

University of Bahrain

College of science



**Environment and Sustainable
Development Program**

Assessing the Methods of Spent Caustic Effluent Treatment from Liquid Petroleum Gas (LPG) Sulphur Purification Process

Thesis submitted in partial fulfillment of the requirements for the
master's degree in Environment and Sustainable Development -Science
and Development

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Abstract

Sweetening natural gas is extremely important to remove contaminants that affect the quality of the final product and could cause serious safety, environmental, health and/or process problems. Sweetening processes varies from single-simple step to multiple-complex steps depending on the type and the quantity of the contaminants. Bahrain's old gas treatment plant utilizes a caustic treatment method that produces an unpleasant smell caused by the presence of hydrogen sulfide and other organic sulfur compounds.

This research aimed to find the best treatment method for the generated spent caustic solution produced upon Liquefied Petroleum Gas (LPG) sulfur purification process.

A third-party laboratory was asked to conduct American Public Health Association (APHA) analysis to measure the wastewater content concentrations. A questionnaire was conducted, and the results were analyzed using Analytical Hierarchy Process (AHP) to find the best treatment option. Among the five AHP model criteria (initial investment cost, operational costs, environmental impact and safety concerns, materials availability, and treatment benefits), the costs (initial investment and operational costs) were the leading criteria, followed by the environmental impact and safety concerns. The leading alternative for the top three criteria was biological treatment. The biological treatment was proven economically with efficiency to remove sulfur compounds.

GRAMM/GRAL software was used for hydrogen sulfide emission dispersions. Hydrogen sulfide concentrations were $30.86 \mu\text{g}/\text{m}^3$ and $16.09 \mu\text{g}/\text{m}^3$ at 1.8m height above the ground and a distance of 21 to 27 meters from weathering pits and 6.4 to 7 meters from the desulfurization unit, respectively, which is above the Bahrain legal standard of $15 \mu\text{g}/\text{m}^3$. From an occupational health point of view, the computed concentrations were well below the hazardous limits for occupational health impacts, i.e. the impact was limited to the bad odor smell.

The main drawn recommendations from this study were: to adopt the biological treatment method for the wastewater and to assess the impact of other odours of organic sulfur compounds.

Dedication

The success of this work is dedicated to the people who were always after me to obtain my Master degree. Many thanks to my parents and friends for their continuous help, support and encouragement throughout my study period.

Acknowledgment

First of all, thanks to Allah the Almighty for granting me the blessing of studying, knowledge and strength to complete my master degree. I owe Allah immeasurable thanks.

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Chapter One

Introduction to the Study

- 1.1 Introduction**
- 1.2 Research Problem**
- 1.3 Research Questions**
- 1.4 Research Objectives**
- 1.5 Research Significance**
- 1.6 Research Settings**
- 1.7 Definition of Terms**

Chapter One

Introduction to the Study

1.1 Introduction

Natural gas processing depends mainly on its constituent concentrations, i.e. the quality and type of components found in the gas. Carbon dioxide (CO_2), hydrogen sulfide (H_2S), nitrogen (N_2), organic sulfur (RSH), helium (He), argon (Ar), water (H_2O), carbonyl sulfide (COS) and other compounds may naturally be present in the natural gas, and they are called “Contaminants”. Removal of the aforementioned contaminants is essential since their presence reduces the quality of the product, reduces the heating value, causes many corrosion and erosion problems in pipelines and equipment, contributes to greenhouse gases (GHGs) effects, causes serious safety problems (Klinkenbijl et al., 1999; Speight, 2011) and last but not the least, they are hazardous to human health when exposed (Othman, 2017; Speight, 2011).

