ponds (Cakir, 2005).

### **2.2.2 Methane Production Mechanisms**

In wastewater systems, microorganisms digest organic content and leads to production of methane through a process known as methanogenesis. The degradation of wastewater and sludge in anaerobic conditions can result in methane production, depending on factors such as the amount of degradable organic material, temperature, and the type of wastewater treatment plant. In uncontrolled treatment systems, higher temperatures lead to increased methane production, while temperatures below 15°C render methanogens inactive, halting methane production (IPCC, 2006).

Anaerobic microorganisms, in the absence of dissolved oxygen, convert organic materials into stable products like carbon dioxide and methane. This degradation process has two phases: acid formation and methane production. During the acid formation phase, bacteria break down complex organic compounds (carbohydrates, proteins, and fats) into simpler compounds, mainly short-chain volatile organic acids (e.g., acetic, lactic, and propionic acids). Non-methanogenic anaerobic bacteria are involved in this phase, leading to minimal reductions in COD and BOD as many microorganisms can use these short-chain fatty acids and alcohols, exerting oxygen demand (Enitan, 2015).

The methane production phase, known as acetogenesis, involves the conversion of short-chain organic acids into acetate, hydrogen gas, and carbon dioxide. Subsequently, several species of anaerobic bacteria (methanogenic microorganisms) convert acetate, hydrogen, and carbon dioxide into methane gas. This process, known as methanogenesis, results in waste stabilization marked by the formation of methane gas (Enitan, 2015). The two primary pathways are:

1. Breakdown of acetic acid to produce methane and carbon dioxide:  $\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2$
2. Reduction of carbon dioxide by hydrogen to form methane gas:  $\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$

In a properly functioning anaerobic pond system, these two degradation phases occur simultaneously in equilibrium: volatile organic acids are converted to methane at the same rate they are produced from more complex organic molecules. If intermediate volatile organic acids accumulate and pH drops, methanogens are inhibited, causing the process to fail without corrective actions. Methanogenesis is the rate-limiting step and should not be inhibited to maintain system efficiency.

### **2.2.3 Comparison of Methane Emissions from Anaerobic and Facultative Ponds**

Stabilization ponds are designed for biological treatment. Anaerobic ponds, which are 4.7 meters deep and narrow, are covered with scum to create anaerobic conditions essential for anaerobic bacteria. These ponds can achieve 60% BOD5 removal at temperatures of 20°C. A hydraulic retention time of one day is sufficient to remove BOD5 levels of up to 300 mg/l from wastewater at temperatures of 20°C or above. Odor production has been a

concern, but it can be minimized if the soluble sulfates concentration in wastewater is below 500 mg/l. Organic matter removal in anaerobic ponds is comparable to that in anaerobic reactors (NCWSC, 2016).

Organic carbon in anaerobic ponds is removed without energy input due to their limited aerobic surface area. In the sludge, anaerobic bacteria and microorganisms produce various metabolic compounds, including methane ( $\text{CH}_4$ ) (Paredes, 2015).

Anaerobic ponds are deep basins with enough volume to pretreat raw wastewater, allowing for sedimentation of solids, digestion of retained sludge, and anaerobic decomposition of some organic substrates that are soluble (USEPA, 2011). At DESTW, raw wastewater enters near the bottom of the pond, mixing with the microbial mass in the sludge blanket. Except for a shallow surface layer where undigested scum and grease accumulate, anaerobic conditions prevail, an impervious crust that retains heat and odor forms on the surface. Effluent is released at the opposite side of the influent.

The 4.7-meter depth of anaerobic ponds at DESTW minimizes oxygen diffusion, maintaining anaerobic conditions. These ponds effectively pretreat high-strength industrial wastewater. Effluents from anaerobic ponds are directed to facultative ponds, as they contain high levels of anaerobic byproducts (NCWSC, 2016).

Anaerobic ponds operate efficiently at an optimal organic loading rate of 3000 kg/ha/day (Quiroga, 2011). In practice, anaerobic ponds are often used alongside facultative ponds (Martinez, 2014). Facultative ponds treat BOD levels ranging from 100-400 kg BOD/ha/day (Kayombo, 2010). To prevent odor nuisance, the maximum anaerobic pond loading recommended is 400g BOD<sub>5</sub>/m<sup>3</sup>/d (Meiring, 1968).

Facultative ponds, measuring approximately 750 meters long, 300 meters wide, and 2.7 meters deep, create aerobic and anaerobic conditions for facultative bacteria. These ponds are designed for BOD5 removal due to low organic surface loads that promote active algal populations. Anaerobic bacteria reside at the bottom, facultative bacteria in the middle, and aerobic bacteria at the surface, with minimal scum compared to anaerobic ponds. Facultative ponds are two types of: primary, which receive raw sewer, and secondary, receiving settled wastewater from the first stage (typically effluent from anaerobic ponds) (NCWSC, 2016).

Wastewater is subsequently transferred to maturation ponds, which are 1.2 meters deep, allowing sunlight penetration to the bottom for UV pathogen removal. Biological microorganisms break down organic particles into carbon dioxide and water. Effluent from facultative ponds enters the maturation ponds, with their size and number depending on the required effluent bacteriological quality. Maturation ponds are shallow and less vertically stratified, ensuring thorough oxygenation (NCWSC, 2016).

## **2.3 Impact of Wastewater Quality Parameters on Methane Emissions**

### **2.3.1 Introduction to Wastewater Quality Parameters**

Assessment of methane emission from DESTW is based on the chief factors that determine methane gas production potential is the amount of organic degradable mater and the volume of the wastewater in anaerobic and facultative ponds. BOD and COD are commonly used parameters in measuring organic component of the wastewater. Higher COD, or BOD concentrations will generally yield more methane gas than with lower COD or BOD concentrations of a wastewater under the same conditions (IPCC, 2006).

### **2.3.2 Effect Wastewater Source on Methane Emissions**

DESTW receives wastewater from industrial sources containing high levels of organic degradable content such as slaughterhouses; alcohol breweries, starch producing factories; organic chemicals producers; paper manufacturers; and other food and drink processors (vegetable oil, vegetables, dairy products, fruits, juice making, and canneries) (NCWSC, 2016).

Concentration of BOD depicts the amount of aerobically biodegradable carbon. Since the BOD may be less effective for determining the organic components in anaerobic environments because it is an aerobic parameter. Type of wastewater and the bacteria present influences the BOD concentration. Frequently, BOD is used for domestic wastewater, while COD is predominantly in industrial wastewater (IPCC, 2013).

Industrial wastewater can be treated onsite or discharged into domestic sewerage system. For DESTW, industrial wastewater is discharged through sewer system. DESTW treats municipal wastewater. Emission therefore is to be included from the domestic and industrial wastewater sources. Industrial wastewater with significant carbon loading will produce methane gas if treated under intended or unintended anaerobic conditions (NCWSC, 2016).

### **2.3.3 Impact of BOD and COD on Methane Emissions**

BOD and COD are measures of the organic matter content in wastewater. Higher BOD and COD levels can lead to increased methane production as methanogenic bacteria utilize organic matter as a substrate for growth and metabolism (Wang et al., 2018). However,

excessive organic loading can also inhibit methane production due to the accumulation of toxic intermediates (Batstone et al., 2002).

#### **2.3.4 Role of Total Organic Waste (TOW) in Methane Production**

TOW is a broader measure of organic matter in wastewater, both biodegradable and non-biodegradable. While BOD and COD would take into consideration the biodegradable organic matter only, TOW would include a wider range of organic compounds that may impact methane production. Higher TOW levels in other studies tend to relate well with increased methane emissions (Fernández-García et al., 2017).

#### **2.3.5 Temperature's Influence on Methane Emissions**

The temperature significantly influences the activity of methanogenic bacteria and, therefore, methane production. Mesophilic methanogens have an optimum between 20-40°C, while thermophilic methanogens can work at higher temperatures: 50-60°C. In general, higher temperatures will result in higher methane production rates, but at extreme temperatures, methanogenic activity is inhibited (Wang et al., 2018).

#### **2.3.6 Interactions Between Parameters**

There is, in general, no mutual dependence of methane gas production in anoxic environments on the different wastewater quality parameters. Interaction of a parameter can affect the overall methane emission. For example, even at high organic matter concentration, high pH can cause inhibition of methanogenic activity. Low temperature decreases the methane gas production at favorable pH and organic matter (Daelman et al., 2012).

## **2.4 Organic Matter Breakdown and Methane Production**

### **2.4.1 Introduction to Organic Matter in Wastewater**

Wastewater contains all kinds of organic matter, including carbohydrates, proteins, fats, and other complicated compounds (Metcalf and Eddy, 2003). The composition and concentration of organic matter in the wastewater can, to a great extent, affect methane production in anaerobic and facultative ponds.

### **2.4.2 Microbial Processes in Organic Matter Breakdown**

It basically means that microbial communities mediate the degradation of organic matter in wastewater. (Kharitonov et al., 2021). All the different groups of microorganisms, such as bacteria, archaea, and fungi, take part in the degradation of organic compounds. These microorganisms use organic matter for energy and nutrients, thereby producing intermediate compounds and eventually methane (Kharitonov et al., 2021).

### **2.4.3 Organic Matter Breakdown in Anaerobic and Facultative Ponds**

In anaerobic and facultative ponds, the decomposition of organic matter is the result of sequential, interlinked microbiological processes. The initial steps involve hydrolysis, which degrades the complex organic molecules into simpler compounds such as carbohydrates, proteins, and lipids (Wang et al., 2018). These simpler compounds are then fermented by acid-forming bacteria into products such as volatile fatty acids and hydrogen gas (Zhang et al., 2016).

These VFAs and hydrogen gas are then converted to methane by the methanogenic bacteria. Methanogens are a group of archaea capable of this peculiar ability of methane production in an anaerobic environment (Angelidaki et al., 2009). However, specific pathways taken

toward methane production depend on the type of VFAs and hydrogen present (Batstone et al., 2002).

#### **2.4.4 Factors Influencing Organic Matter Breakdown and Methane Production**

There are many factors that will determine the rate and extent of organic matter breakdown and production of methane in the ponds. These include:

- **Temperature:** In general, an elevated temperature with regard to the optimum range favors methane production and microbial activities (Imai et al., 2023). Increases in temperature within the optimum range can significantly improve methanogenesis and microbial diversity, although higher temperature levels are capable of significantly reducing methane production due to impaired microbial activities. (Reungsang et al., 2023).
- **pH:** Optimum pH for growth of methanogenic bacteria is within a narrow range; outside this narrow optimum, the activity decreases. Optimum pH for methane production lies in a range from 6.5 to 8.0, and microbial efficiency along with biogas yield changes significantly with every deviation from the optimum value (Zinder, 1984).
- **Nutrient Availability:** Nutrient availability, especially nitrogen and phosphorus, is important in microbial growth and degradation of organic matter in anaerobic processes. These nutrients play an important role in supporting microbial metabolism that directly affects methane production (Imai et al., 2023).
- **Hydraulic Retention Time:** Longer hydraulic retention times would provide more time for the microbial processes to degrade the organic matter, and high methane

production can be expected. HRT is considered one of the critical factors in optimizing the efficiency of anaerobic digestion processes (Imai et al., 2023).

- **Organic Matter Composition:** The organic matter composition of wastewater defines its biodegradability, hence determining the types of microorganisms participating in the degradation. Wastewater with more readily biodegradable material will support higher methane production (Reungsang et al., 2023).

#### **2.4.5 Impact of Organic Matter Quality on Methane Production**

Organic matter, such as sugars and volatile fatty acids, are easily metabolized by methanogens, resulting in higher methane yields. However, complex compounds like plant based organic waste often require pretreatment or longer retention times to degrade efficiently, thereby affecting methane production (Angelidaki et al., 2009; Batstone et al., 2002).

### **2.5. Historical Trends in Methane Emissions (2007-2017)**

#### **2.5.1 Overview of Historical Data Collection and Trends in Methane Emissions**

Methane emission from the Dandora Estate Wastewater Treatment Works within 2007-2017 shows some trends of operational challenges, environmental impacts, and probably some climate mitigation opportunities. Over the same period, intermittent problems plagued the treatment facility to affect methane emissions, which ranged from malfunctioning equipment that impeded fine screening and grit removal to impacted BOD levels and consequently methane production. Researches related to the trends in BOD loading in the case of DEWST, starting from year 2007 up to 2013, also point out the link between high organic load and methane output. On the other hand, the methane emissions

also changed depending on the seasonal changes in waste loading and temperature because anaerobic processes are temperature- and season-sensitive.

Further research was done on biogas recovery, assuming that the DEWST would generate up to 2,738 cubic meters of recovered biogas per day, equivalent to substantial volumes of methane recoverable for energy. In addition, this recovery would be about 495 cylinders of LPG per day serving more than 2,900 households. This potential for energy recovery gives a very strong avenue for mitigation, with an estimated reduction of 16 tons of CO<sub>2</sub>-equivalent emissions per day due to methane capture and utilization, strongly positively correlated with the energy output at  $r = 0.99$ .

### **2.5.2 Factors Influencing Trends in Methane Emissions**

The factors that controlled the trends of the methane emission at DEWST ranged from 2007 to 2017 and included operational adjustments and upgrades, varying environmental conditions, and seasonal variations. Some of the key features that have given rise to variations in this period include the following:

- **Operational Changes and Infrastructure Limitations:** DEWST operations changed from time to time, which also meant changes in methane emissions. In 2008, for instance, a capacity building of the plant was done that included different mechanized equipment such as the programmable logic controls, PLC. These systems failed due to operational problems and caused shutdowns to occur, impacting negatively on the treatment processes and indirectly affecting the methane produced through the quality of organic load coming into the anaerobic ponds.

- **Variability in Organic Loading:** The key factor dominating methane gas emissions into the air in wastewater treatment processes is the concentration of organic matter, expressed as Biochemical Oxygen Demand, and Chemical Oxygen Demand. Higher organic loading rates result in higher methane production by anaerobic decomposition. Seasonal variations, such as heavier loading during the dry months when the dilution would be less, also the concentration of organic matter entering DEWST and subsequently raised methane emissions during certain periods (Omollo, Kirubi, and Manohar, 2024).
- **Temperature and Environmental Conditions:** Anaerobic processes are sensitive to temperature fluctuations, which have a related impact on microbial activity responsible for methane production. The climatic setting in Nairobi characteristically goes through fluctuations in temperature that may retard or enhance the biological processes occurring in anaerobic ponds. For example, higher temperatures increase microbial metabolic rates and hence could lead to a rise in methane output, while during periods of cooler temperatures, these rates could be lowered (Omollo et al., 2024).
- **Energy Recovery Activities:** Capture and utilization of methane as an energy recovery effort were embarked upon in the later years of this period studied - a practice that directly affected the emission levels since some of the methane produced is channeled to useful energy. This activity helped reduce methane emissions by approximately 16 tons of CO<sub>2</sub>-equivalent emissions per day and thus provided a considerable climate benefit.

- **Maintenance and De-sludging Activities:** The maintenance activities, such as de-sludging, carried out from time to time added to the trend in methane emission. De-sludging averts excessive sludge build-up of organic sludge, which if allowed to build up may cause increased generation of methane gas due to enhanced anaerobic decomposition of organic sludge. The emission control regularly carried out the maintenance activities though disruption in regular de-sludging many times resulted in temporary increased methane generation. (IOSR Journals, n.d.).

Overall, the trends in methane emissions at DEWST from 2007 to 2017 show a composite effect of operational efficiency, environmental factors, and strategic interventions in energy recovery, with each contributing to fluctuating levels of methane emissions and climate mitigation opportunities.

### **2.5.3 Changes in Regulations and Environmental Policies**

Between the year 2007 and 2017, there were a few policy changes in the Kenyan Government influential in methane emission, especially at such facilities as Dandora Estate Wastewater Treatment Works.

- **National Climate Change Action Plans and International Commitments:** The national goals took root in 2013 when the government of Kenya came up with the National Climate Change Action Plan of Kenya. That instituted a framework which was supposed to help the country reduce its emission in the different sectors, such as in wastewater management sectors. The plan emphasized methane reduction and green energy projects. These were further augmented when Kenya, under the Paris Agreement of 2015, made commitments to align its national goals with those on

climate action. Indirectly, it thus provided the motivation needed for facilities such as DEWST to include mitigation strategies for methane in their activities.

- **Water Resource Management Policies:** Among many others, the Water Act 2016 promoted the quality of water resource management and waste treatment, with consideration for the environment and pollution control. It thus mitigated methane through effective treatment procedures that reduce organic load—a key raw material in the generation of methane within the wastewater plants.
- **Energy Policy Evolution and Renewable Focus:** The Energy Act of 2019, while enacted a little outside the period of 2007-2017, had the seeds of development from previous policies aimed at increasing investments in renewables and decreasing reliance on fossil fuels. That was important in setting up a framework that targets the mitigation of greenhouse gases from various sectors, and as such, places wastewater in a position where energy recovery from methane becomes one of the many ways of reducing greenhouse gas emissions.

This policy complements emission reduction, enhances climate resilience, and places operations at DEWST and other facilities in a regulatory environment that runs concurrently with national goals on climate.

## **2.6 Gaps in literature**

This literature review has shown deficiencies and knowledge gaps about methane emissions from wastewater treatment, especially from anaerobic and facultative ponds. Among the most important shortcomings is the lack of comprehensive studies that evaluate the variability of critical environmental factors, such as temperature, rainfall, and organic load, which are important in determining methane production. Most of the existing studies

do not consider these factors; therefore, their findings cannot be generalized to different settings and time periods.

Moreover, most literature is focused on methane emissions without giving enough attention to other greenhouse gases, such as carbon dioxide and nitrous oxide, which could also be emitted during the processes of wastewater treatment. This limited scope restricts the understanding of the broader environmental implications of these systems. Most of the studies also use different methodologies, which further makes them inconsistent with results. Such non-consistent findings arise due to the use of different approaches regarding methods to estimate emissions and assumptions about wastewater characteristics. It therefore establishes that there is a great need for more comprehensive and standard research on such grey areas. Further research needs to be performed under a wide range of environmental conditions with the inclusion of several greenhouse gas emissions to obtain a holistic view regarding methane production in the WWT system. The holistic approach will eventually help in the development of better management practices and contribute toward climate change mitigation.

