# DETERMINATION OF BOD KINETIC PARAMETERS FOR DIFFERENT WASTEWATER BY USING DIFFERENT MATHEMATICAL MODEL

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**by**

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| | |
|---|---|
| BOD | Biochemical Oxygen Demand |
| BI | Biodegradability Indices |
| CBOD | Carbonaceous BOD |
| COD | Chemical Oxygen Demand |
| K | Constant Rate |
| DO | Dissolved Oxygen |
| EC | Electrical Conductivity |
| GMM | Generalized Method Of Moments |
| OUR | Oxygen Uptake Rate |
| pH | Power of Hydrogen |
| RNA | Ribonucleic Acid |
| $BOD_{st}$ | Short-Term BOD |
| RE | Relative Errors |
| TVSS | Total Volatile Suspended Solids |
| TDS | Total Dissolved Solid |
| TSS | Total Suspended Solid |
| $L_0$, $BOD_u$ | Ultimate BOD |
| WWTP | Wastewater Treatment Plants |

**PENENTUAN PARAMETER BOD KINETIK UNTUK AIR SISA YANG BERBEZA MENGGUNAKAN PELBAGAI MODEL MATEMATIK**

## ABSTRAK

Salah satu parameter terpenting kualiti air kumbahan adalah biochemical oxygen demand (BOD). Ujian BOD digunakan secara meluas untuk menentukan pencemaran air organik dan mengawal prestasi loji rawatan air kumbahan.Untuk menganggarkan jumlah jirim organik ($BOD_u$), memahami kekuatan air sisa organik dan meramalkan kesan air kumbahan selepas rawatan, ia adalah penting untuk menentukan nilai BOD ($BOD_u$) terunggul dan Pemalar kadar tindakbalas (K). Dalam kajian ini, parameter BOD kinetik ($BOD_u$, K) yang terbaik untuk 5 sumber air kumbahan berlainan iaitu influen, efluen dan air pengudaraan dari loji kumbahan domestic Al-Ramtha, rumah sembelih Amman dan air kumbahan kilang tenusu Alomary di Jordan telah digunakan. Parameter BOD kinetik dianggarkan menggunakan least squares, Thomas, daily difference, iteration, generalised methods od moments dan two stage square methods. Kajian tersebut mendedahkan bahawa BOD kinetik parameter ($L_0$ dan K) daripada air kumbahan mentah adalah yang tertinggi bagi sampel rumah sembelih pada 2017 dan 2018, di mana nilai ultimate BOD adalah 922, 1042 mg/L dan Pemalar kadar BOD adalah 0.553, 0.149 $d^{-1}$ masing-masing dalam masa dua tahun. Kajian mencadangkan bahawa keputusan daripada ciri-ciri untuk loji rawatan Al-Ramtha diklasifikasikan sebagai air kumbahan yang terkuat di Jordan. Julat nilai purata ultimate BOD ($L_0$) dan kadar malar (K) adalah 392-819 mg/L dan 0.126-0.417 $d^{-1}$ masing-masing. Di samping itu, berdasarkan kepada ralat relatif (RE), GMM dan two stage square methods adalah

kaedah yang paling bermanfaat untuk menganggarkan BOD parameter kinetik, di mana nisbah ralat berbeza dari 0.13-0.31 selama dua tahun.

**DETERMINATION OF BOD KINETIC PARAMETERS FOR DIFFERENT WASTEWATER BY USING DIFFERENT MATHEMATICAL MODEL**

## ABSTRACT

One of the most important parameter of the wastewater quality is biochemical oxygen demand (BOD). This test is widely applied to define organic water pollution and to control the performance of wastewater treatment plants and to identify the suitable places that can be used the wastewater after treatment. In order to estimate the total organic matter ($BOD_u$), understanding the organic strength of the wastewater and to predict the impacts of wastewater discharging after treating, determination of ultimate BOD ($BOD_u$) and reaction rate constants (K) are crucial. In this study, the best BOD kinetics parameters ($BOD_u$, K) for 5 different sources of wastewater (influent, effluent and aeration for Al-Ramtha wastewater, Amman slaughterhouse and Alomary dairy factory wastewater) in Jordan are investigated comparatively. The BOD kinetics parameters are estimated by using least squares, Thomas, daily difference, iteration, generalized method of moments, and two stage square methods. The study revealed that the BOD kinetic parameters ($L_0$ and K) of the raw wastewater are the highest for slaughterhouse samples in 2017 and 2018, in which the ultimate BOD values are 922, 1042 mg/L and the BOD rate constants are 0.553, 0.149 $d^{-1}$ respectively in two years. The finding suggests that the result of characteristics for Al-Ramtha treatment plant is classified as a strongest wastewater in Jordan. The range of average values of ultimate BOD ($L_0$) and constant rate (K) are from 392 to 819 mg/L and 0.126 to 0.417 $d^{-1}$ respectively. In addition, based on the relative error (RE), GMM and two stage square methods are the best method for

estimating BOD kinetic parameters, where the ratio of errors varies from 0.13 to 0.31 for two years.