“Sweetening process” is a synonym for the contaminant removal process. It varies from simple one-step to complex with multiple steps. Generally, sweetening falls into five main methods, which are: absorption, adsorption into solid, chemical conversion to another compound, permeation using membrane or condensation (Mitra, 2015; Speight, 2011). Molecular sieve, amine treatment, Shell Sulfinol and Selexol are examples of methods that could remove multiple contaminants (H_2S , CO_2 , RSH and COS). Combine processes such as amine and potassium hydroxide (KOH)/methanol are also employed when various sulfur compounds or contaminants in a stream exist with high concentrations. Each process has its

advantages, disadvantages and limits at which using the same is preferable (Ahmadi et al., 2019; Karimi et al., 2016; Klinkenbijl et al., 1999; Mamrosh et al., 2017; Speight, 2011; Woodall et al., 1981).

Bahrain's old gas treatment plant is based on combined amine and KOH/methanol processes, where Di-Ethanol Amine (DEA) is utilized in the first stage followed by KOH/methanol in the second stage (Banagas, 2009; Operation department, 2019).

The main issues associated with KOH/methanol process sweetening are the spent caustic generation and the unpleasant odour at the site. Therefore, the proper treatment solution for the generated spent caustic needs to be investigated, and the impact of the effluent, as mentioned earlier, also needs to be assessed.

Sustainability is the “development which meets the needs of current generations without compromising the ability of future generations to meet their own needs” (United Nations, 1987). Among the seventeen Sustainable Development Goals (SDGs) which were set in 2015, this research aims to comply with goal no.11, “make cities and human settlements inclusive, safe, resilient” specifically target 11.6, which states: “by 2030, reduce the adverse per capita environmental impact of cities, including paying special attention to air quality and municipal and other waste management” (United Nations, 2015a, 2015b).

1.2 Research Problem

Bahrain's gas treatment plant does not have a wastewater treatment facility. Instead, spent caustic and other process waters are routed through the sewer system to two lined weathering pits. Before 2014 and before weathering pits lining, the accumulated wastewater was

used to be disposed in Asker landfill along with the solid municipal waste. However, due to the complaint of odour from Asker, wastewater was analyzed to determine its characteristics. The wastewater was classified as hazardous waste due to the obtained analysis results, and the same was no longer accepted in Asker landfill. Complaints were received from employees and neighbouring companies regarding the unpleasant odour from the open bonds and the LPG sulfur purification unit. The associated issue of this problem is meeting Bahraini air quality standards.

1.3 Research Questions

The intended research questions are as follow:

1. What is the best treatment for the discharged spent caustic effluent?
2. What is the concentration of hydrogen sulfide around the contaminated areas?
3. Does hydrogen sulfide concentration meet Bahraini legal air quality standards?
4. What are the health impacts of the spent caustic effluent?

1.4 Research Objectives

The objectives of the research are as follows:

1. Investigate the possible treatment methods for the spent caustic wastewater.
2. Identify hydrogen sulfide air dispersion models around the contaminated areas.
3. Identify the health impacts of the spent caustic effluent.

1.5 Research Significance

Since the gas treatment plant in Bahrain does not own any wastewater treatment facility and in addition to the continuous complaint about the odour from workers and nearby neighbours, the present research will propose recommendations for solving the ongoing problem. It will also contribute to sustainability and sustainable development goals, specifically goal no.11, “Make cities and human settlements inclusive, safe, resilient and sustainable” (United Nations, 2015a, 2015b). To my knowledge, this research has not been conducted in Bahrain before.

1.6 Research Setting

The previous literature relevant to the topic (definitions and characteristics, impact, legal limit, reactions, means of handling and treatment options) were reviewed, analysed and presented. The methods and procedures chapter focused on the used methodology. Detailed tools, explanations, and assumptions were also presented with a sample of calculations to ease the readers’ understanding. The data collections were done using AHP structured Questionnaire, APHA wastewater analysis and GRAL modelling. The obtained results were analysed and discussed in the results and discussion part. Furthermore, finally, the drawn conclusion, recommendations and future work advice were presented.