## **CHAPTER THREE: METHODOLOGY**

### **3.1 Research Design**

#### **3.1.1 Introduction to Research Design**

The methodology in the study will be adopted highly, since it researches methane emission from Dandora Estate Sewerage Treatment Works. It focuses on the quantification of methane emissions from anaerobic and facultative ponds while analyzing several quality parameters of wastewater impacting those emissions. Further, the current study investigates organic matter degradation performance by such ponds and assesses the historical trends in methane emissions over a decade.

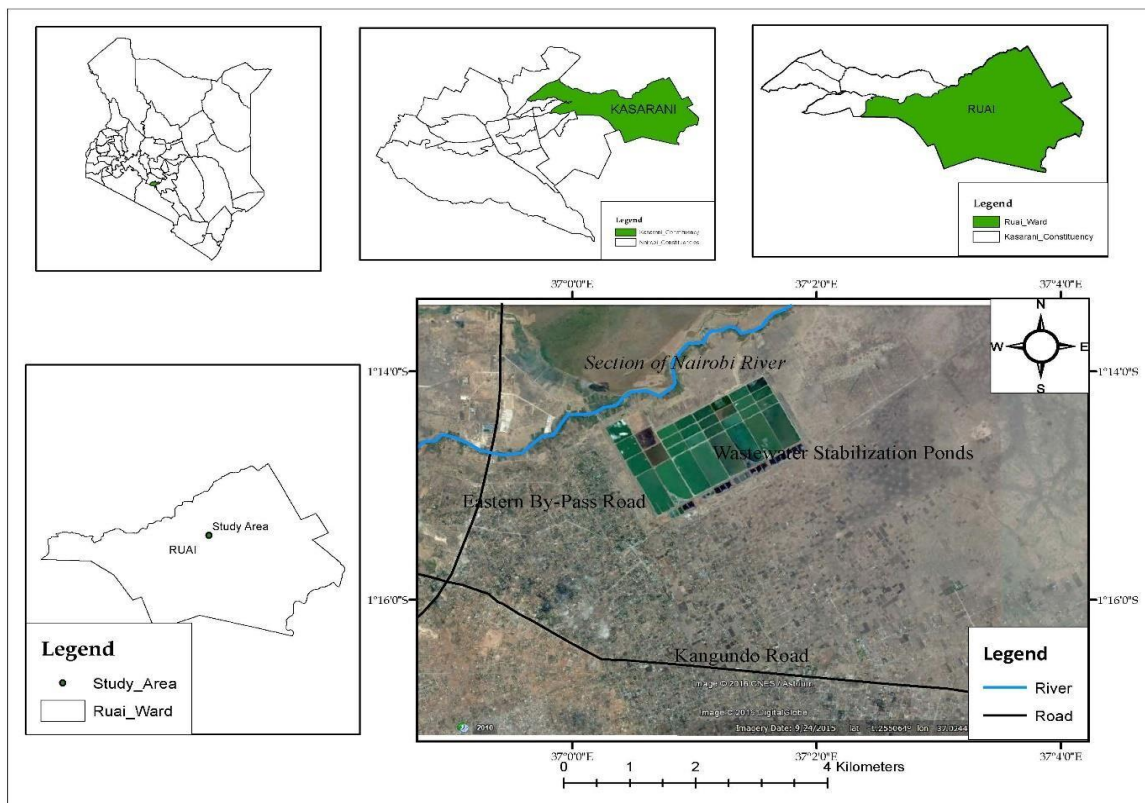
With that objective, a correlational study design was appropriate. This is because, under such a design, the statistical relationship between methane emission and other variables can be investigated without their manipulation. In so doing, stratified sampling ensures that the different zones of the ponds are well represented in order to give a detailed and accurate assessment of methane emissions. It will obtain the data of the previous year from archived records; it will gather the current data from fixed positions within the ponds.

The collection involves the measurement of pH, BOD, COD, TOW, and temperature levels both onsite and in laboratory settings. With appropriate methods for data analysis and great consideration for ethical issues, this study can be useful in devising ways to improve waste water management practices at DESTW and mitigate methane gas emissions effectively.

### 3.1.2 Study Site Description

#### 3.1.2.1 Overview of Dandora Treatment Plant

Dandora Estate Sewerage Treatment Works (DESTW) is located approximately 30 kilometers from Nairobi and approximately 1 km north of Ruai Shopping center off Nairobi-Kangundo Road. DESTW is located at latitude  $1^{\circ}37'42.91''$  South; and longitude  $37^{\circ}1'8.05''$  East. It lies under Environment and Compliance Department of Nairobi water and Sewerage Company (NCWSC). The plant is the largest in East and Central Africa (Pearson, 1996). DESTW is administratively located in Nairobi City County, Kasarani Constituency, Ruai Ward. Satellite map of DESTW is captured in Figure 3.1.



**Figure 3.1: DESTW satellite map**

Source: Google Earth, 2017

### **3.1.2.2 Specifics on Facultative and Maturation Ponds**

Facultative Ponds: The facultative ponds in DESTW are 1.7 meters deep with a surface area of 700 meters by 300 meters. In the ponds, there can be distinguished the presence of two layers: the upper layer, where the aerobic bacteria will be active, and the lower one, which supports anaerobic activities. The average retention time in this pond is around 35 days, presenting substantial reductions in the organic load (Trevino Quiroga, 2021).

Maturation Ponds: Located after the facultative ponds, and approximately 1.2 meters deep, these are 300 meters by 150 meters in area. These ponds enable the sun's rays to penetrate, thus increasing the removal of pathogenic organisms such as E. coli. These further polishes up the effluent before discharge (Arc, 2006).

Methane emissions are a major concern in both types of ponds, since it is very deep and may create anaerobic conditions, especially in the lower layers of facultative ponds. This condition may emanate methane production and could have environmental concerns on operations of the plant (Daelman et al., 2012).

### **3.1.3 Research Design Framework**

#### **3.1.3.1 Type of Study**

This study employs a correlational research design to investigate the relationship between wastewater quality parameters and methane gas emissions from the treatment ponds at the Dandora Estate Sewerage Treatment Works (DESTW). By focusing on the statistical associations between these variables without experimental manipulation, the study aims to identify key factors contributing to methane production and its environmental impact (Daelman et al., 2012).

### **3.1.3.2 Sampling Strategy**

In this respect, the strategy of sampling will ensure that representative data collections from the different ponds at DESTW are carried out in a systematic way. The sample will include coverage of the different zones of the ponds through stratified sampling. On each day of sampling, 16 grab samples were collected: 2 from anaerobic ponds and 14 from facultative ponds, specifically from the ponds' inlet and outlet. During the sampling period, from June to August 2018, 96 samples covering 20 months were collected with the aim of capturing a wide temporal variation in methane emission (Trevino Quiroga, 2021).

Such structured sampling helps in collecting a dataset representative of the diverse conditions existing within the ponds and allows an in-depth analysis of the factors affecting methane production. By having multiple zones of each type of pond considered, this sampling strategy provides a sufficiently robust framework for assessing in depth the relation that exists between the quality parameters of wastewater and the methane emission related to different types of ponds.

### **3.1.4 Data Collection Methods**

The data collection process for this study on methane emissions from the Dandora Estate Sewerage Treatment Works (DESTW) involves three primary sources:

#### **3.1.4 .1 Laboratory Studies of Wastewater**

To evaluate the biochemical characteristics of wastewater, samples will be analyzed in a laboratory setting to determine Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS). This analysis will follow standard methods prescribed by the American Public Health Association (APHA, 2005). Samples

will be collected from the anaerobic and facultative ponds, ensuring representative data from different zones within the treatment plant. BOD and COD samples will be preserved and stored appropriately before analysis: BOD samples in a cool box and COD samples with sulfuric acid, refrigerated at 4°C.

### **3.1.4.2 Methane Emission Factor Data**

The emission factor (EF) is a crucial parameter used to estimate the amount of methane (CH<sub>4</sub>) emitted per unit of organic matter treated in wastewater treatment systems. In the context of the study on methane emissions from anaerobic and facultative ponds at Dandora Estate Sewerage Treatment Works (DESTW), the emission factor is calculated based on the maximum methane-producing capacity of the organic material (B<sub>0</sub>) and the methane correction factor (MCF).

#### **3.1.4.2.1 Key Components of Emission Factor**

##### **3.1.4.2.1.1 Maximum Methane-Producing Capacity (B<sub>0</sub>)**

This represents the potential amount of methane that can be produced from a given quantity of organic matter, typically expressed in kilograms of methane per kilogram of biochemical oxygen demand (kg CH<sub>4</sub>/kg BOD) or chemical oxygen demand (kg CH<sub>4</sub>/kg COD). In the study, a default value of 0.25 kg CH<sub>4</sub>/kg COD was used due to the unavailability of country-specific data.

##### **3.1.4.2.1.2 Methane Correction Factor (MCF)**

The MCF accounts for the extent to which the methane-producing capacity (B<sub>0</sub>) is realized in a specific treatment system. It reflects the operational conditions of the treatment process, such as whether it is aerobic or anaerobic. For deep anaerobic and facultative

ponds, a default MCF value of 0.8 was applied, indicating a high potential for methane production under anaerobic conditions.

#### **3.1.4.2.2 Calculation of Emission Factor**

The emission factor can be calculated using the following formula:

$$EF_j = B_o \times MCF_j$$

Where:

$EF_j$  = emission factor (kg CH<sub>4</sub>/kg BOD or kg CH<sub>4</sub>/kg COD)

$B_o$  = maximum methane-producing capacity (kg CH<sub>4</sub>/kg BOD or kg CH<sub>4</sub>/kg COD)

$MCF_j$  = methane correction factor (fraction)

For example, using the values from the study:

$$B_o = 0.25 \text{ kg CH}_4/\text{kg COD}$$

$$MCF = 0.8$$

The emission factor would be calculated as follows:

$$EF_j = 0.25 \text{ kg CH}_4/\text{kg COD} \times 0.8 = 0.2 \text{ kg CH}_4/\text{kg COD}$$

#### **3.1.4.2.3 Importance of Emission Factor**

The emission factor is essential for estimating total methane emissions from wastewater treatment facilities. By multiplying the emission factor by the total organic load (measured in BOD or COD), researchers and engineers can estimate the total methane emissions from the treatment process.

Understanding the emission factor helps in assessing the environmental impact of wastewater treatment operations and can guide efforts to optimize methane recovery for energy production, thereby reducing greenhouse gas emissions.

#### **3.1.4.3 Methane Emission Data Collection**

There were two anaerobic ponds, six primary facultative ponds and eight secondary facultative ponds at DESTW from which full chemical analysis was done. Data was collected between the months of June to August 2018 twice monthly. The sampling frequency ensures accurate and comprehensive monitoring of temporal variations, improving the reliability and significance of the data collected and allowed for BOD data collection and analysis. On one sampling day, a total of 16 grab samples were collected (2 from anaerobic ponds and 14 from facultative ponds) from the ponds' inlet and outlet negating the need for sampling at varied depths. A total of 96 samples were collected during the sampling period. methane gas was expected to be emitted from these ponds due to their depths. Data collected was sufficient for assessment of the efficiency of the treatment ponds. Samples were collected between 9.00am and 4.00pm. Physio-chemical parameters such as pH, temperature and dissolved oxygen were analyzed onsite. Samples were collected, labelled and preserved for BOD and COD analysis at the laboratory. BOD samples were stored in cool box and analysis of BOD<sub>5</sub> done at the DESTW onsite laboratory. COD samples were preserved with sulphuric acid and refrigerated at 4<sup>0</sup>C (APHA, 2005). pH, temperature and dissolved oxygen were determined by a multimeter, Sensor module WMS-24-01 (DKK-TOA CORPORATION, Japan)

### 3.1.5 Data Analysis Plan

#### 3.1.5.1 Methane Quantification

Methane emission from domestic wastewater is dependent on the characteristics of the wastewater treated by the system. Methane emission is a function of methane emission factors, total organic materials in the wastewater, the amount of sludge removed from the treatment plant for landfilling, incineration or applied to agricultural lands; urbanization statistics of the population discharging wastewater into the treatment plant; and the amount of methane recovered from the treatment plant. If sludge separation is practiced and appropriate statistics available, regardless of the sludge treatment, methane emission from the sludge should not be included in the wastewater treatment plant. Wastewater treatment systems differ for rural and urban residents. In developing countries like Kenya, there is a difference between urban-high income residents and urban-low-income residents. Therefore, factor U, is introduced to express each income group fraction. Rural population, urban-high population and urban-low populations are treated differently. Factor T, is introduced to represent the degree of utilization of the treatment system.

$$CH_4 \text{ Emissions} = [\sum_{i,j} (U_i \cdot T_{ij} \cdot EF_j)](TOW - S) - R \dots\dots\dots$$

Equation 3.3

Source: (IPCC, 2006)

Where:

TOW= Total organics in wastewater in the inventory year, kg BOD/yr

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

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

$T_{ij}$  = degree of utilization of treatment system.

$i$  = income group: rural, urban high income and urban low-income

$j$  = each treatment/ discharge pathway or system

$EF_j$  = emission factor, kg  $CH_4$ / kg BOD

$R$  = amount of  $CH_4$  recovered in the inventory year, kg  $CH_4$ /yr.

Suggested  $U$  and  $T$  for selected countries are at *Appendix V, Table 0.3*

### **3.1.5.2 Comparative Analysis**

The comparative analysis of methane emissions from anaerobic and facultative ponds at Dandora Estate Sewerage Treatment Works (DESTW) involves evaluating the differences in methane production between these two types of treatment systems. This analysis can help in understanding the efficiency and environmental impact of each system in treating wastewater.

#### **3.1.5.2.1 Methane Emission Rate**

The mean methane emission rate was determined and comparative analysis was carried out between the anaerobic and facultative ponds, and between Industrial and domestic wastewater. The comparative analysis of methane emissions from anaerobic and facultative ponds at DESTW reveals critical insights into the efficiency and environmental impact of these treatment systems, highlighting the need for targeted interventions to optimize methane recovery and reduce greenhouse gas emissions.

#### **3.1.5.2.2 Operational Conditions**

Anaerobic ponds are designed to operate without oxygen, promoting the breakdown of organic matter by anaerobic bacteria, which leads to higher methane production.

Facultative ponds operate under both aerobic and anaerobic conditions, which can limit methane production compared to anaerobic ponds. The presence of oxygen allows for the aerobic breakdown of organic matter, which lowers methane production.

#### **3.1.5.2.3 Wastewater Quality Parameters**

The analysis considered various wastewater quality parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Organic Waste (TOW). These parameters influence the amount of organic matter available for methane production.

#### **3.1.5.2.4 Trends Over Time**

The study assessed methane emissions from 2007 to 2017, revealing trends in emissions that could be attributed to changes in wastewater characteristics, treatment efficiency, and operational practices at DESTW.

#### **3.1.5.2.5 Environmental Impact**

The comparative analysis underscores the significant contribution of methane emissions from both types of ponds to the overall greenhouse gas emissions from wastewater treatment facilities. Methane is a potent greenhouse gas, and its release into the atmosphere contributes to climate change.

### **3.1.6 Reliability and Validity Measures**

#### **3.1.6.1 Reliability and Validity Measures**

##### **3.1.6.1.1 Instrument Calibration**

To ensure the accuracy of measurements, all instruments used for data collection will undergo regular calibration and maintenance routines. Calibration procedures will adhere

to standardized protocols to maintain the precision of the instruments (Grubbs, 2004). Maintenance routines will include periodic inspections and adjustments to detect and rectify any deviations from standard performance (ISO, 2017). This process ensures that the instruments provide reliable and valid measurements throughout the data collection period (Tavakol and Dennick, 2011).

#### **3.1.6.1.2 Reproducibility**

To ensure the reproducibility of data collection, several measures will be implemented, including duplicate sampling. Duplicate samples will be collected at different time points and analyzed to verify the consistency of the results (Bland and Altman, 1996). This practice helps identify any discrepancies and allows for necessary adjustments to be made, ensuring that the data collection process can be reliably reproduced under similar conditions (Watson and Petrie, 2010). Additionally, detailed documentation of data collection protocols will be maintained to facilitate reproducibility by other researchers (Koo and Li, 2016).

## **CHAPTER FOUR: RESULTS AND DISCUSSIONS**

### **4.1 Results Section**

The study at Dandora Estate Sewerage Treatment Works (DESTW) provided a comprehensive overview of the performance of anaerobic and facultative ponds and their impact on methane emissions.

#### **4.1.1 Methane Emission from Domestic Wastewater at DESTW**

##### **4.1.1.1 Anaerobic ponds**

In order to estimate the amount of methane emission from anaerobic ponds of DESTW, the (*IPCC, 2006*) methodology was applied. In this methodology, collection of BOD data was required to estimate methane emission from domestic wastewater sources. Additionally, other water quality parameters were also determined to establish the relationship between them and methane emissions.

##### **4.1.1.1.1 Biological Oxygen Demand (BOD)**

Evaluating BOD for both influent and effluent is important to assess the efficiency of the treatment process in removing organic contaminants (Spellman, 2014).

BOD is used in estimating the amount of organic matter in domestic wastewater.

##### **4.1.1.1.2 Total Organics in Wastewater (TOW)**

Total Organics in Wastewater (TOW) quantifies the amount of organically degradable material present in the wastewater. This parameter is important because it provides insight into the extent of organic pollution and the potential impact on the treatment process (Droste, 1997). Understanding the total organics helps in optimizing the treatment strategy

to achieve efficient removal of organic contaminants and minimize environmental impact (von Sperling, 2007).

In order to calculate the total organic in the wastewater, the formula ( $TOW = P.BOD.0.001.I.365$ ) was applied, refer to equation 3.1 above (IPCC, 2006). With this formula, total organics in the wastewater is a product of the BOD data and Nairobi City County population in the inventory year.

There was significant variation in the amount of total organics in the wastewater. Total organics were affected by BOD of the wastewater. High amounts of BOD led to high total organics yields. This was because total organics is a product of the population discharging wastewater into the ponds and the BOD of the wastewater.

**Table 4.1 One-Sample Test for mean BOD and TOW from anaerobic ponds**

Test	Mean	Std. Deviation	t	95% Confidence Interval of the Difference	
				Lower	Upper
Mean BOD from domestic sources (mg/l)	118.829	48.9299	6.425	73.576	164.081
Mean TOW from Anaerobic Ponds from domestic sources (kg BOD/yrX10 <sup>6</sup> )	237.7720	97.9072	6.425	147.2230	328.3211

Mean anaerobic pond's BOD is significantly proportional to mean anaerobic pond's total organics in the wastewater. Mean BOD and mean TOW are correlated at 1.0. Increase in BOD significantly causes increase in total organics with t-value of 6.425 at 95% confidence level. BOD mean of  $118.829 \pm 48.9299$  mg/l yields total organic  $237.772 \times 10^8 \pm 97.9072 \times 10^8$  kg

BOD/yr. The highest anaerobic pond's BOD (217 mg/l) recorded led to total organics yield of  $4.3421 \times 10^8$  kg BOD/yr. Whereas the least anaerobic pond's BOD (59 mg/l) recorded led to the least total organic production,  $1.1806 \times 10^8$  Kg BOD/yr.