# CHAPTER ONE

# INTRODUCTION

## 1.1 Overview

Wastewater pollution can generally affect drinking water and groundwater resources and crop production; jeopardise aquatic resources and human health; contaminate the atmosphere; and destroy nature (Jafarinejad, 2017). Domestic and industrial wastewater (WW) has been under extensive research by the science community because it poses a serious threat to the aquatic, air and soil environment, especially in terms of human and animal health. The WW can contain heavy metals, oil emulsions, inorganic and organic compounds that are difficult to remove due to their water solubility or the presence of persistent and recalcitrant compounds (Liang and Guo, 2010). The limits of pollutant content in WW, applied by laws, have decreased over the years, forcing deeper treatment of WW to reduce the concentration of pollutants before discharge (Boczkaj and Fernandes, 2017).

The dairy industry is generally regarded in many countries as the largest source of wastewater for food processing. As awareness of the importance of improved wastewater treatment standards increases, process requirements have become more stringent. (Tchamango et al., 2010). The volume, concentration and composition of the effluents in a dairy plant depends on the type of product being processed, the production programme, operating procedures, the design of the processing plant, the degree of water management being implemented and the amount of water that is subsequently maintained. However, in the dairy industry potent wastewater is generated and characterised by high biological oxygen demand (BOD) and chemical oxygen demand (COD) concentrations, high dissolved or suspended solids with fats, oils and grease and nutrients such as ammonia or minerals and phosphates, consequently, proper attention before disposal is required (Yavuz et al., 2011). Waste influent in the dairy sector are concentrated in nature, and the main contributors to these effluents are carbohydrates, proteins and fats derived from milk. These effluents can cause serious environmental problems due to high concentrations of organic substances in dairy waste streams (Chokshi et al., 2016).

A large volume of slaughterhouse wastewater (SWW) from animal slaughtering and slaughterhouse cleaning facilities is produced in the meat processing industry. Up to 24% of water consumed by the food and beverage industry is meat processing (Bustillo et al., 2016). Slaughterhouses and Meat Processing Plants (MPPs) are part of the world's largest industry, in which the composition of wastewater depends on the various slaughter process practices. Slaughterhouse wastewater therefore needs considerable processing to ensure a safe and environmentally sustainable release (Bustillo-Lecompte et al., 2016).

The treatment methods are very important processes to consider before using the wastewater in various sources (Henze and Comeau, 2008; Henze et al., 2008; Abdalla and Hammam, 2014; Young and Lipták, 2018). The main methods of treatment are divided into two stages of primary and secondary treatment. About 60% of suspended solids will be removed from wastewater in primary treatment. This treatment also involves aerating wastewater to add oxygen back in which more than 90% of suspended solids are removed in secondary treatment known as biological treatment (Withgott and Brennan, 2009; Guo et al., 2017). Biological treatment is classified as anaerobic (oxygen absent) and aerobic (oxygen present). Aerobic treatment includes many treatment methods, such as activated sludge process, trickling filters and aerobic digestion, where anaerobic treatment, anaerobic digestion is the most commonly used treatment in different treatment systems (Epa, 2011; Samer, 2015).

The quality and treatment of wastewater depends mainly on the type of pollutant, the characteristics and components of contaminated wastewater, the country's population growth rate, the location of the country (the longitude and latitude of the country), country activity (i.e. industrial, non-industrial country) and weather in the country since the location of the country will determine the climate and change the seasons between neighbouring countries. Therefore, each country must have its own methods and standards for treating wastewater. Treatment techniques and standards should be considered by universal standards and nation data-based methods. Jordan is one of the Middle East countries with an area of approximately 90,000 $km^2$ and is one of the dry and semi-dry climatic zones considered to be minimal rainfall and high percentage of evaporation. Recently, the water shortage problem in Jordan has increased dramatically due to high population growth, refugee influxes from Arab countries such as Yemen, Libya, Syria and Iraq, and returns to the country in response to the political situation, increased modernisation and higher living standards (Kamel and Nada, 2008). This will make Jordan facing a very limited water resource in future. As far as water resources are concerned, Jordan is currently considered one of the world's ten poorest countries. The water resources available per capita are declining annually from more than 160 $m^3$/capita/y for all uses to just 91 $m^3$/capita/y by 2025 (Ammary, 2007; Kelpsaite, 2016). As a result, in 2016, the Jordanian government officially recognised the importance of wastewater reuse in their national water strategy.

Unfortunately, many researchers in the field did not consider treating wastewater from different sources in Jordan due to the limited resources in Jordan and the regulations that followed in the industrial plants, this makes the collection of samples from the manufacturing plant exceptionally difficult making the analysis of the wastewater behaviour obscure. Therefore, more research is needed to find alternative methods and techniques to enhance wastewater treatment processes.