1.7 Definition of Terms

List of Abbreviations

AHP:	Analytical Hierarchy Process
AOP:	Advance chemical Oxidation Process
APHA:	American Public Health Association

Banagas:	Bahrain national gas company
BAPCO:	Bahrain Petroleum Company
BOD:	Biological Oxygen Demand
CGP:	Central Gas Plant
CI:	Consistency Index
COD:	Chemical Oxygen Demand
CR:	Consistency Ratio
CS:	Compressor Station
CWAO:	Catalytic Wet Air Oxidation
EPA:	Environmental Protection Agency
GHG:	Greenhouse Gases
KOH:	Potassium hydroxide
LPG:	Liquefied Petroleum Gas
m:	Meter
MCDM:	Multi Criteria Decision Making
MFC:	Microbial Fuel Cell
MMSCFD:	Million Standard Cubic Feet per Day
NaOH:	Sodium hydroxide
OCV:	Open Circuit Voltage
OPEX:	Operational Expenditure
OSHA:	Occupational Safety and Health Administration
RI:	Random Index
ROG:	Refinery Off Gas
SCW:	Spent Caustic Wastewater
SDG:	Sustainable Development Goal
TOC:	Total Organic Carbon
TS:	Total Sulfide
WAO:	Wet Air Oxidization
Wh:	Watt-hour

$\mu\text{g}/\text{m}^3$:	Microgram per cubic meter
ppm:	Parts per million
ppb:	Parts per billion

Chapter Two

Theoretical Framework and Literature Review

- 2.1 Theoretical Framework**
- 2.2 Literature Review**
- 2.3 Research Hypotheses**

Chapter Two

Theoretical Framework and Literature Review

2.1 Theoretical Framework

Analytical Hierarchy Process (AHP) method was used to investigate the best treatment option. Fig.1 shows the structural model of this research. AHP evaluation criteria were: the initial investment cost, operational cost, environmental impact and safety concerns, materials availability and treatment benefits. Alternatives were limited to six alternatives, namely: Wet Air Oxidation (WAO), Catalytic Wet Air Oxidation (CWAO), Advance chemical Oxidation Process (AOP), biological, Microbial Fuel Cell (MFC) and pre-treatment technology/philosophy. Those alternatives were the most applied techniques in real field industry (Abd & Li, 2018; Aldaghman, 2012; Barge & Vaidya, 2018; Ben Hariz et al., 2013; Davarnejad & Bakhshandeh, 2018; Fazli et al., 2018, 2019; Gholipour et al., 2018; M. de Graaff et al., 2011; M. De Graaff et al., 2012; Hawari et al., 2015; Karimi et al., 2016; Ketu, 2013; Mahmood et al., 2007; Ntagia et al., 2020; Pino-Cortés et al., 2020; Rita et al., 2020; Roudsari et al., 2017; Seyedin & Hassanzadeganroudsari, 2018).

The target of the air quality parameters was Bahrain's legal set limits (Official gazette, 2021; Resolution No.2 for the year 2021 with respect to air pollutants emissions, 2021).

Air dispersion modelling assessed both desulfurization unit and disposal locations. GRAL modelling is based on Reynolds-Averaged Navier–Stokes equations (RANS) and mass transfer algorithm equations solutions (Internal Combustion Engines and

Thermodynamics, 2014; Oetl et al., 2012; Öttl & Kuntner, 2020). Assumptions and modelling parameters are detailed in the next chapter.