**4.1.1.1.3 Calculations on Emission Factor**

Calculations on methane emission factor at DESTW was based on (IPCC, 2006).

**EF<sub>j</sub> = B<sub>o</sub> . MCF<sub>j</sub> .....** Equation 3.2

Source: (IPCC, 2006)

In this study, Kenya's country-specific B<sub>o</sub> is unavailable, therefore 0.6 kg CH<sub>4</sub>/kg BOD was used (IPCC, 2006).

According to IPCC (2006), default MCF values for domestic wastewater at *Appendix III* were applied. Since anaerobic and facultative ponds at DESTW are deep lagoons of depth of more than 2 meters, value 0.8 was used as MCF.

$$\begin{aligned}
 EF_j &= B_o . MCF_j \\
 &= 0.6 \text{ kg CH}_4/\text{kg BOD} \times 0.8 \\
 &= 0.48 \text{ kg CH}_4/\text{kg BOD}
 \end{aligned}$$

**4.1.1.1.4 Calculations on Methane Gas Emission**

Methane emission estimation was based on IPCC (2006).

**CH<sub>4</sub> Emissions = [∑(U<sub>i</sub> . T<sub>ij</sub> . EF<sub>j</sub>)] (TOW – S) – R .....**  
Equation 3.3

Source: (IPCC, 2006)

There was no specific  $U_i$  and  $T_{ij}$  values for Nairobi City County, therefore Kenya's default values were used. Kenya's default  $U_i$  and  $T_{ij}$  are at *Appendix V, Table 0.3*. Based on these default values,  $U_i$  for DESTW was 0.38(0.08+0.3) and  $T_{ij}$  for DESTW was 1.2 (0.32+0.37+0.17+0.34).

At DESTW, there was no data on organic component removed as sludge (S). Therefore, it was assumed no sludge was removed from anaerobic and facultative ponds. There was also no data on the amount of methane gas recovered (R) from anaerobic and facultative ponds this was because no methane was recovered from DESTW ponds.

**Table 4.2: Methane emission from domestic sources from anaerobic ponds at DESTW**

Date Sampled	Mean Anaerobic Ponds BOD (mg/l)	Methane emission from Anaerobic Pond (kg BOD/yr) X10 <sup>6</sup>	Methane emission from Anaerobic Pond II (kg BOD/yr) X10 <sup>6</sup>	Mean Methane emission from Anaerobic Ponds from domestic sources (kg BOD/yr) X10 <sup>6</sup>
MEAN	118.8	52.1186	51.9697	52.031

The highest BOD value of 217 mg/l obtained on 3<sup>rd</sup> July 2018 led to production of 95.0398 X10<sup>6</sup> kg CH<sup>4</sup>/yr X10<sup>6</sup> kg CH<sup>4</sup>/yr. Given that methane gas production from domestic sources of wastewater is dependent on the BOD of the wastewater, increase in BOD is significantly proportional to increase in methane production. High amounts of BOD in the wastewater leads to high amounts of methane gas emitted. This is because the high amounts of organic matter required higher amount of dissolved oxygen for biological digestion. This, in turn lead to higher amount of methane gas which is released as one of the by-products of the digestion process.

#### 4.1.1.2 Facultative ponds

##### 4.1.1.2.1 Biological Oxygen Demand (BOD)

To estimate the amount of methane emissions from the facultative ponds at DESTW, the methodology outlined by the Intergovernmental Panel on Climate Change (IPCC) in 2006 was employed. This methodology necessitated the collection of Biochemical Oxygen Demand (BOD) data to infer methane emissions from domestic wastewater sources. Other water quality parameters were measured to explore their relationship with methane emissions, ensuring a comprehensive analysis of the factors influencing methane production.

Samples were collected from the 14 facultative ponds and had their BOD measured. The samples were all of little variations during the sampling period except for samples collected on 3<sup>rd</sup> July where there was high rainfall leading to high surface run-off that caused high BOD measurements. This was due to run-off from agricultural and adjacent commercial facilities getting into the sewerage treatment ponds thereby interfering with the “normal” treatment.

**Table 4.3: BOD (mg/l) Data from Facultative ponds at DESTW**

Date Sampl ed	FP 1	FP 2	FP 3	FP 4	FP5 5	FP 6	FP 7	FP 8	FP9 9	FP 10	FP 11	FP1 12	FP1 13	FP 14	Me an FP
MEA	54.	52.	53	60.	59.	53.	56	59	59.	51	53.	54.	50.	55.	55.
N	83	67		5	83	5			67		3	67	67	5	25

##### 4.1.1.2.2 Total Organics in Wastewater (TOW)

Total organics in facultative ponds’ wastewater is highly affected by its BOD. Increase in BOD of the wastewater in turn causes increase in the total organics. Given that during the

sampling period the population discharging wastewater into the treatment plant remains the same, BOD plays a significant role in determination of total organics in the wastewater. As was with the case with BOD, there was normal variation in the wastewater's total organics except for 3<sup>rd</sup> July where high rainfall caused increased run-off into the treatment system thereby affecting its BOD and in turn causing increase in total organics in the wastewater.

**Table 4.4: Total Organics (kg BOD/yr) X10<sup>6</sup> in Wastewater from Facultative Ponds at DESTW**

Date Sampled	FP1	FP2	FP3	FP4	FP5	FP6	FP7	FP8	FP9	FP10	FP11	FP12	FP13	FP14	Mean TOW
MEAN	109.71	105.39	106.05	121.05	119.71	107.05	112.05	118.05	119.39	102.04	106.65	109.32	101.38	111.05	110.55
STANDARD DEVIATION	3.3	2.9	2.2	5.5	9.9	7.7	1.1	1.1	7.7	3.3	5.5	9.9	9.9	7.7	4.4

**Table 4.5: One-Sample Test from mean BOD and TOW from facultative ponds**

Test	Mean	Std. Deviation	t	Sig. (2tailed)	95% Interval Difference	Confidence of the
					Lower	Upper
Mean BOD from Facultative Ponds from domestic sources (mg/l)	55.25	33.1236	4.086	0.009	20.4889	90.0111
Mean TOW from Facultative Ponds from domestic sources (kg BOD/yr) X10 <sup>6</sup>	110.553	64.3487	4.086	0.01	38.0236	173.0832

BOD and TOW of facultative ponds re correlated at 0.983. Mean facultative pond’s BOD is significantly proportional to mean total organics in the wastewater. Increase in BOD significantly causes increase in total organics with t-value of 4.086 significant at 0.01 at 95% confidence level. BOD mean of  $55.25 \pm 33.1236$  mg/l yields total organic  $11.0553 \times 10^7 \pm 64.3487 \times 10^7$  kg BOD/yr.

**4.1.1.2.3 Calculations on Emission Factor**

Calculations on methane emission factor at DESTW was based on IPCC (2006). Refer to *Equation 3.2* in chapter 3.2.1.2

**EF<sub>j</sub> = B<sub>o</sub> . MCF<sub>j</sub> .....** Equation 3.2

Source: (IPCC, 2006)

In this study, Kenya’s country-specific B<sub>o</sub> is unavailable, therefore 0.6 kg CH<sup>4</sup>/kg BOD was used (IPCC, 2006).

According to IPCC (2006), default MCF values for domestic wastewater at *Appendix III* were applied. Since anaerobic and facultative ponds at DESTW are deep lagoons of depth of more than 2 meters, value 0.8 was used as MCF.

$$\begin{aligned}
 EF_j &= B_o . MCF_j \\
 &= 0.6 \text{ kg CH}^4/\text{kg BOD} \times 0.8 \\
 &= 0.48 \text{ kg CH}^4/\text{kg BOD}
 \end{aligned}$$

**4.1.1.2.4 Calculations on Methane Gas Emission**

Methane emission estimation was based on IPCC (2006). Refer to ..... *Equation 3.3* in Chapter 3.2.1.3

$$\text{CH}_4 \text{ Emissions} = [\sum(U_i \cdot T_{ij} \cdot EF_j)] (TOW - S) - R \dots \dots \dots$$

Equation 3.3

Source: IPCC, 2006

There was no specific  $U_i$  and  $T_{ij}$  values for Nairobi City County, therefore Kenya's default values were used. Kenya's default  $U_i$  and  $T_{ij}$  are at *Appendix V, Table 0.3*. Based on these default values,  $U_i$  for DESTW was 0.38(0.08+0.3) and  $T_{ij}$  for DESTW was 1.2 (0.32+0.37+0.17+0.34).

At DESTW, there was no data on organic component removed as sludge (S). Therefore, it was assumed no sludge was removed from anaerobic and facultative ponds. There was also no data on the amount of methane gas recovered (R) from anaerobic and facultative ponds this was because no methane was recovered from DESTW ponds.

**Table 4.6: Methane emission (kg BOD/yr) X10<sup>6</sup> from domestic sources from facultative ponds at DESTW**

Date Sampled	FP1	FP2	FP3	FP4	FP5	FP6	FP7	FP8	FP9	FP10	FP11	FP12	FP13	FP14	Mean
MEAN	24.014	23.068	23.2125	26.4973	26.2039	23.4315	24.5264	25.8403	26.1338	22.3366	23.3439	23.9439	22.192	24.3074	24.1979

**Table 4.7: One-Sample Statistics of mean methane emission from domestic sources from Anaerobic and Facultative ponds**

	Mean (X10 <sup>7</sup> )	Std. Deviation (X10 <sup>7</sup> )
Mean methane Emission from domestic sources from Anaerobic Ponds	5.2044	2.1429
Mean methane Emission from domestic sources from Facultative Ponds	2.3259	1.2864

In this study, anaerobic ponds produced  $5.2044 \times 10^7 \pm 2.1429 \times 10^7$  kg CH<sup>4</sup>/yr whereas facultative ponds produced  $2.3259 \times 10^7 \pm 1.2864 \times 10^7$  kg CH<sup>4</sup>/yr. In other studies, conducted to determine methane flux from municipal stabilization ponds, (*Picot, 2013*) assessed anaerobic ponds that served a population of 13,800 in France, obtained methane flux of between 358 to 2970 mg CH<sup>4</sup>/hr (3.1361 to 26.0172 kg CH<sup>4</sup>/yr). Assessment of anaerobic ponds with a total treated flow of 3472 L/s in China, obtained methane flux of between 89 to 143 mg CH<sup>4</sup>/hr (0.7796 to 1.2527 kg CH<sup>4</sup>/yr) (*Wang, 2011*). A study on methane emissions from stabilization ponds for municipal wastewater treatment in Mexico, (*Paredes, 2015*) assessed stabilization ponds with total treated flow of between 160 to 1357 L/s and obtained methane flux between 124 to 2440 mg CH<sup>4</sup>/hr (1.0862 to 21.3744 kg CH<sup>4</sup>/yr). The difference in the amount of methane gas produced between this study in comparison to other studies is due to the different methodologies used in methane gas inventories. Also, the population supplying wastewater to DESTW is large in comparison to other studies.

**Table 4.8: One-Sample Test of mean methane emission from domestic sources from Anaerobic and Facultative ponds**

	t	Sig. (2-tailed)	95% Confidence Interval of the Difference (X10 <sup>6</sup> )	
			Lower	Upper
Mean methane Emission from domestic sources from Facultative Ponds	6.425	0.001	32.2242	71.8629
Mean methane Emission from domestic sources from Facultative Ponds	4.784	0.003	11.3626	35.1572

Mean methane production from domestic sources from anaerobic ponds is significantly correlated to mean methane production from facultative pond from domestic sources given the high t-values of 6.425 and 4.784 at 95% confidence level respectively.

### 4.1.2 Methane Emissions from Industrial Waste Water

Wastewater treated at DESTW is of both domestic and industrial sources. Their percentages in proportionality of the raw sewage inflow are not known. Therefore, as part of this study, it's critical that we also consider methane emission from wastewater from industrial sector. Similar to methane emission from domestic wastewater, total organics and emission factors will be considered in assessment of methane.

#### 4.1.2.1 Calculations on Total Organics

Total organics from industrial wastewater was based on (IPCC, 2006). Refer to Equation 3.4 on Chapter 3.2.2.1

$$TOW_i = P_i \cdot W_i \cdot COD_i \dots\dots\dots \text{Equation 3.4}$$

Source: (IPCC, 006)

**Table 4.9: COD data from Anaerobic Ponds**

Date Sampled	Anaerobic Pond I COD (kg COD/m <sup>3</sup> )	Anaerobic Pond II COD (kg COD/m <sup>3</sup> )	Mean Ponds COD (kg COD/m <sup>3</sup> )
MEAN	0.32	0.328	0.324

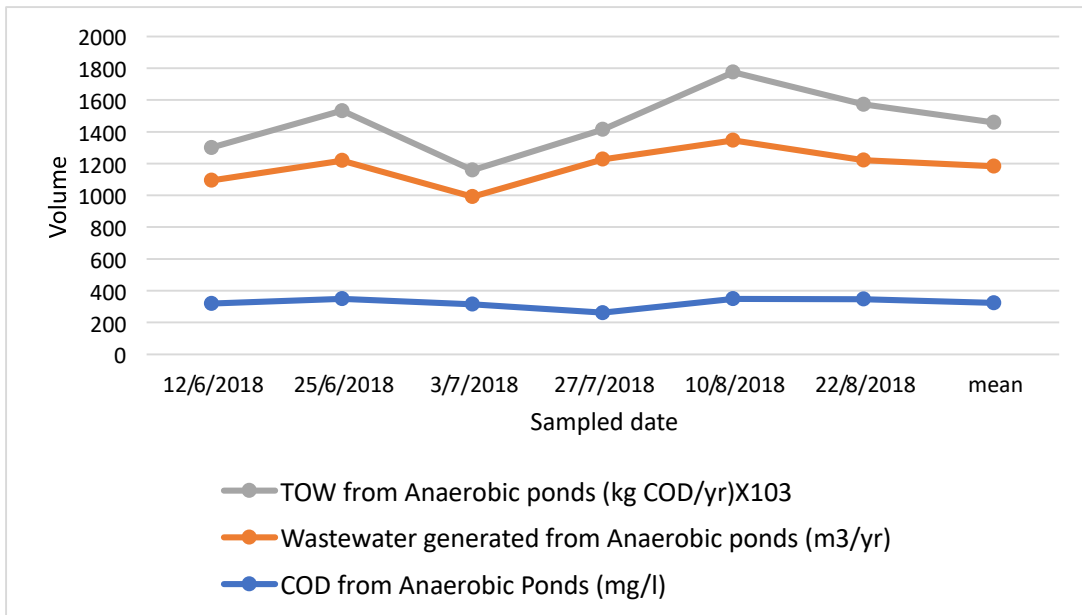
**Table 4.10: COD data from Facultative Ponds**

Date Sam pled	FP 1	FP 2	FP 3	FP 4	FP 5	FP 6	FP 7	FP 8	FP 9	FP 10	FP 11	FP 12	FP 13	FP 14	Me an FP CO D
ME AN	0.2 025	0.2 223	0.2 198	0.2 238	0.2 292	0.2 135	0.2 437	0.2 115	0.2 622	0.2 118	0. 22	0.2 37	0. 29	0.2 728	0.2 328

**Table 4.11: Wastewater generated and Total industrial product data from Anaerobic and Facultative Ponds**

Date Sampled	Total Anaerobic and (m <sup>3</sup> /yr)	industrial product from Anaerobic and Facultative ponds	for Wastewater generated from Anaerobic and Facultative ponds (m <sup>3</sup> /yr)
12/6/2018		830.875	775.3
25/6/2018		1031.19	870.0125
3/7/2018		777.8844	677.8875
27/7/2018		737.9563	965.2625
10/8/2018		1229.943	997.0875
22/8/2018		1151.025	875.275

Source: DESTW, 2018



**Figure 4.1: Stacked line chart for COD, TOW and Wastewater generated from anaerobic ponds from industrial sources**

According to Alexander (1988), the treatment system was designed to work to optimum operational output to treat both industrial and domestic wastewater. This is to ensure that volatile acids from industrial sources do not affect bacteria activity responsible for breaking down of organic matter in the wastewater (Gibb, 1996). Given the formula ( $TOW_i = P_i \cdot W_i \cdot COD_i$ ), the total organics in the wastewater from anaerobic and facultative ponds are given in Table 4.12.

**Table 4.12: Mean Total organics in the Wastewater from Anaerobic and Facultative ponds**

Date Sampled	Mean TOW Anaerobic ponds COD/yr X10 <sup>5</sup> )	from (kg	Mean TOW Facultative ponds COD/yr X10 <sup>5</sup> )	from (kg
12/6/2018	2.0614		1.3496	
25/6/2018	3.1364		2.0957	
3/7/2018	1.6611		1.2814	
27/7/2018	1.8698		1.6918	
10/8/2018	4.2861		3.1885	
22/8/2018	3.5009		2.1459	

The highest anaerobic pond's COD (0.3496 kg COD/m<sup>3</sup>) recorded led to total organics yield of 3.1364 X10<sup>5</sup> kgCOD/yr. High COD was caused by the high volume of wastewater generated in the month of February. The high volume of wastewater contained in it higher organic loads.

Whereas the least anaerobic pond's COD (0.2625 kg COD/m<sup>3</sup>) recorded led to the least total organic production, 1.8698X10<sup>5</sup> KgCOD/yr. This was attributed to lower industrial waste generation leading to the least COD obtained.

The highest anaerobic pond's wastewater generated (997.0875 m<sup>3</sup>/yr) recorded led to total organics yield of 4.2861 X10<sup>5</sup> kg COD/yr. The high volume of wastewater generated attributed to high industrial activities generating high volumes of wastewater into DESTW system. Also, this could have been subject to rainfall run-off into DESTW system thereby causing increase in wastewater generation. Whereas the least anaerobic pond's wastewater generated (677.8875 m<sup>3</sup>/yr) was recorded led to the least total organic production, 1.6611X10<sup>5</sup> KgCOD/yr. The low volume of wastewater generated could have been attributed to lower rainfall, thus causing reduced runoff into DESTW leading to reduced amount of wastewater generation. TOW was a function of the quantity of wastewater generated and the COD of the wastewater.