## 1.2 Problem Statement

Jordan's massive population growth has created a gap between available water supply and demand that makes Jordan's per capita less than 100 $m^3$/year in 2018. Hadadin et al. (2010) showed that water demand in 2010, 2020 and 2040 were 1383, 1602 and 2236, while water supply were 1054, 1152 and 1549 respectively, leading the Jordanian government to find new resources to minimise water demand. The water resource limitations increased Jordan's country's challenge of having a reliable water supply for all human and environmental needs. Methods of treatment of wastewater should be considered to solve this problem. The treated wastewater in Jordan is used for irrigation and agriculture purposes. Researchers have therefore suggested different models for testing the quality of wastewater prior to treatment as used in (Masson et al., 2001; Freese et al., 2004; Piotrowski et al., 2011). Unfortunately, many suggested methods in the literatures cannot be used for all countries because of the following: weather of the country and its location, type of the solid in the wastewater, rainfall in the country and temperature and discharging the wastewater without treatment can cause different effects on the environment such as destroying the life of the fishes and other sea life animals, activating anaerobic microbe, depleting oxygen in samples and causing diseases and viral to the humans. This makes finding the most reasonable variables to describe the wastewater for specific nation a challengeable chore as discussed about by Sarairah and Jamrah, (2008); Akpor et al., (2014); Muserere and Nhapi (2014); Mattoo et al., (2018).

The biological wastewater treatment methods have been discussed by many researchers such as municipal wastewater sample (Han et al., 2018), domestic water (Dash, 2013), river wastewater (Abdulla et al., 2016). However, lack of studies in Jordan tried to discuss effectiveness of treating slaughterhouse, dairy effluent and WWTP samples and where can be utilized after treatment (i.e. industrial, agriculture and housing) and find the suitable variables that can be used to describe the behavior of the treated wastewater and remove soluble, colloidal, suspended organic substances, nitrogen and phosphorus as the BOD test.

Other than that, numerous researchers that considered the wastewater in Jordan utilized and developed a distinctive mathematical method that can depict the behavior of the BOD kinetics parameter. Hence, understanding the trends of the BOD and its parameters will help designing a WWTP, enhancing biological treatment (i.e. ponds, lagoons, trickling bed filter), improving the quality of wastewater, estimating the size of waste-treatment plant required through the use of surface BOD loading, estimating the quantity of oxygen concentration that will be required to stabilize the organic matter present in wastewater using biological processes and ascertaining the critical point and the critical oxygen concentration deficit in oxygen sag curve, which is applicable in the self-purification of water bodies (Oke et al., 2018). To find BOD kinetics parameters different methods can be used as follows daily Difference Method (Oke et al., 2018), least Squares Method (Sibil et al., 2014; Yin and Liu, 2018), Thomas Graphical Method (Ammary and Al-

Samrraie, 2014), iteration Method (Singh, 2007), generalized Method of moments (GMM) (Tamiotti, 2009) and Two stage least squares (Brainerd and Menon, 2014). Unfortunately, lack of studies in Jordan that investigated the most suitable mathematical model to estimate the BOD parameters for 20 days for the slaughterhouse, dairy influent and wastewater treatment plants (WWTP) samples.

## 1.3 Aim and Objectives

The aim of this research is identifying the characteristics of major source of wastewater in Jordan which is includes slaughter house, dairy, and domestics wastewater. Other aim of this study is determining different BOD kinetics parameter by using different type of modeling approach. The objectives of this research are following:

1. To determine the BOD kinetic parameters for domestic, slaughterhouse and dairy influent wastewater in Jordan.
2. To evaluate the best mathematical models to estimate the BOD kinetic parameters.

## 1.4 Research Scopes

This research is bounded by following scopes:

1. In this study samples are collected from three domestic wastewater from Al-Ramtha WWTP (wastewater treatment plan) and two industrial wastewaters, including slaughterhouse and dairy factory.

2. All the samples from domestic, slaughterhouse and dairy effluent were prepared during the summer and autumn and no rainy season in Jordon. The summer and autumn season in Jordan are characterized by the absence of rain for prevent effects on BOD and COD characteristic in the wastewater.
3. In this study, the BOD kinetic parameters including ultimate BOD and rate constant for 20 days at 20°C are considered to detect complete biological decomposition of organic materials by 100% at 20°C, is achieved only after 20 days ($BOD_{20}$)

## 1.5 Thesis Organization

This thesis is organized into five chapters as follows:

Chapter one presents the overview of internal of the wastewater and the biological wastewater treatment, in addition it explains the aim and objectives and scope of the research.

Chapter two presents the literature review and definition that used in the study. The chapter then explains different tests and models that used to achieve the objectives of the research.

Chapter 3 explains the research methodology and the experimental procedures that used to calculate BOD kinetics parameter at different conditions and determine the different characteristic that describe the quality of wastewater samples. The chapter presents the procedure to find the most accurate mathematical model to determine BOD kinetic parameter that’s used to compare between different methods.

Chapter 4 presents the results that obtained by implementing the methodology. In addition, it discusses  the results and the alignment to research objective. The chapter also compares between the results by using different models.

Finally, highlight the conclusion of this research and suggestions for further research. The chapter explains the findings and the achieved objectives and highlights for the future research.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Introduction

This chapter provides the relevant background to understand the principle of wastewater quality tests, the characteristics of wastewater, the estimation methods used to find the BOD kinetics parameters. The chapter also discusses the researches gaps that lead to the main problems of wastewater treatment. This chapter begins with Section 2.2, which describes the domestic and industrial Jordan's wastewater. The main wastewater characteristics used (i.e. $BOD_5$, COD, pH, DO, TSS, TDS, TVSS, EC) to explain the samples in the field are then discussed in Section 2.3. It also presents the BOD parameters and mostly used methods for estimating the BOD kinetic parameters in Section 2.4 and 2.5, respectively. Section 2.6 explains the wastewater literature review and the main tests used to evaluate the quality of wastewater samples. A summary is finally presented in Section 2.7.