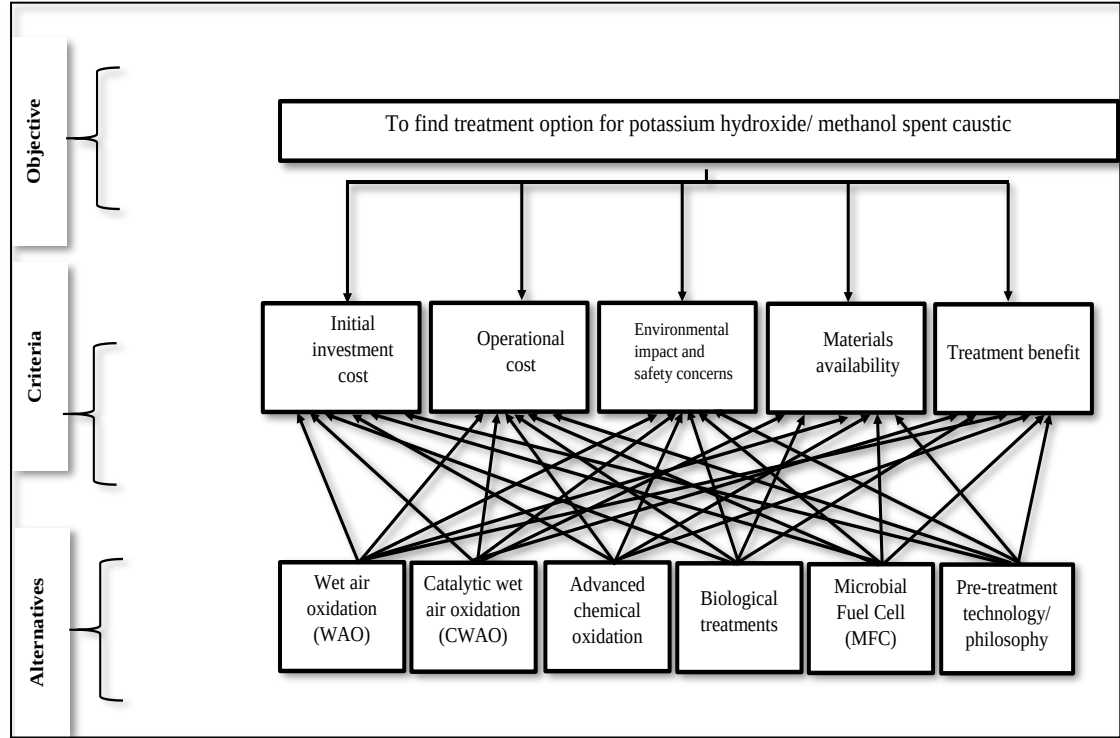


Fig.1: AHP structural model

2.2 Literature review

2.2.1 Natural gas sweetening process

Molecular sieve, which is zeolite, is one of the oldest solid adsorption methods where solid material (Adsorbent) selectively removes the undesired components upon contact. Its selective removal depends on the size of the adsorbent pores and the operating conditions. Molecular sieves are regenerable, i.e. they could be regenerated and used again in the process. The main drawbacks of this method are: (1) sizeable initial capital cost, (2) high ongoing operating cost, (3) huge possibility of undesirable side reactions products, (4) product loss, about 2% of the generated product gas is lost in the regeneration

process, and another portion is lost due to the adsorption, (5) H_2S and CO_2 on the zeolite surface tends to form COS, which decomposes to H_2S during regeneration, (6) Insoluble free water in the zeolite beds leads to powdering and caking, resulting in higher pressure drop and poor gas distribution throughout the bed. Furthermore, (7) CO_2 react with water and form carbonic acid (H_2CO_3), which effects zeolite's physical properties, (8) Heavy metals could also be adsorbed in the pores and effects the adsorbent physical efficiency and lastly, (9) the spent regenerated gas will always need sulfur treatment or recovery or disposal unit to recover or safely destroy the harmful contaminants (Institut français du pétrole, 2002; Mokhatab et al., 2019b; Speight, 2011).

Processes that use amine base solution such as Monoethanolamine (MEA), Diethanolamine (DEA), Diisopropanolamine (DIPA), Diglycolamine (DGA) or methyl Diethanolamine (MDEA) are commonly used for removing H_2S and CO_2 through chemical absorption. Process advantages include: (1) high selectivity to H_2S and CO_2 , (2) ability to flush the acid gas and regenerate the solution, (3) low solvent cost and (4) low fixed cost. In comparison, process disadvantages include: (1) high vulnerable of its mechanical equipment failure, (2) heavy loss of solvent due to amine's high vapor pressure and (3) high operating cost due to thermal energy requirement (Kidnay & Parrish, 2006; Lokhandwala & Baker, 1995). Shell Sulfinol process, on the other hand, is also a widely known process where mixed (chemical and physical) solvents are used. The usual mixtures of the process are Sulfinol (physical absorption solvent), water and diisopropylamine or methyl Diethanolamine (chemical absorption solvent). This process combines the advantages of both chemical and physical absorption processes. Merits include