**Table 4.13: Paired Samples Test for COD, TOW and Wastewater generated from anaerobic ponds from industrial sources**

	95% Confidence Interval		t-value	correlation	Sig. (2tailed)
	of the Difference				
	Lower	Upper			
COD from Anaerobic Ponds (kg COD/m <sup>3</sup> ) – TOW from Anaerobic ponds (kg COD/yr) X10 <sup>5</sup>	-3.2934	-1.5638	-0.6872	0.75	0.052
Wastewater generated from Anaerobic ponds – TOW from Anaerobic ponds (kg COD/yr) X10 <sup>3</sup>	757.6534	957.1164	21.036	0.626	0.133

Anaerobic pond's wastewater generated is significantly proportional to anaerobic pond's total organics in the wastewater and correlated at 0.626 at 0.133 significance. 62.6% of the wastewater generated contained organic matter. The strong positive correlation between wastewater generated and total organics showed that significant portion of the wastewater generated contained high amount of organic matter. Increase in wastewater generated significantly causes increase in total organic matter with t-value of 21.036 at 95% confidence level.

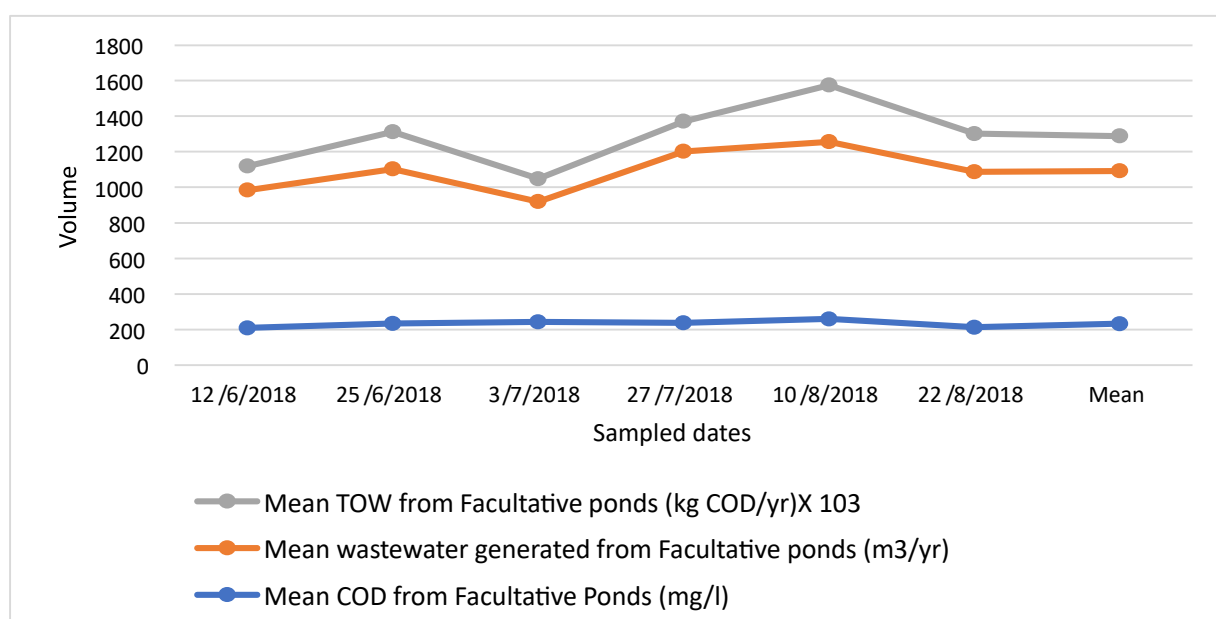
Anaerobic pond's COD is significantly proportional to anaerobic pond's total organics in the wastewater and correlated at 0.75 at 0.052 significance. Chemical oxygen demand of the wastewater is highly dependent on the amount of organic matter in the wastewater. 75% of COD was dependent on the amount of organic matter in the wastewater. Increase in organic matter significantly causes increase in COD with t-value of -0.6872 significant at 95% confidence level.

**Table 4.14: Paired Samples Statistics for Mean COD, TOW and Wastewater generated from anaerobic ponds from industrial sources**

	Mean	Std. Deviation	Std. Error Mean
COD from Anaerobic Ponds (kgCOD/m <sup>3</sup> )	0.324	0.0309	0.0117
Wastewater generated from Anaerobic ponds (m <sup>3</sup> /yr)	860.1375	108.4325	40.9836
TOW from Anaerobic ponds (kg COD/yr) X10 <sup>5</sup>	2.7526	0.9581	0.3621

COD mean of  $0.324 \pm 0.0309$  kgCOD/m<sup>3</sup> yields total organic  $2.7526 \times 10^5 \pm 0.9581 \times 10^5$  kg COD/yr. Wastewater generated mean of  $860.1375 \pm 108.4325$  m<sup>3</sup>/yr yields total organic  $2.7526 \times 10^5 \pm 0.9581 \times 10^5$  kg COD/yr.

### Facultative ponds



**Figure 4.2: Stacked line chart for Mean COD, TOW and Wastewater generated from Facultative ponds from industrial sources**

The highest facultative pond's COD ( $0.26$  kg COD/m<sup>3</sup>) recorded led to total organics yield of  $3.1885 \times 10^5$  kg COD/yr. High COD obtained could have been caused by the

wastewater influent containing high amounts of protein and starch which require higher amounts of oxygen to break down. Whereas the least facultative pond's COD (0.213 kg COD/m<sup>3</sup>) was recorded led to the least total organic production, 2.1459X10<sup>5</sup> Kg COD/yr. Low level of COD obtained could have been subject to the industrial influent discharged containing organic matter which is easily digested with low oxygen demand.

**Table 4.15: Paired Samples Correlations for Mean COD, TOW and Wastewater generated from Facultative ponds from industrial sources**

	Correlation	Sig.
Mean COD from Facultative Ponds (mg/l) and Mean TOW from Facultative ponds (kg COD/yr) X10 <sup>3</sup>	0.538	0.271
Mean wastewater generated from Facultative ponds and Mean TOW from Facultative ponds (kgCOD/yr)X10 <sup>3</sup>	0.766	0.076

Mean facultative pond's wastewater generated is significantly proportional to mean facultative pond's total organics in the wastewater and correlated at 0.766 at 0.076 significance. Increase in wastewater generated significantly causes increase in total organics with t-value of 20.57 at 95% confidence level. Wastewater generated mean of 908.472±137.1667 m<sup>3</sup>/yr yields total organic 2.2689 X10<sup>5</sup> ±8.2648 X10<sup>4</sup> kg COD/yr as shown in Table 4.16 below.

**Table 4.16: Paired Samples Test for COD, TOW and Wastewater generated from Facultative ponds from industrial sources**

	95% Confidence Interval-t-value		Sig. (2-tailed)
	of the Difference		
	Lower	Upper	
COD from Facultative Ponds (kgCOD/m <sup>3</sup> ) – TOW from Facultative ponds (kg COD/yr) X10 <sup>3</sup>	-269.3586	-121.9383	-6.823 0.001
Wastewater generated from Facultative ponds – TOW from Facultative ponds (kg COD/yr) X10 <sup>3</sup>	581.2441	747.2684	20.57 0.0

**Table 4.17: Paired Samples Statistics for COD, TOW and Wastewater generated from Facultative ponds from industrial sources**

	Mean	Std. Deviation
COD from Facultative Ponds (kgCOD/m <sup>3</sup> )	0.2327	0.1898
Wastewater generated from Facultative ponds	860.1375	118.7819
TOW from Facultative ponds (kg COD/yr) X10 <sup>3</sup>	195.8812	70.2481

Facultative pond's COD is significantly proportional to facultative pond's total organics in the wastewater and correlated at 0.538 at 0.271 significance. Increase in COD significantly causes increase in total organics with t-value of -6.823 significant at 95% confidence level. COD mean of  $0.2327 \pm 0.1898$  kg COD/m<sup>3</sup> yields total organic  $1.958 \times 10^5 \pm 0.7023 \times 10^5$  kg COD/yr.

#### 4.1.2.2 Calculations on Emission Factors

Methane emission factors calculations were based on IPCC (2006). Refer to *Equation 3.5* in chapter 3.2.2.2

$$EF_j = B_o \cdot MCF_j \dots\dots\dots \text{Equation 3.5}$$

Source: (IPCC, 2006)

MCF is the fraction of wastewater treated anaerobically. In this study, Kenya’s country-specific  $B_o$  is unavailable, therefore 0.25 kg CH<sup>4</sup>/kg COD was used (IPCC, 2006).

According to the (IPCC, 2006), default MCF values for domestic wastewater at *Appendix VII* were applied. Since anaerobic and facultative ponds at DESTW are deep lagoons of depth of more than 2 meters, value 0.8 will be used as MCF.

$$\begin{aligned} EF_j &= B_o \cdot MCF_j \\ &= 0.25 \text{ kg CH}^4/\text{kg COD} \times 0.8 \\ &= 0.2 \text{ kg CH}^4/\text{kg COD} \end{aligned}$$

#### 4.1.2.3 Calculations on Methane Gas Emission

Methane emission calculations from industrial wastewater were based on (IPCC, 2006).

$$CH_4 \text{ Emissions} = \sum[(T O W_i - S_i)E F_i - R_i] \dots\dots\dots$$

Equation 3.6

Source: (IPCC, 2006)

At DESTW, no sludge has been removed from anaerobic and facultative ponds in the inventory year 2017. There was also no methane recovered ( $R_i$ ) from DESTW ponds.

**Table 4.18: Paired Sample Statistics of methane emission from Industrial sources from Anaerobic and Facultative ponds**

	Mean (X10 <sup>4</sup> )	Std. Deviation (X10 <sup>4</sup> )
Mean CH <sup>4</sup> Emission from Industrial sources from Anaerobic ponds	5.5053	1.9162
Mean CH <sup>4</sup> Emission from industrial source from Facultative ponds	3.9176	1.2826

Mean methane emitted from industrial sources from anaerobic ponds was  $5.5053 \times 10^4 \pm 1.9162 \times 10^4$  kg CH<sup>4</sup>/yr and  $3.9176 \times 10^4 \pm 1.2826 \times 10^4$  kg CH<sup>4</sup>/yr from facultative ponds. In a similar study conducted by Paredes et al., (2015) on methane emissions from stabilization ponds for municipal wastewater treatment in Mexico in the year 2010, a total of 2186 municipal wastewater treatment plants were sampled, treating a total flow of 93.6 m<sup>3</sup>/s, representing 45% of the collected municipal wastewater collected at national level, produced  $600.4 \times 10^3$  kg of methane.

**Table 4.19: Paired Samples Correlations of methane emission from Industrial sources from Anaerobic and Facultative ponds**

	Correlation	t-value	Sig.
CH <sup>4</sup> Emission from Industrial sources from Anaerobic ponds and CH <sup>4</sup> Emission from industrial source from Facultative ponds	0.943	5.08	0.001

Methane emitted from anaerobic ponds is correlated to methane emitted from facultative ponds at 0.943 and significant at 0.001 with t-value of 5.08 at 95% confidence level. The strong positive correlation showed that significant portion of industrial wastewater from both anaerobic and facultative ponds was converted to methane gas. Methane emitted from industrial sources from anaerobic ponds is significantly proportional to methane emitted from facultative ponds.

**Table 4.20: One-Sample Test of methane emission from Industrial sources from Anaerobic and Facultative ponds**

	t	95% Confidence Interval of the Difference	
		Lower	Upper
CH <sup>4</sup> Emission from Industrial sources from Anaerobic ponds	7.601	3.7331	7.2775
CH <sup>4</sup> Emission from industrial source from Facultative ponds	8.082	2.7315	5.1038

At 95% confidence level, mean methane emitted from industrial sources from anaerobic ponds has t-value of 7.601 whereas facultative ponds have t-value of 8.082 at 95% confidence level. Anaerobic ponds have a moderate t-value (7.601) in comparison to facultative ponds (8.082) indicating that other factors such as pH and organic loading affect methane production at anaerobic ponds. Methanogenic bacteria could only survive in a very narrow pH range close to neutral pH (Tabatabaei, 2011).

#### **4.1.3 Environmental Parameters and Methane Emission Correlations**

##### **4.1.3.1 Total Organics in the Wastewater and Methane Production**

The correlation between Total Organics in Wastewater (TOW) and methane production is a critical area of study in wastewater treatment processes. TOW represents the concentration of organically degradable material present in the wastewater, which serves as a substrate for microbial activity (Droste, 1997). The biodegradation of these organic materials by anaerobic microorganisms leads to the production of methane, a potent greenhouse gas (Metcalf and Eddy, 2014). Understanding this correlation is essential for optimizing the treatment process and minimizing methane emissions (Rittmann and McCarty, 2001). Research has shown that higher levels of TOW typically result in increased methane production due to the greater availability of

organic substrates for microbial metabolism (Gerardi, 2003). By analyzing the relationship between TOW and methane production, it is possible to develop strategies to enhance the efficiency of wastewater treatment systems and reduce their environmental impact (Henze et al., 2008).

**Table 4.21: TOW and methane gas emission from anaerobic ponds**

Date Sampled	TOW from Anaerobic Ponds (kg BOD/yr) X10 <sup>8</sup>	Mean Methane Emission from Anaerobic Ponds (kg CH <sup>4</sup> /yr) X10 <sup>7</sup>
Mean	2.3771	5.2031

The highest total organics, 4.3421 X10<sup>8</sup> kg BOD/yr recorded led to 9.5039 X10<sup>7</sup> kg CH<sup>4</sup>/yr the highest methane production. This was due to increase in organic loading. For anaerobic conditions to occur successfully in anaerobic, BOD loading rate should be between 0.04-0.3 kg/m<sup>3</sup>/d (Kaewmai, 2013). The long desludging period of anaerobic ponds, 5 years, could also be another reason for high BOD values obtained. In the anaerobic and primary facultative ponds, sewage BOD is converted into algal BOD (Marais, 1970). The primary function of these ponds is BOD reduction. Anaerobic ponds BOD obtained were higher than the design expectations of 20mg/l (Alexander, 1988). High BOD may be attributed to re-suspension of settled solids and algal BOD converted from sewage BOD.

High amounts of organic loading at ambient pH (7.0 - 7.5) and temperature (22 - 25<sup>0</sup>C) causes increased anaerobic digestion of the wastewater thereby leading to increased methane gas production. The least total organics 1.1806 X10<sup>8</sup> kg BOD/yr obtained led to 2.584 X10<sup>7</sup> kg CH<sup>4</sup>/yr, the least methane emission. This was attributed to lower organic loading.

**Table 4.22: One-Sample Statistics for Mean TOW and mean methane emission from anaerobic ponds**

	Mean	Std. Deviation
Mean TOW from Anaerobic Ponds (kg BOD/yr) X10 <sup>8</sup>	2.3778	0.9791
Mean methane Emission from Anaerobic Ponds (kg CH <sup>4</sup> /yr) X10 <sup>7</sup>	5.2044	2.143

At total organics mean of  $2.3778 \times 10^8 \pm 0.9791 \times 10^8$  kg BOD/yr from anaerobic ponds from domestic sources, mean methane emission is  $5.2044 \times 10^7 \pm 2.143 \times 10^7$  kg CH<sup>4</sup>/yr. In Kristianstad, Sweden, 200 tons of biomass are daily digested in a co-digestion system fed with manure, organic household waste and industrial wastes from abattoirs and distilleries producing between 8000 to 9000 Nm<sup>3</sup> of biogas per day (Mes, 2003).

The significant deviation in TOW is attributed to dilution effect during rainy period. BOD is significantly proportional to methane production. Increase in BOD causes increase in methane production. This is because increase in BOD is caused by increase in organic matter in the wastewater, breakdown of the organic matter by methanogenic bacterial activity leads to production of methane gas and water as the final products.

**Table 4.23: One-Sample Test for TOW and methane emission from anaerobic ponds**

	t	95% Confidence Interval of the Difference	
		Lower	Upper
TOW from Anaerobic Ponds (kg BOD/yr)	6.425	1.4722	3.2832
Methane Emission from Anaerobic Ponds (kg CH <sup>4</sup> /yr)	6.425	3.2224	7.1863

Total organics is significantly proportional to methane emission with t-value of 6.425 at 95% confidence level. Total organics has a significant effect on methane production.

This is because, organic loading has been known to affect the production of methane gas (Habeeb, 2011). Total Organics in Wastewater obtained in anaerobic ponds and methane emissions have a similar higher t-value as methane emission because total solids are highly dependent on the physical, chemical and biochemical reactions within the ponds. Total solids recorded at DESTW were below 1200 mg/l permissible by Water Quality Regulations, Kenya (2006).

#### **4.1.3.2 Temperature and Methane Production**

For a pond to be efficient in production of a substantial amount of methane, two important factors are critical, ambient air and pond temperatures. A power law relationship between biogas production and ambient temperature has been developed and is expressed in the following equation (McGrath, 2004):

$$R=1.241(T_a)^{1.127}$$

Where  $R$  is the areal biogas production ( $L/m^2$  day) and  $T_a$  the ambient temperature ( $^{\circ}C$ ). Anaerobic ponds recorded a mean temperature of  $22^{\circ}C$ . These are ambient temperatures in hot climate countries and are conducive for anaerobic reactions. BOD removal of up to 60% can be achieved at temperatures above  $20^{\circ}C$  (Gambrill, 1986). Temperature is one of the factors that affect methane production during anaerobic digestion (Sukias, 2011). When the methanogenesis process is stressed by shock loads or temperature fluctuations, methanogenic bacteria activity happens more slowly than the acid formers and an imbalance occur.