## 2.2 Overview of Wastewater in Jordan

Jordan is categorized between the arid and semi-arid countries with more than 90% of Jordan's total area receiving less than 200 mm of rainfall per year and more than 70% of the country receiving less than 100 mm of precipitation per year. In addition, the north-western highlands have an annual precipitation exceeding 300 mm, which is considered to be 2% of Jordan's area, where the northern highlands can receive about 600 mm. Approximately 5.5% of Jordan's area has annual rainfall ranging from 200 to 300 mm, while the total average volume of precipitation in

Jordan is around 8.5 x 109 $m^3$/y and 92% of this volume is evaporated (Kamel and Nada, 2008; Abdulla et al., 2016). Moreover, the population of Jordan has increased rapidly from 0.58 million in 1950 to more than 9.9 million in 2018 (Abuhashesh et al., 2019). This increase resulted in a high growth rate of 2.61% annually in 2017 and successive immigrants from Palestine, Iraq, Libya, Syria and Yemen. Due to water limitations in Jordan, the main source of water is primarily from surface and ground water (considered as fresh water), with treated wastewater being increasingly used for farm irrigation. Treated wastewater provides a major irrigation use in Jordan and is considered an additional source of water, but there are limitations on its use in various sectors, including industrial, domestic and commercial.

Wastewater is considered a dirty water from any combination of domestic, industrial, commercial or farming activities, stormwater or surface runoff and any sewer inflow or sewage infiltrations (Tilley et al., 2014). Wastewater characteristics can be divided into chemical parameters (i.e. heavy metal, toxins), physical parameters (i.e. colour, odor, solids and temperature), and biological parameters (i.e., bacteria, viruses and protozoa). Jordan's main wastewater sources were generated from domestic and industrial sectors. Sources of domestic wastewater may include human excreta (i.e. feces and urine), washing water (i.e. personal, cloths) and surplus manufactured liquids (i.e. cooking oil, cleaning liquids) (Kamel and Nada, 2008; Ahmed, 2012; Mara, 2013), Where industrial wastewater sources are produced by wastewater industrial activities consist of industrial waste cooling water, organic or biodegradable waste and toxic waste of metal, etc. (Mara, 2013).

The treated wastewater in Jordan is collected from general and private WWTP, factories, rivers and dams, the total quantity of wastewater entering to the plants is about 175.964 $mm^3$/year based on the annual reports of Jordanian ministry of water and irrigation in 2017; Benedict and Hussein, 2019). In addition, sewage quantities are large compared to other countries, high population growth rate, increased demand for water and climate change to dry up, all of the previous reasons lead to the reuse of wastewater in Jordan. Studies have also shown that water quality in Jordan has deteriorated significantly due to high fecal coliforms counts from non-point pollution sources, spring water contains 70% of biological contaminants, significant levels of toxic materials in water resources, industrial discharges are improperly treated as well as the increase of nitrates and phosphorus in water supplies due to unregulated fertilizer and pesticide. Thus, clean water will be contaminated, thus increasing carriers of disease and putting people and environment at risk. These impacts can harm the depletion of oxygen, wildlife populations, beach closures, and fish restrictions. However, the issue of water scarcity is not only due to nature and poor resources, but is largely man-made (Mohsen, 2007; Qasim , 2017; Kelpsaite , 2016).

In addition, many treatment methods and techniques could be used to minimise contaminated water in wastewater. The purpose of wastewater treatment is to remove pollutants that can harm the aquatic environment, remove toxic organic chemicals and remove the suspended solids as much as possible. The treatment processes are mainly divided into three treatment methods including physical (i.e. sediment and centrifuge), chemical (i.e. coagulate and flocculate) and biological (i.e. aerobic and anabatic) (Demirbas et.al., 2017). The biological treatment method is the most common method used globally for wastewater treatment. This method was invented in the early twentieth century. The method of biological treatment depends on the involvement of micro-organisms (i.e. bacteria, algae) in the treatment process. Micro-organisms can eat and digest organic matter carbon and become a network of water free from organic contaminants. Under certain conditions, treated water can be reused. Although the principle of biological treatment is simple, it is very complex to control the process using this method. In addition, this process cannot guarantee the results obtained. This is because of the complexity of the factors that affects their work (Grady Jr et al., 2011). As a result, wastewater treatment processes are used to ensure a sound environment and good public health, economic and social (Metcalf and Eddy, 1999; Kamel and nada, 2008).

The processes of wastewater treatment depend mainly on the characteristics of wastewater that can be extracted using different methods and techniques. Wastewater has many physical (i.e. color and temperature), chemical (i.e. alkalinity and chlorides) and biological properties that can affect the wastewater treatment process as will be discussed in the following section.

## 2.3 Wastewater Characteristics

Wastewater can be divided into: storm water runoff, industrial and domestic as shown in figure 2.1. Storm water runoff is street water, farms, open yard that comes after a rainfall event that runs through drains or sewers, where industrial wastewater is liquid waste generated by industrial activities such as factories, production units, and so on. In addition, domestic wastewater also known as municipal wastewater is basically wastewater from homes, commercial and business buildings and institutions. Domestic water is divided into black water that comes from the bathroom, laundry and grey water comes from urine and feces. Industrial and domestic sectors are considered major sources of wastewater, as there is only one rainy season (Landa-Cansigno et al., 2019; Ahmed, 2012).