(1) capability to remove H_2S selectively, CO_2 , RSH and COS, (2) high reliability since Sulfinol solution is less corrosive and it acts as foam inhibitor, (3) low energy consumption, (4) the physical character for targeting RSH and COS could be adjusted depending on the solution concentration, (5) the ability to produce a gas with lower water content compared to amine process, (6) availability of the solvent components and (7) ability to operate at low CO_2 concentrations, low temperature and high pressure. The main drawbacks are the high solubility characteristics to hydrocarbons, the need for solvent recovery system and the need for contaminants recovery or destroying unit (Klinkenbijl et al., 1999; Sahabi et al., 2010; TOTALFINAELF, 2002).

The Selexol process is similar to the Shell Sulfinol process, with the same benefits and drawbacks. The only difference is the type of solution used for the absorption. Selexol solution consists of Dimethyl Ether of Polyethylene Glycol, which has a tendency to water in addition to the other contaminants (TOTALFINAELF, 2002).

An example of combined processes is amine treatment with the potassium hydroxide (KOH)/methanol process. In the first step, a regeneratable amine-based solution is used to absorb H_2S and CO_2 in a countercurrent absorber. The sour solution is then regenerated and recycled for process use. The gas is treated in non-regeneratable adsorbent KOH briquettes with methanol solution to remove RSH, COS and traces of entrained H_2S and CO_2 . Characteristics of this combination are design simplicity, low operating and capital costs, quick installation, minimum utility requirements and efficient effluent production. The drawbacks are: (1) the need for downstream regenerated gas treatment or recovery or disposal unit, (2) generation of spent caustic liquid solution which requires disposal, (3) the need

to change-out/ refill the adsorbent material and (4) generation of spent adsorbent which could be considered as hazardous material (Mamrosh et al., 2017; Woodall et al., 1981).

2.2.2 Spent caustic types and characteristics

Spent caustic is the liquid wastewater generated from refineries due to the sweetening processes. It is usually hazardous, odorous, and corrosive, making it a real dilemma worldwide. Two types of caustic treatment processes generate the spent caustic solution: regenerative caustic processes (e. g. NaOH washing) and non-regenerative caustic processes (e.g. Solid potassium hydroxide adsorption). Generally, spent caustics are classified into three main types depending on the source of generation and its characteristics: sulfidic, cresylic and naphthenic. Sources could be from ethylene plants or LPG unit (sulfidic type), or from refining gasoline unit (cresylic type), or refining jet/kerosene unit (naphthenic type) (Aldaghman, 2012; Barge & Vaidya, 2018; Mokhatab et al., 2019a; Rita et al., 2020). The general characteristics of spent caustics are as follow:

1. High Chemical Oxygen Demand (COD): 10,000-100,000 (ppm)
2. High Biochemical Oxygen Demand (BOD): 5,000- 50,000 (ppm).
3. High sulfides composition: 5,000 to 35,000 (ppm)
4. High Total Organic Carbon (TOC): 1,000 - 5,000 (ppm)
5. High pH value

Comparing the three types, sulfidic spent caustic is usually characterized by high sulfides and mercaptans concentration with low COD value. Cresylic has high concentrations of organic compounds

such as cresols and phenols in addition to sulfides and mercaptans, while naphthenic spent caustic consists of high organic compounds concentrations such as naphthenic acids (Rita et al., 2020; Roudsari et al., 2017). Table (1) shows a comprehensive comparison between the three spent caustic types (Hawari et al., 2015).