**Table 4.24: Methane emission from domestic and industrial sources and temperature from anaerobic ponds**

Date Sampled	Domestic sources Mean CH <sup>4</sup> Emission Anaerobic(kgCH <sup>4</sup> /yr) X10 <sup>7</sup> From Ponds	Industrial Sources Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr)X 10 <sup>4</sup>	Anaerobic Ponds Temperature (°C)
12/6/2018	5.3871	4.1227	21.5
25/6/2018	5.2119	6.2729	22
3/7/2018	9.5039	3.3221	21
27/7/2018	2.584	3.7397	21.5
10/8/2018	3.8104	8.5723	22.5
22/8/2018	4.7301	7.0019	21

Given that atmospheric temperatures cannot be controlled; we cannot therefore control methane production at DESTW in relation to temperature fluctuations. However, in a study conducted by (USEPA, 2011) at East Bay Municipal Utility District, methane gas production increased when anaerobic digesters were operated at thermophilic rather than mesophilic temperatures because there was higher growth rate of the methanogens at higher temperatures. In this study, methane gas appears to increase with increase in atmospheric temperatures. Peak gas production occurred at 22<sup>0</sup>C and 22.5<sup>0</sup>C. This is likely due to higher temperatures allow higher populations of the slower growing methanogens to develop and produce more methane gas.

**Table 4.25: Paired Samples Test of mean methane emission from domestic and industrial sources and temperature from anaerobic ponds**

	Mean	Std. deviation	95% Confidence Interval of the Difference		Confidencet-value
			Lower	Upper	
Domestic sources methane Emission from Anaerobic Pond	5.2046	2.3475	2.741	7.6681	5.431
Industrial sources CH <sub>4</sub> Emission from Anaerobic ponds	5.5053	2.0991	3.3024	7.7081	6.424
Anaerobic Ponds Temperature (°C)	21.583	0.5845	20.97	22.197	90.447

At anaerobic ponds temperature of  $21.58^{\circ}\text{C} \pm 0.5845^{\circ}\text{C}$ , mean methane emission from domestic sources from anaerobic ponds at DESTW was  $5.2049 \times 10^7 \pm 2.3475 \times 10^7$  kg CH<sub>4</sub>/yr, and  $5.5053 \times 10^4 \pm 2.0991 \times 10^4$  kg CH<sub>4</sub>/yr from industrial sources from anaerobic ponds. Since this is a natural treatment system, it is critical to understand that temperature cannot be regulated. The mean temperature obtained in this study was  $21.58^{\circ}\text{C}$ . Temperature increase leads to higher methane production (Gupta, 2012). Optimum temperatures are within the range of  $25^{\circ}\text{C}$  to  $40^{\circ}\text{C}$ . Anaerobic bacteria are ineffective below  $15^{\circ}\text{C}$ . Anaerobic activity decreases rapidly at temperatures below  $15^{\circ}\text{C}$ , when temperatures drop below freezing, biological activity stops (Gupta, 2012).

**Table 4.26: Paired Samples Correlation of mean methane emission from domestic and industrial sources and temperature from anaerobic ponds**

	Correlation	Sig.
Domestic sources CH <sup>4</sup> Emission from Anaerobic Pond and Anaerobic Ponds Temperature (°C)	0.481	0.334
Industrial sources CH <sup>4</sup> Emission from Anaerobic ponds and Anaerobic Ponds Temperature (°C)	0.618	0.191

Mean methane emission from domestic sources from anaerobic ponds and mean anaerobic ponds temperature are correlated at 0.481 and significant at 0.334. Methane emission from industrial sources from anaerobic ponds and anaerobic ponds temperature are correlated at 0.618 and significant at 0.191.

The research done by Gudasz (2014) looked at the effect of specifically thermophilic bacteria. Higher temperatures speed up the reaction and allow for a shorter hydraulic retention time. It was shown that the maximum specific methanogenic activity of the effluent was best at 50°C when compared to 60°C, 30°C or 40°C. When the temperature was between 50°- 60°C, hydrolysis was negatively affected, possibly causing an increase in NH<sub>3</sub> which in turn negatively affects methanogenesis (Gudasz, 2014).

#### **4.1.3.3 pH and Methane Production**

Several studies have reported failure or under performance of anaerobic treatment system in harnessing methane due to low pH values (Tabatabaei, 2011; Visser, 1993). According to USEPA final report of 2008 on East Bay Municipal Utility District, to maintain a healthy methanogens population, pH of the anaerobic digesters was maintained between 7 and 7.5. This is through a balance between the acetogens and methanogens. Acetogens produce acid, and methanogens consume acid (increasing alkalinity) to produce methane gas (Poh, 2009).

**Table 4.27: Methane emission from domestic and industrial sources and pH from anaerobic ponds**

Date Sampled	Mean CH <sup>4</sup> Emission from Domestic Wastewater from Anaerobic ponds (kg CH <sup>4</sup> /yr) X10 <sup>7</sup>	Mean CH <sup>4</sup> Emission from Industrial Wastewater from Anaerobic ponds (kg CH <sup>4</sup> /yr) X10 <sup>4</sup>	Anaerobic ponds pH
12/6/2018	5.3871	4.1227	7.88
25/6/2018	5.2119	6.2729	7.76
3/7/2018	9.5039	3.3221	7.31
27/7/2018	2.584	3.7397	7.72
10/8/2018	3.8104	8.5723	7.45
22/8/2018	4.7301	7.0019	7.09

pH is an important factor to consider in methane production in wastewater stabilization ponds because it will assist in producing an effective biogas system (Kaewmai, 2013). pH values above 7 to help develop the methanogenic bacteria population (Mara, 1998). Optimum pH values between 6 and 8 is suitable for methanogenesis (McGarry, 1970). At DESTW, pH does not fluctuate much. Fluctuation in pH value has an effect on the anaerobic digestion process as hydrogen ion concentration has direct impact on methanogenic bacteria development. Methanogens growth rate decreases below pH value 6 and above pH value 8.3 and causes poor performance and insufficiency of anaerobic digester (Lay, 1997). pH value 6 is the lowest limit for anaerobic reaction to take place (Lettinga, 1993). This is because products from the preceding acidogenesis reaction may accumulate and lead to pH decrease (Gambrill, 1986). If the acetogens outpace the methanogens, pH will drop, which can inhibit methanogens, and ultimately lead to an upset the digester (USEPA, 2011).

**Table 4.28: Paired Samples Statistics of Mean methane emission from domestic and industrial sources and pH from anaerobic ponds**

	Mean	Std. Deviation
Mean CH <sup>4</sup> Emission from domestic sources from Anaerobic Pond (kg CH <sup>4</sup> /yr X10 <sup>7</sup> )	5.2046	2.3475
Mean CH <sup>4</sup> Emission from industrial sources from Anaerobic ponds (kg CH <sup>4</sup> /yr X10 <sup>4</sup> )	5.5053	2.0991
Mean Anaerobic ponds pH	7.535	0.3032

pH influences the chemical and biochemical reactions of the wastewater. According to (USEPA, 2011), the pH value should range from 6.6 to 8.0, but should not drop below 6.2 because methanogenic bacteria cannot function below this level. The growth rate and metabolism of the methanogenic bacteria can be adversely affected by small fluctuations in pH substrate concentrations, and temperature, however, the performance of acid-forming bacteria is more tolerant over a wide range of conditions. Sudden fluctuations of pH will inhibit anaerobic activity (USEPA, 2011). It is necessary that pH does not fluctuate or goes below value 6.2 as methane production process is sensitive to pH change. pH balance can be achieved through pretreatment of industrial wastewater at the source industries before being discharged into DESTW system.

At mean anaerobic ponds pH of  $7.535 \pm 0.3032$ , mean methane emission from domestic sources from anaerobic ponds at DESTW was  $5.2046 \times 10^7 \pm 2.3475 \times 10^7$  kg CH<sup>4</sup>/yr, and  $5.2053 \times 10^4 \pm 2.0991 \times 10^4$  kg CH<sup>4</sup>/yr from industrial sources from anaerobic ponds. Increase in pH causes increase in alkalinity of the wastewater up to an optimum pH value of 7.5 favors development of methanogenic bacteria which leads to production of higher amounts of methane (Mara, 1998).

**Table 4.29: Paired Samples Test of Mean methane emission from domestic and industrial sources and pH from anaerobic ponds**

	95% Interval Difference		Confidence Interval of the Difference		Sig. (2-tailed)
	Lower	Upper	Lower	Upper	
CH <sup>4</sup> emission from domestic sources from Anaerobic Pond – Anaerobic ponds pH	-4.9066	0.2457	-2.325	0.068	
CH <sup>4</sup> emission from industrial sources from Anaerobic ponds – Anaerobic ponds pH	-4.3586	0.2991	-2.24	0.075	

Methane emission from domestic sources from anaerobic ponds and anaerobic ponds pH has t-value of -6.584 and 0.001 significant at 95% confidence level. Methane emission from industrial sources from anaerobic ponds and anaerobic ponds pH has t-value of -2.24 and 0.075 significant at 95% confidence level. The high difference in t-value could be attributed to storm and agricultural run-off from point and non-point sources of pollution. Human activities for instance, accidental chemical spills, sewer overloads and discharge of chemicals by Nairobi

City County residents and industries can have significant effect on pH levels (Gambrill, 1986).

**Table 4.30: Paired Samples Correlation of methane emission from domestic and industrial sources and pH from anaerobic ponds**

	Correlation	Sig.
CH <sup>4</sup> emission from domestic sources from Anaerobic Pond and Anaerobic ponds pH	-0.297	0.567
CH <sup>4</sup> emission from industrial sources from Anaerobic ponds and Anaerobic ponds pH	-0.335	0.516

The high pH values are attributed to reactions of carbonate and bicarbonate ions which provide carbon dioxide for the algae, leaving an excess of hydroxyl ions (Marais, 1970). High pH values may also indicate industrial or other non-domestic wastewater discharges (IDEQ, 2006). Methane emission from domestic sources from anaerobic

ponds and anaerobic ponds pH are correlated at -0.297 and significant at 0.567. Methane emission from industrial sources from anaerobic ponds and anaerobic ponds pH are correlated at -0.335 and significant at 0.516. According to this study, increase in anaerobic ponds pH significantly causes increase in methane emissions by greater than 78%. Increase in pH above the optimum pH 7.6, however, causes decrease in methane production (Mara and Pearson, 1998). Methanogenic bacteria responsible for the production of methane gas often grow at pH range of 6.5 to 8.2 (Anunputtikul, 2004).

#### 4.1.3.4 Biochemical Oxygen Demand and Methane Production

At the aerobic layer near the surface of the pond, methane oxidizes to carbon dioxide. However, methane emission has been observed to be much higher than carbon dioxide emission (Silva, 2012). This is attributed to carbon dioxide usage by the photosynthetic algae, leading to rise in pH. At higher pH levels, carbon dioxide is converted to carbonic acid and bicarbonates. Nonetheless, carbon dioxide emission is dependent on pH value of the wastewater pond (Silva, 2012).

**Table 4.31: Mean methane gas emission and BOD from anaerobic ponds**

Date Sampled	Domestic sources CH <sup>4</sup> Emission from Anaerobic Ponds (kg CH <sup>4</sup> /yr) X10 <sup>7</sup>	Anaerobic Ponds BOD (mg/l)
12/6/2018	5.3871	123
25/6/2018	5.2119	119
3/7/2018	9.5039	217
27/7/2018	2.584	59
10/8/2018	3.8104	87
22/8/2018	4.7301	108

High BOD in anaerobic ponds could be due to high organic loading. High pollution levels of the wastewater could also lead to high BOD values obtained. BOD values

obtained are higher than 102 mg/l obtained in Egypt (Fatma, 1998) and could be due to the high Nairobi City population discharging wastewater into DESTW.

The mean temperature of anaerobic ponds obtained at DESTW were higher than 20°C and this could have contributed to high BOD values since waste stabilization is achieved by physical, chemical and biochemical reactions influenced by temperature, amongst other factors. Temperatures above 20°C are conducive for bacterial action on organic matter (Gambrill, 1986).

**Table 4.32: One-Sample Statistics of Mean methane emission and BOD from anaerobic ponds**

	Mean	Std. Deviation
Methane Emission from Anaerobic Ponds (kg CH <sup>4</sup> /yrX10 <sup>7</sup> )	5.2046	2.3475
Anaerobic Ponds BOD (mg/l)	118.833	53.6

At mean anaerobic ponds BOD of 118.833 mg/l ± 53.6 mg/l, mean methane emission from domestic sources from anaerobic ponds at DESTW was 5.2046 X10<sup>7</sup> kg CH<sup>4</sup>/yr ± 2.3475 X10<sup>7</sup> kg CH<sup>4</sup>/yr. The long desludging period of anaerobic ponds, 5 years, could also be another reason for high BOD values obtained.

**Table 4.33: One-Sample Test of Mean methane emission and BOD from anaerobic ponds**

	t	Correlation	Sig.(2-tailed)	95% Confidence Interval of the Difference	
				Lower	Upper
Methane Emission from Anaerobic Ponds (kg CH <sup>4</sup> /yrX10 <sup>7</sup> ) - Anaerobic Ponds BOD (mg/l)	-5.431	1.0	0.003	-167.415	-59.8425

Methane emission from domestic sources from anaerobic ponds and mean anaerobic ponds BOD have t-value of -5.431 with a correlation value 1.0 at 95% confidence level.

BOD is significantly proportional to methane production. Increase in BOD causes increase in methane production. The t-value could be attributed to high sulphides, organo-chlorides and heavy metals concentration in the wastewater. Possible toxicity of dissolved oxygen can enter anaerobic ponds with the wastewater influent (Rinzima, 1988).

#### **4.1.3.5 Chemical Oxygen Demand and Methane Production**

Understanding this correlation is crucial for optimizing wastewater treatment systems and reducing methane emissions, a potent greenhouse gas with a significant impact on climate change (IPCC, 2014). Research has demonstrated that as COD levels increase, there is a corresponding rise in methane production, emphasizing the need for efficient COD reduction strategies to mitigate environmental impacts (Gerardi, 2003). By analyzing the relationship between COD and methane production, it is possible to enhance the efficiency of wastewater treatment processes and develop effective mitigation measures (Henze et al., 2008).

High COD obtained in the wastewater could be attributed to conversion of effluent into carbon dioxide, water and bacterial and algae cells in presence of oxygen. Algae found in the aerobic zone of the facultative ponds require sunlight and carbon dioxide to photosynthesize, they produce oxygen, an excess of which is used by bacteria to further breakdown organic matter within the effluent (Marais, 1970).

High COD in the anaerobic ponds could also be attributed to high industrial effluents discharged into DESTW system (IDEQ, 2006). The plant receives both domestic and industrial wastewater effluents (APHA, 2005). The mean COD obtained in this study was higher than 250 mg/l obtained at a treatment plant with similar treatment system as DESTW in Egypt (Fatma, 1998).

**Table 4.34: One-Sample Statistics of Mean methane emission and COD from anaerobic ponds**

	Mean	Std. Deviation
CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yrX10 <sup>4</sup> )	5.5053	2.0991
Anaerobic Ponds COD (mg/l)	324.017	33.8736

At mean anaerobic ponds COD of 324.017 mg/l  $\pm$  33.8736 mg/l, mean methane emission from industrial sources from anaerobic ponds at DESTW was 5.5053 X10<sup>4</sup> kg CH<sup>4</sup>/yr  $\pm$  2.0991 X10<sup>4</sup> kg CH<sup>4</sup>/yr. High COD suggests high organic overloading and inorganic wastes toxicity discharged into the system (Alexander, 1988).

**Table 4.35: One-Sample Test of methane emission and COD from anaerobic ponds**

	Correlation	Significance	t	95% Confidence Interval of the Difference	
				Lower	Upper
CH <sup>4</sup> emission from Anaerobic ponds (kg CH <sup>4</sup> /yrX10 <sup>4</sup> ) - Anaerobic Ponds COD (mg/l)	0.75	0.86	-24.133	-352.4377	-284.5851

Methane emission from industrial sources from anaerobic ponds has t-value of -24.133 at 95% confidence level. Methane emission and anaerobic COD are correlated at 0.75 with 0.86 significance. The performance of methane production as a function of the quantity of COD showed that high concentration of organic matter in the wastewater was used for methane production (Enitan, 2015). COD is significantly proportional to methane production. Increase in COD leads to increase in methane production. The difference in t-value is due to biodegradable pollutants and non-biodegradable oxidizable pollutants contained in the wastewater (Tchobanoglous, 2003).

#### 4.1.3.6 Total Solids and Methane Production

Total solids (TS) include all particles suspended in the wastewater which will not pass through a filter, and total dissolved solids. Total solids often include high concentrations of dissolved compounds which are not removed in the wastewater and can add a laxative effect (Olivia, 1980). Total solids often contain ions which might affect pH of the wastewater and in turn affect methane production. Total solids are removed from the ponds when they settle as sludge (Mumba, 1999).

Total Solids is used to monitor the solids content of the wastewater in the ponds. They represent the organic, or biodegradable fraction of the wastewater (USEPA, 2011). Higher amounts of total solids concentration led to production of higher amount methane emissions. Highest total solids findings obtained in the wastewater,  $9.97 \times 10^2$  mg/l, led to production of the highest amount of methane production,  $9.5039 \times 10^7$  kg  $\text{CH}_4$ /yr in the domestic wastewater. This means that less total solids can be consumed by methanogenic bacteria, yielding more methane gas. Low amounts of total solids were digested causing production of higher amounts of methane gas. The remaining total solids were moved on to the next pond (facultative pond) for further breakdown. Total solids can either be inert or pass through the digestion process leading to production of methane gas or can be removed as residual biomass remaining after digestion. This shows a lower total solid content favors the final methane yield. Such a result is consistent with previous findings (Li, 2011) obtained using different biodegradable substrates and confirms that the conversion of acids to methane by methanogenic bacteria can be negatively influenced by the lack of water (Lay, 1997).

**Table 4.36: Paired Samples Statistics of Mean methane emission from domestic and industrial sources and Total solids from anaerobic ponds**

	Mean	Std. Deviation
Domestic sources methane emission from anaerobic ponds kg CH <sup>4</sup> /yr X10 <sup>7</sup>	5.2046	2.3475
Mean Anaerobic Ponds Total Solids (mg/l X 10 <sup>2</sup> )	9.1533	0.7929
Industrial sources methane emission from anaerobic ponds kg CH <sup>4</sup> /yr X10 <sup>4</sup>	5.5053	2.0991

Mean anaerobic ponds total solids of  $9.1533 \times 10^2$  mg/l obtained at DESTW was lower than 1404 mg/l obtained in Los Angeles County joint WTPs on a study on quality of raw wastewater and primary effluent at selected plants in California (Asano, 1987). This could be attributed to variety of inorganic and organic compounds in the influent quantity. At mean anaerobic ponds total solids of  $9.1533 \times 10^2$  mg/l  $\pm 0.7929 \times 10^2$  mg/l, mean methane emission from domestic sources from anaerobic ponds at DESTW was  $5.2046 \times 10^7$  kg CH<sup>4</sup>/yr  $\pm 2.3475 \times 10^7$  kg CH<sup>4</sup>/yr, and  $5.5053 \times 10^4 \pm 2.0991 \times 10^4$  kg CH<sup>4</sup>/yr from industrial sources from anaerobic ponds.