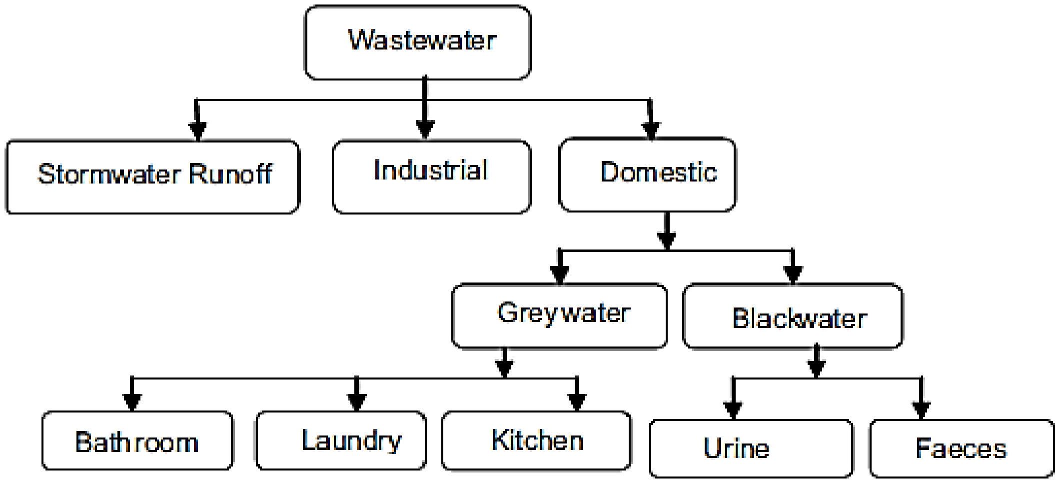


*Figure 2.1*. Type of wastewater (Bani, 2011).

In Jordan, there are numerous wastewater sources that are deemed the most important in terms of wastewater characteristics, location and wastewater content, so that wastewater sources may be described as follows:

### 2.3.1 Al-Ramtha wastewater treatment plant

The wastewater treatment plant of Al-Ramtha (RWWTP) is located in northern Jordan. Established in 1988, RWWTP was considered one of Northern Jordan's famous WWTPs. In 2017, the total inflow and reclaimed wastewater to these plants was respectively 4268 and 3957 $m^3$/day. The value of $BOD_5$ in years 2005 to 2013 of the influent stage was 852 mg/L and 1310 mg/L, respectively (2017; Abdulla et al., 2016; Alaa et al., 2014). Moreover, before plant upgrading, effluent quality does not meet Jordanian standards and additional studies need to focus on wastewater quality (Obeidat et al., 2013).

The sewage treatment plant of Al-Ramtha has the required operating units arranged one after the other for the treatment and final disposal of sewage with hydraulic design capacity 5400 $m^3$/day and 3492 $m^3$/day operating capacity (Obeidat et al., 2013; Alaa et al., 2014).

Al-Ramtha WWTP consists four processes to treat the wastewater including preliminary treatment, primary treatment, secondary or biological treatment and tertiary or advanced treatment. In the first stage, the preliminary treatment include of floating materials and inorganic solids such as leaves, paper, sand and substance (i.e., fat, oil and greases) by using three types of equipment, screeners, grit chambers, and skimming tanks. The wastewater then starts moving out to the primary treatment, removing fine suspended organic solids at this stage that can not be removed in the preliminary treatment.

In the next step, wastewater will be transferred to secondary or biological treatment, at this stage it is desired to remove dissolved and fine organic colloidal matter, including the use of microorganisms (bacteria, algae, fungi, protozoa, rotifers and nematodes) to break down organic matter from unstable forms to stable inorganic forms. Biological processes are generally classified as processes of aerobic, anaerobic and pond treatment. After all the secondary treatment stages have been completed, the wastewater is transferred to tertiary treatment or advanced treatment, the residual of suspended, dissolved substances, nitrogen, phosphorus and pathogenic organisms must be removed after conventional primary and secondary treatment.

Tertiary treatment processes are broadly classified as solids removal, biological nitrogen removal, biological phosphorus removal, disinfection depending on the composition of waste water and the requirements (Quach-Cu et al., 2018).

### 2.3.2 Amman Slaughterhouse

The largest slaughterhouse was selected in Amman city in Jordan, the Amman slaughterhouse was set up in 1972 with an area of 20000 $m^2$. The activities of the slaughterhouse include slaughtering cattle, sheep and chicken and it serves approximately over 2 million. The previous studies on Amman slaughterhouse found that the ranges of $BOD_5$, COD TDS and pH are from 463 to 3828 mg/L, 807 to 17968 mg/L, 846 to 5444 mg/L and 4.59 to7.89, respectively. In addition, In addition, Amman slaughterhouse is chosen to provide further analysis of the characteristics of the slaughterhouse and to address the problem of the lack of studies not involving the wastewater slaughterhouse (Sarairah and Jamrah, 2008).