Table (1): Comprehensive comparison between spent caustic types (Hawari et al., 2015)

Type of spent caustic	Sulfidic	Cresylic	Naphthenic	Ref.
Source	Ethylene and Liquefied Petroleum Gas (LPG)	Gasoline	Kerosene and Diesel	(Kumfer et al. 2010)
Content	High concentration of sulfide and mercaptans	Hight concentration of phenols & cresols	High concentration of polycyclic aliphatic organic compounds	(Ahmed, 2010)
COD (ppm)	5,000-90,000	50,000-100,000	150,000-240,000	
TOC (ppm)	20-3,000	10,000-24,000	24,000-60,000	
Sulfide (ppm)	2,000-52,000	<1	0-63,000	

Total phenol (ppm)	2-30	1,900-1,000	14,000-19,000	
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2.2.3 Impact of spent caustic

Spent caustic as aforementioned is odorous with high COD, BOD, TOC, sulfides and pH values. Its impact includes hazards to human health and conventional biological processes. When sulfur gas evolves, and humans get exposed to only 50ppm, humans will experience nose and throat irritations and lower respiratory tract, while at 1000ppm, humans can instantly die. Table (2) shows the symptoms/ effect when humans get exposed to contaminated air with hydrogen sulfide at different concentrations (Occupational Safety and Health Administration, 2017).

Biologically, spent caustic causes noxious odors, foaming, pH swings, poor settling of biological solids and eutrophication when discharged to water media. The eutrophication phenomenon is the “condition of natural water that can lead to the death of animal life “this happens due to the depletion of the dissolved oxygen in water (Mohammed & Alewi, 2019; Roudsari et al., 2017).

Table (2): Symptoms/ effects of hydrogen sulfide exposer (Occupational Safety and Health Administration, 2017)

Concentrations ppm ($\mu\text{g}/\text{m}^3$)	Symptoms/ effects
0.00011-0.00033 (143-429)	Typical background concentrations

Concentrations ppm ($\mu\text{g}/\text{m}^3$)	Symptoms/ effects
0.01-1.5 (1.3×10^4 - 1.95×10^6)	Odor threshold (when rotten eggs smell is first noticeable to some). Odor becomes more offensive at 3-5ppm. Above 30ppm. Odor described as sweet or sickeningly sweet.
2-5 (2.6×10^6 - 6.5×10^6)	Prolonged exposure may cause nausea, tearing of the eyes, headaches or loss of sleep. Airway problems in some asthma patients.
20 (2.6×10^7)	Possible fatigue, loss of appetite, headache, irritability, poor memory, dizziness.
50-100 (6.5×10^7 - 1.3×10^8)	Slight conjunctivitis (“gas eye”) and respiratory tract irritation after 1 hour. May cause digestive upset and loss of appetite.
100 (1.3×10^8)	Coughing, eye irritation, loss of smell after 2-15 minutes (olfactory fatigue). Altered breathing, drowsiness after 15-30 minutes. Throat irritation after 1 hour. Gradual increase in severity of symptoms over several hours. Death may occur after 48 hours.
100-150 (1.3×10^8 - 1.95×10^8)	Loss of smell (olfactory fatigue or paralysis)
200-300 (2.6×10^8 - 3.9×10^8)	Marked conjunctivitis and respiratory tract irritation after 1 hour. Pulmonary edema may occur from prolonged exposure.
500-700	Staggering, collapse in 5 minutes. Serious damage to the eyes in 30 minutes. Death after 30-60 minutes.

Concentrations ppm ($\mu\text{g}/\text{m}^3$)	Symptoms/ effects
(6.5×10^8 - 9.1×10^8)	
700-1000 (9.1×10^8 - 1.3×10^9)	Rapid unconsciousness, “knockdown” or immediate collapse within 1 to 2 breathes, breathing stops, death within minutes.
1000-2000 (1.3×10^9 - 2.6×10^9)	Nearly instant death

2.2.4 Spent caustic and legal limits

One of the impacted environmental aspects associated with spent caustic generation is the air. The air quality in Bahrain was obligated by ministerial order No. 10 for the year 1999 concerning environmental measurements (air and water). However, lately, in April 2021, a new resolution was issued with updated values and additional parameters. Table (3) shows the legal set limit for air quality and comparison with the U.S. Environmental Protection Agency (EPA) standards. The EPA standard was unlike Bahrain’s standard since the EPA regulates six principle pollutants, called pollutant criteria. EPA also classifies the standards into two categories, primary and secondary. The earlier is provided for public health protection, including children, the elderly and asthmatic people (“Sensitive population”), while the latter is provided for public welfare protection. The main concerns of the secondary standard are to set the levels at which pollutants could cause damage to crops,

buildings, wildlife or when vision (visibility) is decreased. The contaminated area near the weathering pits and desulfurization unit shall not exceed the obligated limit set by the Kingdom of Bahrain (EPA, 2016a; Ministerial Order No. 10 of 1999 Concerning Environmental Measurements (Air and Water), 1999; Resolution No.2 for the year 2021 with respect to air pollutants emissions, 2021).