**Table 4.37: Paired Samples Test of methane emission from domestic and industrial sources and Total solids from anaerobic ponds**

	95% Confidence Interval of the Difference		t-value	Sig. (2-tailed)
	Lower	Upper		
Domestic sources methane emission from Anaerobic Pond (kg CH <sup>4</sup> /yr X10 <sup>7</sup> ) – Mean Anaerobic Ponds Total Solids (mg/l X 10 <sup>2</sup> )	-5.8033	-2.0941	-5.473	0.003
Industrial sources methane emission from anaerobic ponds (kg CH <sup>4</sup> /yr X10 <sup>4</sup> ) – Anaerobic ponds Total Solids (mg/l X 10 <sup>2</sup> )	-6.1573	-1.1388	-3.737	0.013

Methane emission from domestic sources from anaerobic ponds and mean anaerobic ponds total solids have t-value of -5.473 and 0.003 significant at 95% confidence level whereas industrial source has t-value of -3.737 significant at 0.013. This could have been attributed to high concentration of protein in the influent before treatment. Protein can easily be converted to biomass which in turn increases total solids in the wastewater (Enitan, 2015). Total solids are inversely proportional to methane production, increase in total solids leads to decrease in methane production from domestic wastewater sources; whereas total solids are significantly proportional to methane production from industrial wastewater sources at anaerobic ponds.

**Table 4.38: Paired Samples Correlation of methane emission from domestic sources and Total solids from anaerobic ponds**

	Correlation	Sig.
Domestic sources methane Emission from Anaerobic Pond (kg CH <sup>4</sup> /yr X10 <sup>7</sup> ) – Anaerobic Ponds Total Solids (mg/l X 10 <sup>2</sup> )	0.81	0.051
Industrial sources methane emission from anaerobic ponds (kg CH <sup>4</sup> /yr X10 <sup>4</sup> ) – Anaerobic ponds Total Solids (mg/l X 10 <sup>2</sup> )	-0.205	0.697

Methane emission from domestic sources from anaerobic ponds and mean anaerobic ponds total solids are correlated at -0.656 and significant at 0.157. Industrial wastewater sources are correlate to anaerobic ponds total solids at 0.399 significant at 0.433. Total solids are inversely proportional to methane production, increase in total solids leads to decrease in methane production for methane emission from domestic sources; whereas total solids are significantly proportional to methane production from industrial sources at anaerobic ponds.

It is worth noting a decreasing trend of the initial methane production rate when increasing the TS percentage as already observed during the anaerobic digestion of other organic wastes more or less rapidly biodegradable: dehydrated sludge mixed with dry kitchen waste, waste excavated from a sanitary landfill, paper waste, cellulose and cardboard (Lay, 1997). At a lower TS concentration, owing to the increasing water content and to the more favorable transport and mass transfer conditions, it seems plausible that the microorganisms are better sustained with soluble substrates, so that the process takes place more rapidly (Li, 2011). More research has to be done to confirm the observed trend with a wider TS range.

DESTW phase two was completed in 1990 and commissioned in 1992. In order to analyze the trend of methane emission, it was critical to access COD and BOD data dating back to 1992. However, due to data inconsistency we analyzed data between the years 2007 and 2017. Nonetheless, the data was helpful to get an understanding on how methane emission occurred at anaerobic and facultative ponds of DESTW.

#### **4.1.4 Methane Emission at DESTW from 2007 to 2017**

DESTW phase two was completed in 1990 and commissioned in 1992. In order to analyze the trend of methane emission, it was critical to access COD and BOD data dating back to 1992.

However, due to data inconsistency we analyzed data between the years 2007 and 2017. Nonetheless, the data was helpful to get an understanding on how methane emission occurred at anaerobic and facultative ponds of DESTW.

##### **4.1.4.1 Methane Emissions from Domestic Wastewater**

###### **4.1.4.1.1 Calculation of Total Organics**

Assessment of methane emission trend from domestic wastewater was based on total organics.

(IPCC, 2006). Refer to Equation 3.1 in chapter 3.2.1.1

$$TOW = P \cdot BOD \cdot 0.001 \cdot I \cdot 365 \dots\dots\dots \text{Equation 3.1}$$

Source: (IPCC, 2006)

I = correction factor for additional industrial BOD discharged into sewers (for collected default was 1.25, for uncollected was 1.00) (IPCC, 2006). It represents industries and establishments' BOD that was co-discharged with domestic wastewater. For this study, 1.25 was used as the correction factor.

**Table 4.39: Mean BOD (mg/l) from Anaerobic and Facultative Pond at DESTW**

Year	Mean Anaerobic Ponds BOD (mg/l)	Mean Facultative Ponds BOD (mg/l)
2007	139	41.6667
2008	119.4444	77.7778
2009	206.0909	82.6813
2010	159.1667	74.75
2011	203	122.6818
2012	160.5417	79.0417
2013	147.1111	72.7222
2014	176.625	75.3375
2015	95.6667	62.0825
2016	96.3	59.5
2017	119.5	52.3571

Source: (DESTW, 2017)

**Table 4.40: Mean pH from Anaerobic and Facultative Pond at DESTW**

Year	Mean Anaerobic Ponds pH	Mean Facultative Ponds pH
2007	6.82	7.5256
2008	6.8125	7.2766
2009	7.3391	7.8204
2010	6.78	7.5645
2011	6.6975	7.4175
2012	7.0642	7.6475
2013	7.413	8.013
2014	7.36	7.9022
2015	7.4433	8.4075
2016	7.4682	8.1127
2017	7.5429	8.1971

Source: (DESTW, 2017)

#### **Nairobi's Population from 2007 to 2017**

DESTW serves Nairobi City County's population. The fraction of the population discharging wastewater to the DESTW was unknown, therefore it was assumed the entire Nairobi's population discharges wastewater into DESTW system.

**Table 4.41: Nairobi City County Population Statistics**

<b>Year</b>	<b>Population</b>
2007	2,901,511
2008	3,004,423
2009	3,138,295
2010	3,236,589
2011	3,360,123
2012	3,490,160
2013	3,625,229
2014	3,765,525
2015	3,913,512
2016	4,064,965
2017	4,222,279

Source: (World Urbanization Prospects, 2018)

According to United Nations' World Urbanization Prospects (2018), the population of Nairobi in the year 2017 was estimated to be 4,222,279 having grown from 3,138,295 from the 2009 population Census. This represents an annual 3.88% population increase. These estimations represent urban agglomeration of Nairobi, which includes Nairobi's population in addition to adjacent suburban areas. Given the (IPCC, 2006) formula ( $TOW = P.BOD.0.001.I.365$ ), total organic in the wastewater from domestic wastewater from the year 2007 to 2017 are as provided below:

**Table 4.42: Total Organics in Wastewater from Anaerobic and Facultative Ponds at DESTW from 2007 to 2017**

YEAR	Mean TOW from Anaerobic Ponds (kg BOD/yr)	Mean TOW from Facultative Ponds (kg BOD/yr)
2007	184010200.7	55158977.2
2008	163730560.6	106615318.9
2009	295090656.2	118386979.1
2010	235040468.1	110382856.4
2011	311210392.1	188078084.1
2012	255644275.2	125864857
2013	243323338.1	120283299.2
2014	303445420.5	129431390.6
2015	170816705.2	110850777.7
2016	178601859.1	110351096.7
2017	230206567.9	100861492

**4.1.4.1.2 Calculations on Emission Factor**

Methane emission factor was calculated based on IPCC (2006)

$$EF_j = B_o \cdot MCF_j \dots\dots\dots \text{Equation 3.2}$$

Source: (IPCC, 2006)

In this study, Kenya's country-specific  $B_o$  was unavailable, therefore 0.6 kg CH<sup>4</sup>/kg BOD was used (IPCC, 2006).

According IPCC (2006), default MCF values for domestic wastewater at *Appendix III* was applied. Value 0.8 was used as MCF as was the case in the inventory year 2017 since anaerobic and facultative ponds at DESTW are deep lagoons of depth of more than 2 meters.

$$EF_j = B_o \cdot MCF_j$$

$$= 0.6 \text{ kg CH}^4/\text{kg BOD} \times 0.8$$

$$= 0.48 \text{ kg CH}^4/\text{kg BOD}$$

#### 4.1.4.1.3 Calculations on Methane Gas Emission

Methane emission estimations from domestic wastewater in assessment of methane emission trend was based on IPCC (2006). Refer to ..... Equation 3.3 in chapter 3.2.1.3

$$\text{CH}_4 \text{ Emissions} = [\sum(U_i \cdot T_{ij} \cdot EF_j)] (TOW - S) - R \dots \dots \dots$$

Equation 3.3

Source: IPCC, 2006

Kenya's default  $U_i$  and  $T_{ij}$  for selected countries are at *Appendix V, Table 0.3*.

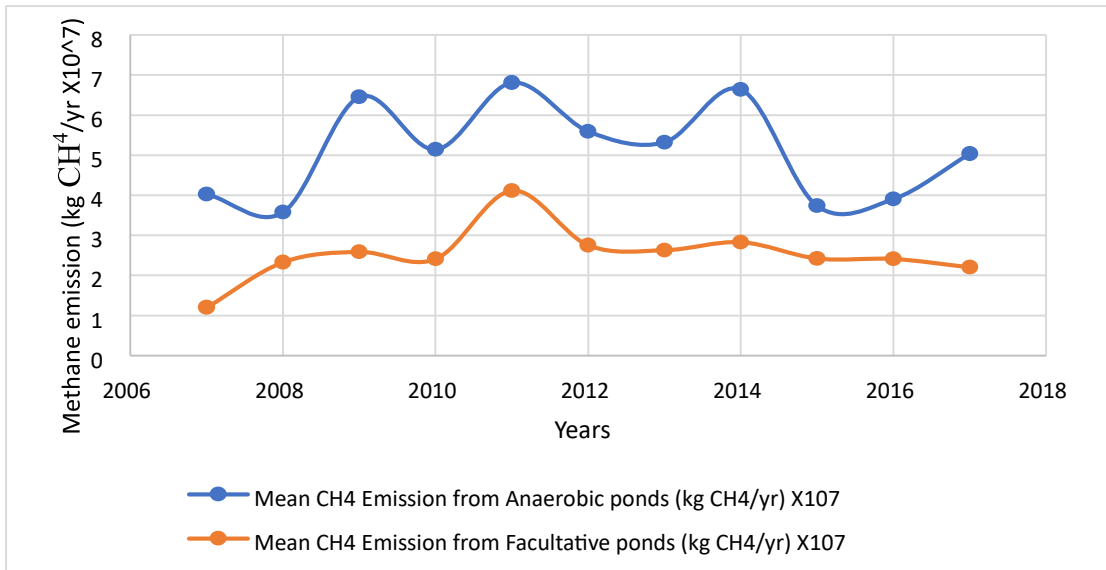
Based on these default values,  $U_i$  for DESTW was 0.38 (0.08+0.3) and  $T_{ij}$  for DESTW was 1.2 (0.32+0.37+0.17+0.34). There was no specific  $U_i$  and  $T_{ij}$  values for Nairobi City County, therefore Kenya's default values were used.

At DESTW, there was no data on organic component removed as sludge (S). There was also no data on the amount of CH<sup>4</sup> recovered (R) from anaerobic and facultative ponds this was because no methane is recovered from DESTW ponds.

**Table 4.43: Mean Methane Emission from domestic sources from Anaerobic and Facultative Ponds at DESTW between the years 2007 to 2017**

Mean annual sample	Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr) X10 <sup>7</sup>	Mean CH <sup>4</sup> Emission from Facultative ponds (kg CH <sup>4</sup> /yr) X10 <sup>7</sup>
2007	4.0276	1.2073
2008	3.5837	2.3336
2009	6.4589	2.5913
2010	5.1446	2.4161
2011	6.8118	4.1167
2012	5.5955	2.7549
2013	5.3259	2.6328
2014	6.6418	2.8329
2015	3.7388	2.4263
2016	3.9092	2.4154
2017	5.0388	2.2077

Highest methane production from domestic wastewater sources, 6.8118 X10<sup>7</sup> kg CH<sup>4</sup>/yr, was obtained in the year 2011 from anaerobic ponds, whereas 4.11167 X10<sup>7</sup> kg CH<sup>4</sup>/yr from facultative ponds. This was attributed to high BOD values obtained in the year 2011 from the wastewater. In 2011, anaerobic ponds had mean BOD of 203 mg/l and 122.6818 mg/l from facultative ponds. High BOD leads to high total organics in the wastewater (3.1121X10<sup>8</sup> kg BOD/yr) causing high methane production. As was the case with anaerobic ponds, facultative ponds obtained the highest BOD values in the same year leading to high TOW value (1.8808 X10<sup>8</sup> kg BOD/yr) and thus high methane emission in that year. This has been further shown in the Figure 4.3 below.



**Figure 4.3: Mean Methane Emission from domestic sources from Anaerobic and Facultative Ponds at DESTW between the years 2007 to 2017**

Anaerobic ponds emit higher amounts of methane than facultative ponds and are correlated at 0.67 with 0.024 significance as shown in Table 4.44 below. This is because anaerobic ponds receive wastewater with high organic matter which is highly broken down into to produce methane gas. Organic matter that did not break down at anaerobic ponds level is passed onto facultative ponds for further digestion. This leads to the higher methane production in the anaerobic ponds in comparison to facultative ponds.

**Table 4.44: Paired Samples Correlations of mean methane emission from Anaerobic and Facultative ponds**

	Correlation	Sig.
Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr) and Mean CH <sup>4</sup> Emission from Facultative ponds (kg CH <sup>4</sup> /yr)	0.67	0.024

**Table 4.45: One-Sample Statistics of mean methane emission from Anaerobic and Facultative ponds**

	Mean	Std. Deviation	Std. Error Mean
Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr X10 <sup>7</sup> )	5.1161	1.1905	0.359
Mean CH <sup>4</sup> Emission from Facultative ponds (kg CH <sup>4</sup> /yr X10 <sup>7</sup> )	2.5396	0.6784	0.2045

Mean methane emission from anaerobic ponds was  $5.1161 \times 10^7 \pm 1.1905 \times 10^7$  kg CH<sup>4</sup>/yr and  $2.5396 \times 10^7 \pm 0.6784 \times 10^7$  kg CH<sup>4</sup>/yr from facultative ponds.

**Table 4.46: One-Sample Test of mean methane emission from Anaerobic and Facultative ponds**

	t	df	95% Confidence Interval of the Difference	
			Lower	Upper
Mean CH <sub>4</sub> Emission from Anaerobic ponds (kg CH <sub>4</sub> /yr)	14.253	10	4.3162	5.9159
Mean CH <sub>4</sub> Emission from Facultative ponds (kg CH <sub>4</sub> /yr)	12.416	10	2.0838	2.9953

At 95% confidence level, mean methane emission from anaerobic ponds has t-value 14.253; whereas t-value of 12.416 from facultative ponds. From the sampled years, increase in methane production from anaerobic ponds is significantly proportional to increase in methane production from facultative ponds.

#### 4.1.4.2 Methane Emission from Industrial Wastewater

##### 4.1.4.2.1 Calculations on Total Organics

Total organics from industrial wastewater was calculated based on IPCC (2006). Refer to *Equation 3.4* in Chapter 3.2.2.1

$$TOW_i = P_i \cdot W_i \cdot COD_i \dots\dots\dots \text{Equation 3.4}$$

Source: (IPCC, 2006) Where:

$TOW_i$  = Total organics in wastewater in the inventory year, kg COD/yr

$i$  = Pond type

$P_i$  = total industrial product for pond type  $i$ , t/yr

$W_i$  = wastewater generated, m<sup>3</sup>/t product

$COD_i$  = chemical oxygen demand in wastewater, kg COD/m<sup>3</sup>

**Table 4.47: Mean COD data from Anaerobic and Facultative Ponds at DESTW**

Year	Mean Anaerobic Ponds COD (kg COD/m <sup>3</sup> )	Mean Facultative Ponds COD (kg COD/m <sup>3</sup> )
2007	0.34	0.2358
2008	0.3715	0.3363
2009	0.502	0.437
2010	0.4232	0.283
2011	0.3715	0.354
2012	0.3215	0.2308
2013	0.2482	0.2265
2014	0.3892	0.2785
2015	0.2962	0.2143
2016	0.2814	0.221
2017	0.3496	0.2336

Source: (DESTW, 2017)

**Table 4.48: Mean total industrial product data and mean wastewater generated data from Anaerobic and facultative ponds at DESTW**

Mean annual sample	Mean total industrial product for Anaerobic and Facultative ponds (m <sup>3</sup> /yr)	Mean wastewater generated from Anaerobic and Facultative ponds (m <sup>3</sup> /yr)
2007	994.5857	377.95
2008	1052.493	477.4375
2009	1012.655	820.425
2010	1004.196	1103.088
2011	1009.038	1048.4
2012	982.6961	1886.763
2013	901.6057	1774.638
2014	998.517	1584.975
2015	824.025	1087.363
2016	854.4007	1237.038
2017	905.8625	1077.3101

Source: (DESTW, 2017)

Given the IPCC (2006) formula ( $TOW_i = P_i \cdot W_i \cdot COD_i$ ), the total organics in the wastewater from anaerobic and facultative ponds are given in table 4.49 below

**Table 4.49: Total organics in the Wastewater from Anaerobic and Facultative ponds at DESTW**

Mean annual sample	Mean TOW from Anaerobic ponds (kg COD/yr)	Mean TOW from Facultative ponds (kg COD/yr)
2007	127807.2	88638.08
2008	186678.6	168990.6
2009	417065.4	363062.9
2010	468785.6	313483.8
2011	393000.7	374487.9
2012	596097.9	427929.7
2013	397125.9	362405.4
2014	615957.4	440760.9
2015	265399.4	192015.9
2016	297419	233580.7
2017	341172.8	227969

#### 4.1.4.2.2 Calculations on Emission Factors

Methane emission factors calculations were based on IPCC (2006). Refer to *Equation 3.5* in chapter 3.2.2.2

$$EF_j = B_o \cdot MCF_j \dots\dots\dots \text{Equation 3.5}$$

Source: (IPCC, 2006)

MCF was the fraction of wastewater treated anaerobically. In this study, Kenya's country specific  $B_o$  was unavailable, therefore 0.25 kg CH<sup>4</sup>/kg COD was used (IPCC, 2006).