### 2.3.3 Alomary Dairy Factory

Alomary dairy factory located in Northern Jordan. Diary wastewater samples contain milk solids, sanitisers, wastes of milk and cleaning water. Diary wastewater has high organic and inorganic materials with high nutrient concentrations. The diary wastewater sample investigator showed that the COD and BOD ranges range from 80 to 95,000 mg/L and 40 to 48,000 mg/L. The ranges of pH, TSS and nutrients vary from 4.7 to 11, 0.024 to 4.5 g/L, and 14 to 830 mg/L, respectively. In addition, Alomary dairy factory is chosen to shows more analysis of the dairy wastewater characteristics and to address the problem of the lack of studies not involving the dairy wastewater since the dairy industry is considered to be the most polluting industry in terms of the volume of effluent generated. (Shakhatreh et al., 2015).

Wastewater could be reused efficiently in different sectors after treatment to minimise contaminated water and pollution of the environment. Furthermore, wastewater has many physical, chemical and biological properties that can affect the process of treating wastewater. The most common wastewater characteristics can be summarised as follows:

1- Biochemical Oxygen Demand (BOD): Biochemical Oxygen Demand (BOD) is the test that used to estimate the amount of consumed oxygen in wastewater over a specific period under temperature 20°C for five or 20 days based on the type of the test. During the test, the bacteria begin to consume organic matter as a food (i.e. carbohydrates, proteins, petroleum hydrocarbons, phosphor, carbon, nitrogen, etc.) by using oxygen to produce $CO_2$ and $NO_3$ as a gas. (Von Sperling, 2017; Sawyer et al., 2016; Kiepper, 2010).

2- Chemical Oxygen Demand (COD): The COD test indicates the level of organic matter in the tested sample, by considering the consumption of oxygen, the chemical oxidation of the organic matter will be calculated to find the COD value. The main advantages of the COD test are: fast test to determine the goodness of sample within two to three hours, the test can be used for operational control, the test gives an indication of the oxygen that needed to reach the stabilisation state and finally the test is not affected by nitrification. However, the main limitations of the COD test are: the test may overestimate the oxygen to be consumed in the biological treatment, the test does not return any information about the growth rate of the organic matter (Von Sperling, 2017; Maiti, 2003).

3- Total Suspended Solids (TSS): are the amounts of solids that can be filtered in the wastewater sample, including stirred bottom sediment, silt, organic matter, decaying plant material, sewage treatment effluent, etc. Under laboratory conditions, TSS is found using standard filtration and drying techniques, where the increase in filter weight is measured after considering a known volume of filtered wastewater. TSS is used to measure the pollution degree in natural water. The estimate value of TSS in raw untreated wastewater is around 250 mg/L (Adams, 2017, Buehler et al., 2012, Maiti, 2003).

4- Total Dissolved Solid (TDS): TDS is the solid that uses a 2 mm (or smaller) pore filter to pass through the filter, consisting mainly of inorganic salts that yield ions such as (Na, Ca, Cl-), dissolved gases and small amounts of organic matter . TDS is found under the laboratory conditions using the oven at 103-105° C to dry the filtrate (liquid) after filtration, then the remaining residue is weighed and calculated as mg/L of TDS. The concentration of TDS varies depending on the source of wastewater tested and can range from 250 mg/L to 1,000 mg/L (Adams, 2017; Buehler et al., 2012; Maiti, 2003).

5- Total Volatile Solid (TVSS): TVSS is total suspended solids that can be burned in at high temperature of 550˚C. The amount of the volatile TSS is considered a general measure with organic material, where TVSS can be reported as mg/L. TVSS is considered an indicator of the use of wastewater for drinking, where water containing high volatile solids can not be used for drinking, this refers to water pollution from domestic or industrial waste. (Adams, 2017; Buehler et al., 2012).

6- Electrical Conductivity (EC): EC is used as an indicator of water quality problems and to monitor the amount of nutrients, salts or impurities in the water, besides being used to find a substance's ability to conduct electricity. The conductivity of water has a linear function of the concentration with dissolved ions. Besides that, TDS and EC have a direct relationship, in which TDS can be calculated using EC value as follows (Corwin and Yemoto, 2019 Rusydi, 2018):

$$\begin{cases} EC < 2000, & TDS = EC \times 0.62 \\ EC > 2000, & TDS = EC \times 0.64 \end{cases} \qquad (2.1)$$

7- pH: pH is a measure of the amount of free hydrogen ions in water. A following equation is used to find a pH value using a hydrogen ion count.

$$pH = -\log[H+] \qquad (2.2)$$

Because pH value is calculated using a logarithmic scale, therefore an increase of one unit indicates an increase of ten times of hydrogen ions.

A pH of 7 is considered to be a standard and neutral value, in which acidity increases as pH values decrease, and alkalinity increases as pH values increase (Alwan, 2012; Alwan, 2008).