Table (3): Air quality obligation and EPA limits (EPA, 2016a; Ministerial Order No. 10 of 1999 Concerning Environmental Measurements (Air and Water), 1999; Resolution No.2 for the year 2021 with respect to air pollutants emissions, 2021)

Pollutant Name & symbol	Bahrain's legal standard $\mu\text{g}/\text{m}^3$ (ppb) > averaging period	EPA limit comparison	
		Comments	EPA duration and set maximum value
Nitrogen dioxide (NO₂)	200 (106 ppb) > 1-hour mean 150 (80 ppb) > 24-hour mean 40 (21 ppb) > annual mean	Different than Bahrain's standard • Primary • Primary and secondary	• 1 hour: 100 ppb • 1 year: 53 ppb
Sulfur dioxide (SO₂)	300 (115 ppb) > 1-hour mean 125 (48 ppb) > 24-hour mean 50 (19 ppb) > annual mean	Different than Bahrain's standard • Primary • Secondary	• 1 hour: 75 ppb • 3 hours: 500 ppb
Particulate matters (PM₁₀)	340 > 24-hour mean 80 > annual mean	Different than Bahrain's standard Primary and secondary	• 24-hour: 150 $\mu\text{g}/\text{m}^3$

Particulate maters (PM2.5)	50>24-hour mean 25>annual mean	Different than Bahrain's standard • Primary • Secondary • Primary and secondary	• 1 year: 12 µg/m³ • 1 year: 15 µg/m³ • 24 hours: 35 µg/m³
Ozone (O₃)	150 (76 ppb)>8-hour mean 200 (100 ppb)>1-hour mean	Different than Bahrain's standard Primary and secondary	• 8 hours: 0.070 ppm
Carbon monoxide (CO)	20000 (17 ppm)>1-hour mean 10000 (9 ppm)>8-hour mean	Different than Bahrain's standard Primary	• 8 hours: 9 ppm • 1 hour: 35 ppm
Benzene (C₆H₆)	13 (4 ppb)>24-hour mean 5 (1.56 ppb)>annual mean		
Toluene (C₇H₈)	1130 (300 ppb)>24-hour mean 400 (106 ppb)>annual mean		
Xylene (C₈H₁₀)	434 (100 ppb)>24-hour mean 100 (23 ppb)>annual mean		
TNMHC's	160 (0.24 ppm)>3-hours mean		

Hydrogen sulfide (H₂S)	42 (30 ppb)>1-hour mean 15 (11 ppb)>24-hours mean		
Ammonia (NH₃)	100 (144 ppb)>24-hour mean		
Additional Criteria in EPA standard			
Pollutant	Comments	EPA duration and set maximum value	
Lead (Pb)	Primary and secondary	(rolling 3-month average): $0.15 \frac{\mu\text{g}}{\text{m}^3}$	

The limit of hydrogen sulfide in California is 0.03 ppm for 1-hour mean. While 0.2 ppm for 1-hour mean in Montana and 10 ppm maximum north Dakota (Story, 2000).