According to IPCC (IPCC, 2006), default MCF values for domestic wastewater at *Appendix VII* were applied. As anaerobic and facultative ponds at DESTW are deep lagoons of depth of more than 2 meters, value 0.8 was used as MCF.

$$\begin{aligned}
 EF_j &= B_o \cdot MCF_j \\
 &= 0.25 \text{ kg CH}^4/\text{kg COD} \times 0.8 \\
 &= 0.2 \text{ kg CH}^4/\text{kg COD}
 \end{aligned}$$

#### 4.1.4.2.3 Calculations on Methane Gas Emission

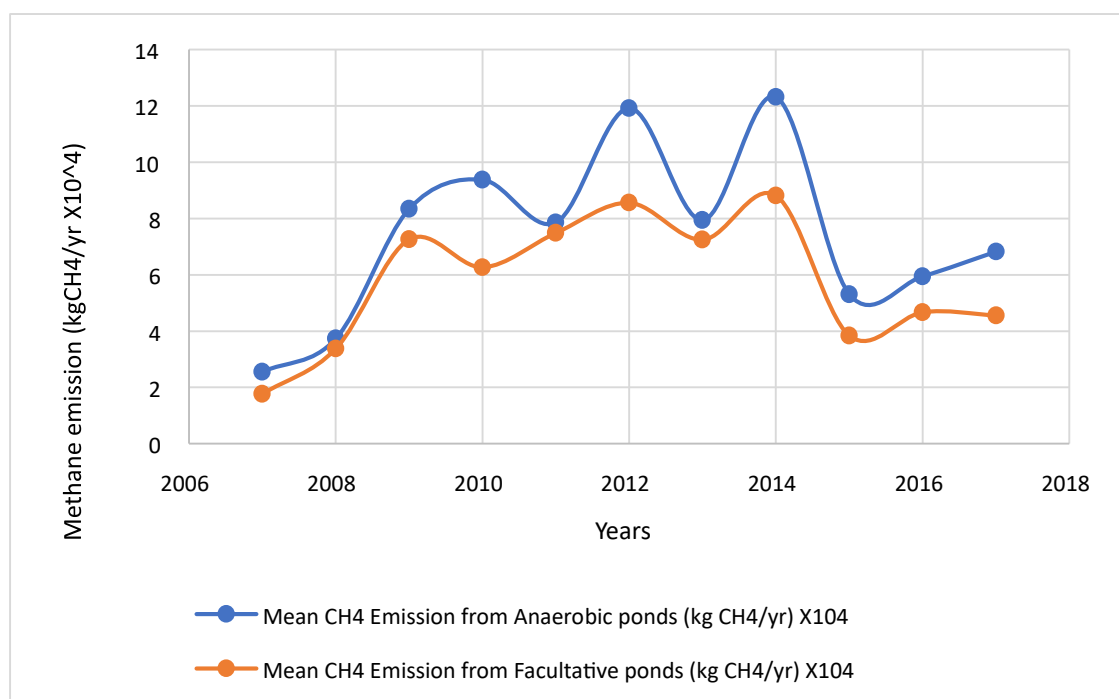
Methane emission estimations from industrial wastewater in assessment of methane emission trend was based on IPCC (IPCC, 2006). Refer to *Equation 3.6* in chapter 3.2.2.3

$$\text{CH}_4 \text{ Emissions} = \sum_i [(T O W_i - S_i) E F_i - R_i] \dots\dots\dots \text{Equation 3.6 Source: (IPCC, 2006)}$$

At DESTW, there was no data on organic component removed as sludge ( $S_i$ ) since 2007. There was also no data on the amount of CH<sup>4</sup> recovered ( $R_i$ ) from anaerobic and facultative ponds this was because no methane was recovered from DESTW ponds.

**Table 4.50: Methane Emission from industrial sources from Anaerobic and Facultative ponds at DESTW between the years 2007 to 2017**

Mean sample	annual Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr) X10 <sup>4</sup>	Mean CH <sup>4</sup> Emission from Facultative ponds (kg CH <sup>4</sup> /yr) X10 <sup>4</sup>
2007	2.5561	1.7728
2008	3.7336	3.3798
2009	8.3413	7.2613
2010	9.3757	6.2697
2011	7.86	7.4898
2012	11.9219	8.5585
2013	7.9425	7.2481
2014	12.3192	8.8152
2015	5.3079	3.8403
2016	5.9484	4.6716
2017	6.8235	4.5594



**Figure 4.4: Methane Emission trend from industrial sources from Anaerobic and Facultative ponds at DESTW between the years 2007 to 2017**

The illustration above is used to show the trend in methane emission from industrial sources from both anaerobic and facultative ponds between the years 2007 to 2017.

Highest methane emitted from industrial source at DESTW from anaerobic ponds,

1.2319 X10<sup>5</sup> kg CH<sup>4</sup>/yr, and 8.8152 X10<sup>4</sup> kg CH<sup>4</sup>/yr from facultative ponds was recorded in the year 2014. This was due to the high amount of total organics in the wastewater in those respective ponds during those years. The lowest methane emitted from industrial source at DESTW from anaerobic ponds, 10195.47 kg CH<sup>4</sup>/yr was recorded in the year 2005, and 1.2817X10<sup>4</sup> kg CH<sup>4</sup>/yr from facultative ponds was recorded in the year 2004. In both years, 2005 and 2004, there was low total organic in the wastewater 50977.37 kgCOD/yr and 64083.21 kgCOD/yr respectively. This led to the low methane gas emission estimations.

**Table 4.51: Paired Samples Statistics of mean methane emission from anaerobic and Facultative ponds**

	Mean	Std. Deviation
Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr)	67968.96	33471.569
Mean CH <sup>4</sup> Emission from Facultative ponds (kg CH <sup>4</sup> /yr)	51174.97	26870.156

In a study to determine biogas production and removal of COD, BOD and TSS from wastewater industrial alcohol (vinasse) by modified UASB bioreactor, (Isni, 2016) obtained maximum 4.6042 kg CH<sup>4</sup> produced per day. In this study, industrial wastewater produced a mean 6.7969 X10<sup>4</sup>±3.3472 X10<sup>4</sup> kg CH<sup>4</sup>/yr methane emission from anaerobic ponds and 5.1174 X10<sup>4</sup>±2.6871 X10<sup>4</sup> kg CH<sup>4</sup>/yr from facultative ponds. The correlation of Mean CH<sup>4</sup> Emission from Anaerobic ponds (kg CH<sup>4</sup>/yr) and Mean CH<sup>4</sup> Emission from Facultative ponds (kg CH<sup>4</sup>/yr) is 0.915. Mean methane emission from anaerobic ponds is correlated to mean methane emission from facultative ponds by 0.915. This shows that there is similarity in the amount of methane emitted from both types of ponds by 91.5%.

**Table 4.52: Paired Samples Test of mean methane emission from anaerobic and Facultative ponds**

	95% Confidence Interval oft-value		
	the		
	Difference		
	Lower	Upper	
Mean CH <sup>4</sup> Emission from Anaerobic ponds (kg CH <sup>4</sup> /yr) – Mean CH <sup>4</sup> Emission from Facultative ponds (kg CH <sup>4</sup> /yr)	8325.314	25262.672	4.321

Methane production from anaerobic ponds is significantly proportional to methane production from facultative ponds at 0.001 and has t-value of 4.321 at 95% confidence level. Mean methane Emission from Anaerobic ponds and Mean Methane Emission from Facultative ponds are correlated at 0.915.

## CHAPTER FIVE: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Summary

This study focused on methane emission. Anaerobic ponds emit higher amounts of methane ( $3.2641 \times 10^7$  kg CH<sub>4</sub>/yr from domestic wastewater sources and  $5.5053 \times 10^4$  kg CH<sub>4</sub>/yr from industrial sources) than facultative ponds ( $1.5176 \times 10^7$  kg CH<sub>4</sub>/yr from domestic wastewater sources and  $3.9176 \times 10^4$  kg CH<sub>4</sub>/yr from industrial sources). This is because anaerobic ponds have a higher organic matter loading than facultative ponds. Methane production is dependent on the amount of organic matter in a pond.

Total organics was significantly proportional to BOD of the wastewater. Increase in BOD led to increase in total organics in the wastewater. Total organics was significantly proportional methane emission. In domestic wastewater sources, total organics at anaerobic ponds had t-value 8.352 and 5.69 at facultative ponds to methane emission at 95% confidence level. In industrial wastewater sources, total organic from anaerobic ponds had t-value 6.599 and 8.804 from facultative ponds to methane emission at 95% confidence level.

Assessment of the trend in methane emission between the years 2007 to 2017 was done. Highest methane production from domestic wastewater sources was recorded in the year 2011,  $6.8543 \times 10^7$  kg CH<sub>4</sub>/yr from anaerobic ponds, whereas  $4.1424 \times 10^7$  kg CH<sub>4</sub>/yr from facultative ponds. The lowest methane production from domestic wastewater sources,  $2.874 \times 10^7$  kg CH<sub>4</sub>/yr, was recorded in the year 2016 from anaerobic ponds, and  $1.2073 \times 10^7$  from facultative ponds in the year 2007. Highest methane emitted from industrial sources was recorded in the year 2014,  $1.23192 \times 10^5$  kg CH<sub>4</sub>/yr from anaerobic ponds, and  $8.8152 \times 10^4$  kg CH<sub>4</sub>/yr from facultative ponds. This was attributed to high COD obtained in those respective years leading to high total

organics, thereby the high methane production. The lowest methane emitted from industrial source from anaerobic ponds was recorded in the year 2007,  $2.5561 \times 10^4$  kg  $\text{CH}_4/\text{yr}$ , and  $1.7728 \times 10^4$  kg  $\text{CH}_4/\text{yr}$  from facultative ponds. This was due to low total organics obtained in the respective ponds during those periods.

The study indicates that a significant amount of methane is emitted from anaerobic and facultative ponds at DESTW and appropriate measures should be instituted to collect the gas which can be used as a source energy and production of electricity. Pond design considerations should include sludge management and maintenance of a proper organic removal with biogas recovery (DeGarie, 2000).

## **5.2 Conclusions**

The overall methane emission assessment at DESTW is given on the basis of the methodology proposed by the Intergovernmental Panel on Climate Change (2006) on National Greenhouse Gas Inventories. Generally, the plant's anaerobic and facultative ponds significantly emit methane into the atmosphere. Mean methane emission from anaerobic ponds was  $5.2031 \times 10^7$  kg  $\text{CH}_4/\text{yr}$  whereas mean methane emission from facultative ponds was  $2.4198 \times 10^7$  kg  $\text{CH}_4/\text{yr}$ . Industrial wastewater sources mean methane emission from anaerobic ponds was  $5.5053 \times 10^4$  kg  $\text{CH}_4/\text{yr}$  and  $3.9176 \times 10^4$  kg  $\text{CH}_4/\text{yr}$  from facultative ponds.

Methane production is dependent on typical wastewater parameters such as pH, BOD, COD, TOW and temperature. Total organics in the wastewater is directly proportional to methane production and has a t-value of 6.425. pH and methane production have a negative correlation of -0.297 in the domestic wastewater and -0.335 from industrial sources. Increase in pH above neutral pH value 7 leads to increased alkalinity leading to reduced enzyme activity thus reduction of methane production. BOD and COD in

the wastewater is affected by total organics in the wastewater. BOD is directly proportional to methane production and has a correlation value 1.0 with a t-value 5.431. COD and methane production have a correlation of 0.75. Methane production is affected by both BOD and COD in the wastewater. Optimization of pH, temperature, organic loading and retention time is important in effective biogas production system (Kaewmai et al.,2013). For anaerobic conditions to occur successfully in anaerobic and facultative ponds, BOD loading rate should be between 0.04-0.3 kg/m<sup>3</sup>/d (Kaewmai et al,2013).

On the assessment of how the performance of the ponds affects methane emission, on average, anaerobic ponds have a BOD removal efficiency of 56.35%. This efficiency is similar to methane emission efficiency. This means that from domestic wastewater sources, fluctuations in the BOD of wastewater affects methane emission from domestic sources. Effluent from the anaerobic ponds has a much lower level of COD with a reduction percentage of 59.6%. This is similar to methane emission from industrial wastewater sources. COD as a measure of organic content in industrial wastewater, plays a critical role in methane emission. Increase in COD translates to increase in methane emission.

On the assessment of the trend of methane emission trend between the years 2007 and 2017, mean methane emission from anaerobic ponds and mean methane emission from facultative ponds have a correlation of 0.67 from domestic wastewater sources. Mean methane emission from anaerobic ponds and mean methane emission from facultative ponds have a correlation of 0.915 from industrial wastewater.

### **5.3 Recommendations from the Study**

#### **5.3.1 Policy Recommendations**

It is recommended that given the high methane gas yield from the inventory, methane gas should be captured from anaerobic and facultative ponds. The gas can be used as a source of energy for production of electricity.

It is recommended to separate domestic wastewater from industrial wastewater to allow for future efficient methane gas inventories to be conducted.

Industries should be under strict regulations to treat their own waste prior to disposal into DESTW system. This will enable for reduction of volatile acids composition which would otherwise affect the population and distribution of methanogenic bacteria.

Surface runoff in the event of heavy rains and storm should be channeled away from anaerobic and facultative ponds. Surface runoff might affect the pH of the wastewater thereby affecting the production of methane. Provisions should be made to divert surface runoff around the ponds. Runoff can also be prevented by erecting a protective barrier around the ponds.

#### **5.3.2 Recommendations for Further Studies**

More studies should be done on methane inventories at the treatment plant using alternate methodologies apart from the Intergovernmental Panel for Climate Change (2006) methodology.

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## APPENDICES

### Appendix I: Ponds Layout at DESTW

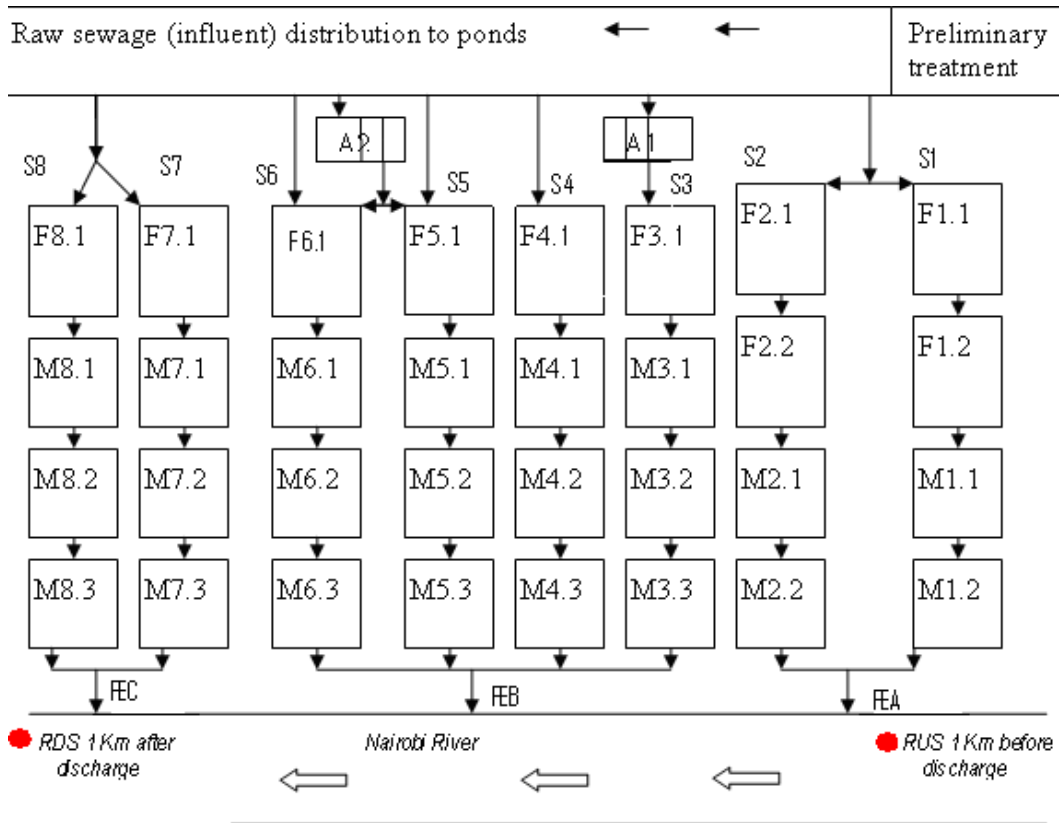


Figure A1: Ponds layout at DESTW

Source: NCWSC, 2016

KEY:

<p>←</p> <p>A1</p> <p>A2</p> <p>F</p> <p>M</p> <p>FEB</p> <p>S 1 – S 8</p> <p>FEA</p> <p>RUS</p> <p>RDS</p>	<p>Direction of flow of Nairobi River</p> <p>Anaerobic ponds along series 3</p> <p>Anaerobic ponds along series 5</p> <p>Facultative ponds</p> <p>Maturation ponds</p> <p>Final effluent (S3+S4+S5 +S6); FEC – Final effluent (S7 +S8)</p> <p>Series (1 - 8)</p> <p>Final effluent (S1+S2)</p> <p>Sampling point River upstream</p> <p>sampling point River downstream</p>
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## Appendix II: Decision Tree for Methane Gas Emission from Domestic and Industrial Wastewater