8- Ammonium ($NH_4$): It is a non-toxic salt, an ionized form of $NH_3$ (toxic ammonia). However, $NH_4$ has the ability to change to $NH_3$ with a pH and/or temperature change. As a result, engineers are worried about high $NH_4$ levels when testing wastewater as high $NH_4$ samples have a higher chance of becoming $NH_3$ in the hydrosphere. Ammonium ions are considered to be the primary form of nitrogen contaminants resulting in increased oxygen demand and biological eutrophication in water sources and effects on aquatic life when concentrations exceed standard values (Gupta et al., 2015; Gajewska et al., 2015).

The most common problems in biological water treatment is the flow of a small amount of toxic substances that lead to discouraging micro-organisms, which will lead to stop biological treatment (Akpor et al., 2014). The main objective of biological treatment is to reduce organic matter by using biological and chemical oxygen demand to reduce the concentration of nutrients such as phosphorus and nitrogen in the treated samples. The presence of a sufficient concentration of DO is critical issue to maintaining the aquatic life and aesthetic quality of streams and lakes. Determining how organic matter affects the concentration of dissolved oxygen in a stream or lake is integral to water-quality management. The oxidation of organic matter in wastewater is measured as biochemical or chemical oxygen demand that can lower dissolved oxygen concentrations (Sawyer et al., (2016); Pulkkinen, 2018). Finally, $BOD_5$ is the most used test to check water quality, besides that many researchers suggested using ultimate BOD to find water quality because of its ability to give extra explanation about the rate of growth of bacteria in wastewater and the final value of BOD. The previous ultimate BOD parameters are defined as parameters of the BOD kinetics.

## 2.4 BOD Kinetic Parameters

BOD testing is a procedure that measures the oxygen consumed by bacteria from the decomposition of organic matter (Sawyer et.al, (2016); Maiti, 2003). The change in concentration of dissolved oxygen (DO) is measured at a specified temperature in water samples over a given period of time. Moreover, the BOD test could measure oxygen consumption of carbonaceous compounds only or a combination of these and the oxygen used to convert ammonium to nitrate. Defining whether the test was used to measure ammonium conversion by defining CBOD that C refers to carbonaceous or nitrification inhibited tests has become a reasonably common practice today.

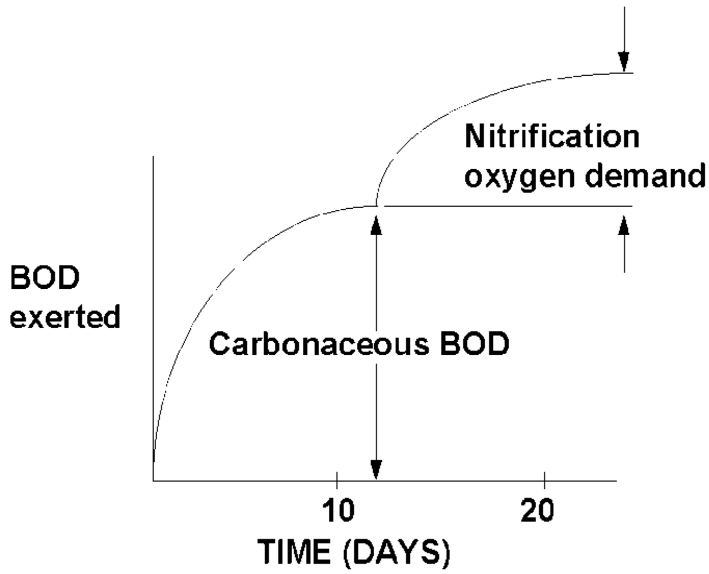


*Figure 2.2.* Biochemical oxygen demand curve modified from (Sibil et al., 2014).

The ultimate BOD is the total of the concentration of degradable organic matter based on the total oxygen required to oxidize it. The ultimate BOD depends on the wastewater characteristics, i.e., the chemical composition of the organic matter in the wastewater and its biodegradable properties and incubation temperature. Oxygen depletion, however, is related to both the ultimate BOD and the BOD rate constant (K). In order to understand the nature of wastewater, the constant BOD rate (K) must be determined, which is dependent on the nature of the waste, the temperature and the ability of the organisms in the system to use the waste. The constant rate is important for estimating the strength of wastewater and for predicting the effects of wastewater discharge. After treatment, wastewater discharge will affect life, dissolved oxygen and BOD values (Manab et al., 2018; Abdelrasoul, 2001).

There are two stages of decomposition in the BOD test including a carbonaceous stage and a nitrogenous stage as shown in Figure 2.2. The carbonaceous stage represents the portion of the oxygen demand involved in the conversion of organic carbon into carbon dioxide. While the nitrogenous stage represents a combined carbonaceous plus nitrogenous demand, when organic nitrogen, ammonia, and nitrite are converted to nitrate. The demand for nitrogen oxygen generally begins after about 6 days (Maiti, 2003). For some sewage, especially discharge from wastewater treatment plants using biological treatment processes, nitrification can occur in less than 5 days if ammonia, nitrite, and nitrifying bacteria are present. The previous stages are used to estimate the ultimate BOD value which is calculated by adding an ultimate carbonaceous demand and ultimate nitrogenous demand. Moreover, the percentage of oxidation of the carbonaceous organic matter after 5 days is around 60% to 70%, where after 20 days it is about 95% to 99% (Roppol et al., 2009; Krantzberg et al., 2010; Riffat, 2012). In addition, two parameters that are ultimate BOD value ($L_0$) and growth rate (K) are used to report the ultimate BOD ($BOD_u$) of a tested sample. The $BOD_u$ process usually takes 20 to 50 days or more depending on the environment and the samples used (Krantzberg et al., 2010). In addition, $BOD_u$ is a living system that relies on mixed biological culture to break down organic waste and remove organic matter; these living organisms are bacteria, algae, and fungi. The increasing number of bacteria in the sample is therefore directly proportional to the amount of BOD available. The growth rate of bacteria in the sample can be divided into four phases as shown in Figure 2.3, the phases of the bacteria are as follows:

1- **Lag phase:** The first step of sample incubation starts from the first hour in which the bacteria attempts to adapt the conditions of growth. Enzymes, ribonucleic acid synthesis (RNA) and other molecules occur during the lag phase and cells change very little. This is because the cells in a new medium do not immediately reproduce. This phase starts from first hour and can last for several days.

2- **Log phase** This phase is characterized by cell doubling, in which the growth of bacteria is rapidly increasing. If growth is considered unlimited, doubling the number of bacteria will continue at a constant rate that can be defined as exponential growth. Using a linear formula with an exponential plot can be used to calculate the slope representing the organism's growth rate. The actual growth rate of the organism depends on the conditions of the sample, which affect cell division.

3- **Stationary phase**: In stationary phase growth rate and death rate are almost equal to each other. The result of phase is a horizontal linear.

4- **Death phase**: The phase of death is defined as the phase of decline in which bacteria die. This could be due to lack of nutrients and environmental temperatures (Wang et al., 2015; Rolfe et al., 2012; Watkinson, 2008).

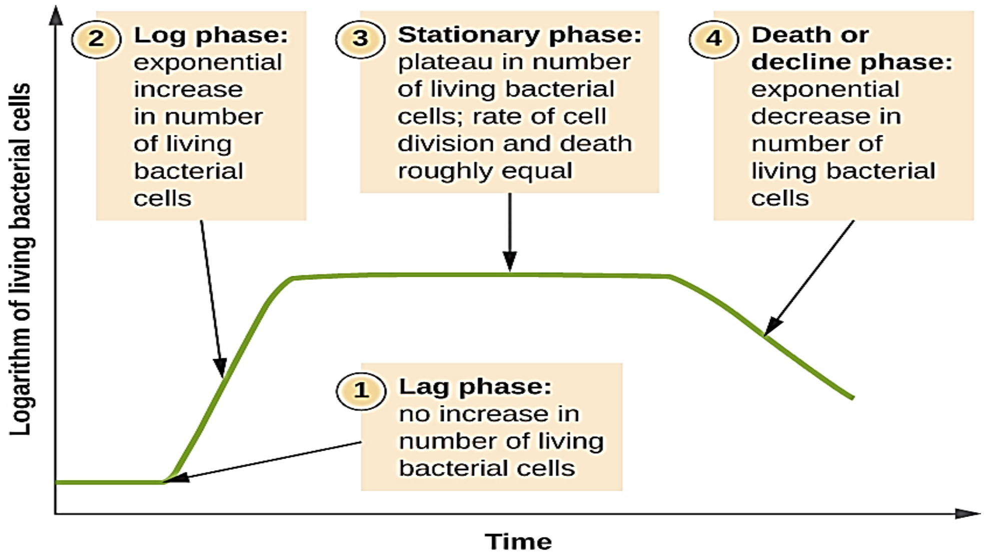


*Figure 2.3.* The four phase's growth curve of microorganisms modified from (Wang et al., 2015).

Moreover, some laboratory samples should be diluted because most of wastewater samples contain higher BOD values that cannot be read using the BOD devices or the amount of oxygen available in the bottle is lower than the accepted standard that used during the incubation period. This dilution is done by adding dilution water (which contains distilled water with chemical solutions) to the sample in the BOD bottle. After diluting the sample the result of BOD value of the sample should be within the standard ranges that discussed (Pepper, 2011), the standard BOD values for the diluted wastewater are shown in Table 2.1.

Table 2.1

*The range of BOD standard using a direct pipetting into 300 mL BOD bottles (5210 B; Ghosh et al., 2014)*

| Sample (mL) | BOD rang (mg/L) |
|---|---|
| 0.02 | 30000-105000 |
| 0.05 | 12000-42000 |
| 0.1 | 6000-21000 |
| 0.2 | 3000-10500 |
| 0.5 | 1200-4200 |
| 1 | 600-2100 |
| 2 | 300-1050 |
| 5 | 120-420 |
| 10 | 60-210 |
| 20 | 30-105 |
| 50 | 12-24 |
| 100 | 6-21 |
| 300 | 0-7 |

As shown in Table 2.1, the addition of 0.02 ml from the sample will result in very large BOD values ranging from 30,000 to 105,000 mg/L, while very low BOD values ranging from 0 to 7 mg/L for 300 ml of the sample (Ghosh et al., 2014) . If the sample is not diluted and no diluted water is added, the microorganism's biological activity will use the dissolved oxygen in the BOD bottle before the end of the incubation period. Many researchers used different mathematical models to calculate the BOD kinetic parameters including the ultimate BOD value ($L_0$) and the growth rate (K) as shown in Table 2.2.