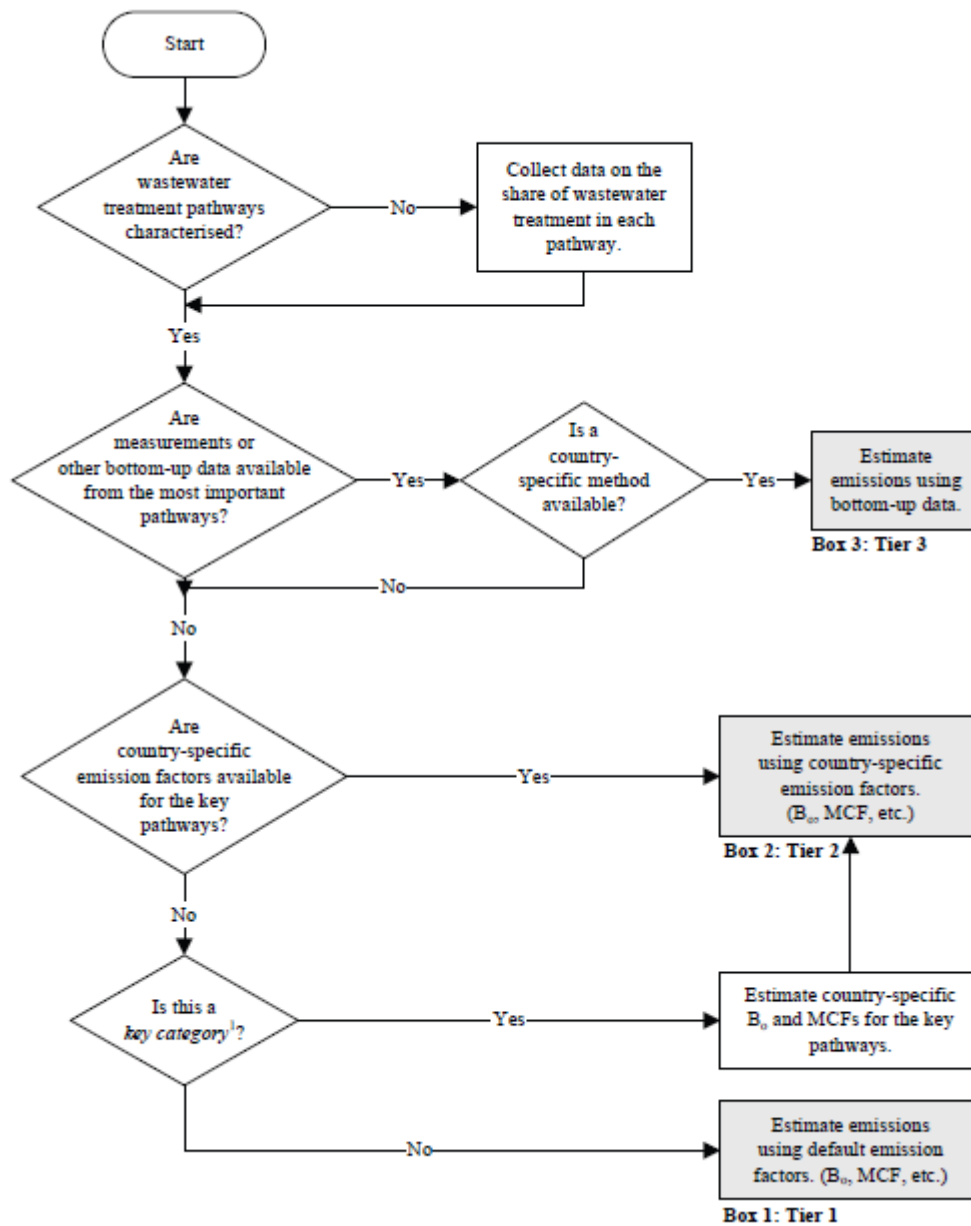


Figure A2: Decision tree for Methane Gas Emission for domestic and industrial wastewater

Source: IPCC, 2006

### Appendix III: Default MCF Values for Domestic Wastewater

DEFAULT MCF VALUES FOR DOMESTIC WASTEWATER			
Type of treatment and discharge pathway or system	Comments	MCF <sup>1</sup>	Range
<b>Untreated system</b>			
Sea, river and lake discharge	Rivers with high organics loadings can turn anaerobic.	0.1	0 – 0.2
Stagnant sewer	Open and warm	0.5	0.4 – 0.8
Flowing sewer (open or closed)	Fast moving, clean. (Insignificant amounts of methane gas from pump stations, etc)	0	0
<b>Treated system</b>			
Centralized, aerobic treatment plant	Must be well managed. Some methane gas can be emitted from settling basins and other pockets.	0	0 – 0.1
Centralized, aerobic treatment plant	Not well managed. Overloaded.	0.3	0.2 – 0.4
Anaerobic digester for sludge	Methane gas recovery is not considered here.	0.8	0.8 – 1.0
Anaerobic reactor	Methane gas recovery is not considered here.	0.8	0.8 – 1.0
Anaerobic shallow lagoon	Depth less than 2 meters, use expert judgment.	0.2	0 – 0.3
Anaerobic deep lagoon	Depth more than 2 meters	0.8	0.8 – 1.0
Septic system	Half of BOD settles in anaerobic tank.	0.5	0.5
Latrine	Dry climate, ground water table lower than latrine, small family (3-5 persons)	0.1	0.05 – 0.15
Latrine	Dry climate, ground water table lower than latrine, communal (many users)	0.5	0.4 – 0.6
Latrine	Wet climate/flush water use, ground water table higher than latrine	0.7	0.7 – 1.0
Latrine	Regular sediment removal for fertilizer	0.1	0.1
<sup>1</sup> Based on expert judgment by lead authors of this section.			

Table A3: Default MCF values for domestic wastewater Source: IPCC, 2006

**Appendix IV: Estimated BOD5 Values in Domestic Wastewater for Selected Regions and Countries**

<b>Country/Region</b>	<b>BOD5 (g/person/day)</b>	<b>Range</b>	<b>Reference</b>
Africa	37	35 – 45	1
Egypt	34	27 – 41	1
Asia, Middle East, Latin America	40	35 – 45	1
India	34	27 – 41	1
West Bank and Gaza Strip	50	32 – 68	1
Japan	42	40 – 45	1
Brazil	50	45 – 55	2
Canada, Europe, Russia, Oceania	60	50 – 70	1
Denmark	62	55 – 68	1
Germany	62	55 – 68	1
Greece	57	55 – 60	1
Italy	60	49 – 60	3
Sweden	75	68 – 82	1
Turkey	38	27 – 50	1
United States	85	50 – 120	4
<p>Note: These values are based on an assessment of the literature. Please use national values, if available. Reference:</p> <ol style="list-style-type: none"> <li>1. Doorn and Liles (1999).</li> <li>2. Feachem <i>et al.</i> (1983).</li> <li>3. Masotti (1996).</li> </ol>			

*Table A4: Estimated BOD5 values in domestic wastewater for selected regions and countries*

Source: IPCC, 2006

**Appendix V: Suggested Values for Urbanization (U) and Degree of Utilization of Treatment, Discharge Pathway or Method (Tij)  
for Each Income Group for Selected Countries.**

Country	Urbanization(U) <sup>1</sup>			Degree of utilization of treatment or discharge pathway or method for each income group (T <sub>ij</sub> ) <sup>3</sup>														
	Fraction of Population			U=rural					U= urban high income					U=urban low income				
	Rural	urban-high <sup>2</sup>	urban-low <sup>2</sup>	Septic Tank	Latrine	Other	Sewer <sup>4</sup>	None	Septic Tank	Latrine	Other	Sewer <sup>4</sup>	None	Septic Tank	Latrine	Other	Sewer <sup>4</sup>	None
<b>Africa</b>																		
Nigeria	0.52	0.10	0.38	0.02	0.28	0.04	0.10	0.56	0.32	0.31	0.00	0.37	0.00	0.17	0.24	0.05	0.34	0.20
Egypt	0.57	0.09	0.34	0.02	0.28	0.04	0.10	0.56	0.15	0.05	0.10	0.70	0.00	0.17	0.24	0.05	0.34	0.20
Kenya	0.62	0.08	0.30	0.02	0.28	0.04	0.10	0.56	0.32	0.31	0.00	0.37	0.00	0.17	0.24	0.05	0.34	0.20
South Africa	0.39	0.12	0.49	0.10	0.28	0.04	0.10	0.48	0.15	0.15	0.00	0.70	0.00	0.17	0.24	0.05	0.34	0.20
<b>Asia</b>																		
China	0.59	0.12	0.29	0.00	0.47	0.50	0.00	0.3	0.18	0.08	0.07	0.67	0.00	0.14	0.10	0.03	0.68	0.05
India	0.71	0.06	0.23	0.00	0.47	0.10	0.10	0.33	0.18	0.08	0.07	0.67	0.00	0.14	0.10	0.03	0.53	0.20
Indonesia	0.54	0.12	0.34	0.00	0.47	0.00	0.10	0.43	0.18	0.08	0.00	0.74	0.00	0.14	0.10	0.03	0.53	0.20
Pakistan	0.65	0.07	0.28	0.00	0.47	0.00	0.10	0.43	0.18	0.08	0.00	0.74	0.00	0.14	0.10	0.03	0.53	0.20
Bangladesh	0.72	0.06	0.22	0.00	0.47	0.00	0.10	0.43	0.18	0.08	0.00	0.74	0.00	0.14	0.10	0.03	0.53	0.20
Japan	0.20	0.80	0.00	0.20	0.00	0.50	0.30	0.00	0.00	0.00	0.10	0.90	0.00	0.10	0	0	0.90	0
<b>Europe</b>																		
Russia	0.27	0.73	0.00	0.30	0.10	0.00	0.60	0.00	0.10	0.00	0.00	0.90	0.00	NA	NA	NA	NA	NA
Germany <sup>5</sup>	0.06	0.94	0.00	0.20	0.00	0.00	0.80	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA
United Kingdom	0.10	0.90	0.00	0.11	0.00	0.00	0.89	0.00	0.00	0.00	0.00	1.00	0.00	NA	NA	NA	NA	NA
France	0.24	0.76	0.00	0.37	0.00	0.00	0.63	0.00	0.00	0.00	0.00	1.00	0.00	NA	NA	NA	NA	NA
Italy	0.32	0.68	0.00	0.42	0.00	0.00	0.58	0.00	0.04	0.00	0.00	0.96	0.00	NA	NA	NA	NA	NA
<b>North America</b>																		
United States	0.22	0.78	0.00	0.90	0.02	0.00	0.08	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA
Canada	0.20	0.80	0.00	0.90	0.02	0.00	0.08	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA
<b>Latin America and Caribbean</b>																		
Brazil	0.16	0.25	0.59	0.00	0.45	0.00	0.10	0.45	0.00	0.20	0.00	0.80	0.00	0.00	0.40	0.00	0.40	0.20
Mexico	0.25	0.19	0.56	0.00	0.45	0.00	0.10	0.45	0.00	0.20	0.00	0.80	0.00	0.00	0.40	0.00	0.40	0.20
<b>Oceania</b>																		
Australia and New Zealand	0.08	0.92	0.00	0.90	0.02	0.00	0.08	0.00	0.05	0.00	0.00	0.95	0.00	NA	NA	NA	NA	NA

Notes:

1. Urbanization projections for 2005 (United Nations, 2002).
2. Suggested urban-high income and urban low income division. Countries are encouraged to use their own data or best judgment.
3.  $T_{i,j}$  values based on expert judgment, (Doorn and Liles, 1999).
4. Sewers may be open or closed, which will govern the choice of MCF, see Table 3.3
5. Destatis, 2001.

Note: These values are from the literature or based on expert judgment. Please use national values, if available.

*Table A5: Suggested Values for Urbanization (U) and degree of utilization of treatment, discharge pathway or method (T<sub>ij</sub>) for each income group for selected countries*

Source: IPCC, 2006

According to IPCC (2006), the following parameters are believed to be uncertain.

- The level by which wastewater in developing countries is treated in latrines, septic tanks, or removed by sewer, for urban high, urban low-income groups and rural population ( $T_{i,j}$ ).
- The number of sewers that are ‘open’, as well as the level to which open sewers in developing countries are anaerobic and will emit methane gas. This will depend on retention time and temperature, and on other factors including the presence of a facultative layer and possibly components that are toxic to anaerobic bacteria.

The quantity of industrial TOW that is discharged into open or closed domestic sewers for each country is very difficult to quantify.

## Appendix VI: Default Uncertainty Ranges for Domestic Wastewater

Parameter	Uncertainty Range
<b>Emission Factor</b>	
Maximum CH <sup>4</sup> producing capacity	± 30%
Fraction treated anaerobically (MCF)	The MCF is technology dependent. See Table 45. Thus, the uncertainty range is also technology dependent. The uncertainty range should be determined by expert judgement, bearing in mind that MCF is a fraction and must be between 0 and 1. Suggested ranges are provided below.  Untreated systems and latrines, ± 50%
<b>Activity Data</b>	
Human population (P)	± 5%
BOD per person	± 30%
Fraction of population income group (U)	Good data on urbanization are available, however, the distinction between urban high income and urban low income may have to be based on expert
Degree of utilization of treatment/ discharge pathway or system for each income	Can be as low as ± 3% for countries that have good records and only one or two systems. Can be ± 50% for an individual method/pathway. Verify that total
Correction factor for additional industrial BOD discharged into	For uncollected, the uncertainty is zero %. For collected the uncertainty is ± 20%

Table A6: Default Uncertainty ranges for domestic wastewater

Source: IPCC, 2006

## Appendix VII: Default MCF Values for Industrial Wastewater

Type of treatment and discharge pathway or	Comments	MCF <sup>1</sup>	Range
<b>Untreated</b>			
Sea, river and lake discharge	Rivers with high organics loadings may turn anaerobic, however this is not considered here.	0.1	0 – 0.2
<b>Treated</b>			
Aerobic treatment plant	Must be well managed. Some methane gas can be emitted from settling basins and other pockets.	0	0 – 0.1
Aerobic treatment plant	Not well managed. Overloaded	0.3	0.2 – 0.4
Anaerobic digester for sludge	CH <sup>4</sup> recovery not considered here	0.8	0.8 – 1.0
Anaerobic reactor	CH <sup>4</sup> recovery not considered here	0.8	0.8 – 1.0
Anaerobic shallow lagoon	Depth less than 2 meters, use expert judgment	0.2	0 – 0.3
Anaerobic deep lagoon	Depth more than 2 meters	0.8	0.8 – 1.0
<sup>1</sup> Based on expert judgment by lead authors of this section			

*Table A7: Default MCF values for industrial wastewater*

Source: IPCC, 2006

## Appendix VIII: Examples of Industrial Wastewater Data

<b>EXAMPLES OF INDUSTRIAL WASTEWATER DATA</b>				
<b>Industry Type</b>	<b>Water Generation W</b>	<b>ange for W</b>	<b>COD</b>	<b>OD Range</b>
	<b>(m<sup>3</sup>/ton)</b>	<b>(m<sup>3</sup>/ton)</b>	<b>(kg/m<sup>3</sup>)</b>	<b>(kg/m<sup>3</sup>)</b>
Alcohol Refining	24	16 – 32	11	5 – 22
Beer and Malt	6.3	5.0 – 9.0	2.9	2 – 7
Coffee	NA	NA –	9	3 – 15
Dairy Products	7	3 – 10	2.7	1.5 – 5.2
Fish Processing	NA	8 – 18	2.5	
Meat and Poultry	13	8 – 18	4.1	2 – 7
Organic Chemicals	67	0 – 400	3	0.8 – 5
Petroleum Refineries	0.6	0.3 – 1.2	1.0	0.4 – 1.6
Plastics and Resins	0.6	0.3 – 1.2	3.7	0.8 – 5
Pulp and Paper	162	85 – 240	9	1 – 15
Soap and Detergents	NA	1.0 – 5.0	NA	0.5 – 1.2
Starch Production	9	4 – 18	10	1.5 – 42
Sugar Refining	NA	4 – 18	3.2	1 – 6
Vegetable Oils	3.1	1.0 – 5.0	NA	0.5 – 1.2
Vegetables,	20	7 – 35	5.0	2 – 10
Wine and Vinegar	23	11 – 46	1.5	0.7 – 3.0
Notes: NA =				
Not Available.				
Source: Doom				

*Table A8: Examples of Industrial wastewater data*

Source: IPCC, 2006

## Appendix IX: Default Uncertainty Ranges for Industrial Wastewater

Parameter	Uncertainty Range
<b>Emission Factor</b>	
Maximum CH <sub>4</sub> producing capacity	± 30%
Methane correction factor (MCF)	The uncertainty range should be determined by expert judgement, bearing in mind that this is a fraction and uncertainties cannot take it outside the range of 0 to 1.
<b>Activity Data</b>	
Industrial production (P)	± 25% Use expert judgement regarding the quality of data source to assign more accurate uncertainty range.
Wastewater/unit production (W)	These data can be very uncertain as the same sector might use different waste handling procedures at different plants and in different countries. The product of the parameters (W.COD) is expected to have less uncertainty. An uncertainty value can be attributed directly to kg COD/tonne of product. -50 %, +100% is suggested (i.e., a factor of 2).
COD/unit wastewater (COD)	

Table A9: Default Uncertainty Ranges for Industrial wastewater

Source: IPCC, 2006

## Appendix X: COD Analysis Procedure

1.5 ml of digestion solution is dispensed into a digestion tube, 2.5 ml of sample is added using a pipette and mixed well, 3.5 ml of catalyst solution (silver sulphate in 2.5 liters of sulphuric acid ) is added, the tube is capped tightly using a PTFE sealing gasket, the tubes contents are then mixed by gentle swirling, the tubes are then placed in a digestion block at 1500 C for 120 minutes, contents of the tube are transferred quantitatively to 100ml conical flask and sufficient water added to a final volume around 25 ml , 1 drop of ferroin indicator is added and the solution mixed well, it is titrated with FAS (N/40) until the faint blue colour changes to red and the value of the titre T ml recorded, a blank titration is carried out following the same procedure but using distilled water instead and the value of blank titre B ml recorded.

COD calculated as follows:  $COD = (B-T) / S \times 1000$  mg/l (NCWSC, 2016).

## Appendix XI: BOD Analysis Procedure

The standard 5 days, 20<sup>0</sup>C, BOD bottle test is used.

### Reagents

Dilution water, ferric chloride solution, manganous sulphate solution, sodium azide solution, alkali- iodide solution, 90 % orthophosphoric acid, N/40 sodium thiosulphate, starch solution.

### Procedure

Dilution water is prepared, sample added and incubated at 20<sup>0</sup>C for 5 days to determine dissolved oxygen, remove stopper from the BOD bottle and 2ml each of manganous sulphate solution, sodium oxide solution, alkali- iodide solution, immediately after the addition of alkali-iodide reagent a brown flocculent precipitate forms therefore the bottle is shaken to ensure that all the dissolved oxygen reacts with the reagents, when the floc settles add 2ml orthophosphoric acid and shaken until the bottle contents turn yellow, 205 ml of the bottle contents is titrated with N/40 sodium thiosulphate until pale yellow, 1 ml starch solution is added drop by drop until the color suddenly turns from blue to colorless.

BOD is calculated as follows:  $BOD = (\text{ml of thiosulphate used}) \times 0.025 / N$  (NCWSC, 2016).