The second aspect related to spent caustic generation is associated with its disposal. Criteria shall meet Bahrain's legal set limit specified in resolution no.3 for the year 2021 concerning the environmental standards of water. That is the latest version of the water criteria standard for Bahrain. It was issued after a series of modifications to ministerial order no.3 for the year 2001 with respect to amending some environmental standards (air and water), which was mentioned in ministerial order no.2 of the year 2001, ministerial decree no.2 for the year 2001 and order no.10 for the year 1999 with respect to environmental standards (air and water). The resolution mainly classifies pollutants into four primary characteristics: physiochemical, biochemical, chemical and biological characteristics. Table (4) summarizes the set limit and compare the same with the EPA standard for wastewater discharge. The U.S. EPA standard was unlike Bahrain's. It is more detailed with no characterization. pH, Sulfide, total suspended solids and oil & grease limits were the only similar characteristics in both standards (FAO, 2014; Ministerial Order No. 10 of 1999 Concerning Environmental Measurements (Air and Water), 1999; Official gazette, 2021; Ministerial order No.3 of the year 2001 with respect of amending some environmental standards (Air and water) mentioned ministerial order No.2 of 2001, 2001).

Table (4):Wastewater discharge obligation and EPA limits (FAO, 2014; Ministerial Order No. 10 of 1999 Concerning Environmental Measurements (Air and Water), 1999; Official gazette, 2021; Ministerial order No.3 of the year 2001 with respect of amending some environmental standards (Air and water) mentioned ministerial order No.2 of 2001, 2001)

Characteristics		Bahrain legal limit		EPA limit and comparison	
		Monthly average (ppm)	Maximum (ppm)	Comments (Similar or different than Bahrain's limit)	EPA Set maximum Value (ppm)
Physiochemical characteristics	Floating materials	Nil	Nil		
	Hydrogen concentration (pH) *	6-9	6-9	Similar	6-9
	Total suspended solids (TSS)	20	30	Similar	30
	Temperature **	3± (ΔT)	3± (ΔT)	Different	Water discharged to water bodies other than ocean

				They categorize based on the receiving body type and season	in the period May-September (below 38°C) while in the period October- April (below 35°C) Water discharged “directly into the marine, the discharge point shall not exceed 42°C and temperature difference should not exceed 4°C for surface water at 500 meters from the discharge point”.
	Turbidity level (NTU)	25	50		
Biochemical characteristics	Bio-chemical oxygen demand (BOD)	15	25	Different	30
	Chemical oxygen demand (COD)	100	150	Different	100
	Total organic carbon	50	50		
	Total nitrogen by Kjeldhal method	5	10		
	Oils and grease	8	10	Similar	10

	Dissolved oxygen	Min 4	Min 4		
	Phenols	0.2	0.2	Different	1
Chemicals characteristics	Ammonia	1	3	Different	10
	Residual chlorine	0.5	1		
	Total cyanide	0.05	0.1	Different	1
	Fluoride	15	25	Different	15
	Nitrate	10	10	Different	50
	Sulfide	0.5	1	Similar	1
	Total phosphorous	1	2	Different	4
	Arsenic	0.05	0.1	Different	0.5
	Cadmium	0.01	0.05	Different	0.03
	Total chromium	0.1	1	Different	2
	Copper	0.2	0.5	Different	3
	Lead	0.1	0.5	Different	1
	Mercury	0.001	0.001	Different	0.005
	Nickel	0.1	0.5	Different	1
	Aluminum	1	5		
	Iron	1	2	Different	10

	Zinc	0.5	1	Different	5
Biological characteristics	Total coliform (most probable number MPN)/ 100 Millilitre	1000	2500		
Additional Characteristics in EPA standard					Maximum
Anionic surfactants					10
Soluble manganese					10
Hexavalent chromium					0.5
Methyl mercury					0.0000002
Silver					0.5
Selenium					0.5
Boron					1
Formaldehyde					3
PCB (Polychlorinated biphenyl)					0.00005
Total organophosphorus compounds					0.5
Total aminomethyl-carbmate					0.5
Herbicides					1
Endosulfan					0.03

Endrin	0.0002
Lindane	0.004
Heptachlor and its derivatives	0.001
DDT and its derivatives	0.001
Aldrin, Dieldrin	0.003
Pentachlorophenol and its salts	0.005
Toxaphene	0.005
Pentachloronitrobenzene	0.00005
Folpet	0.00025
Captafol	0.00025
Captan	0.00025
Dioxin (g-TEQ/L)	10
True color *	550

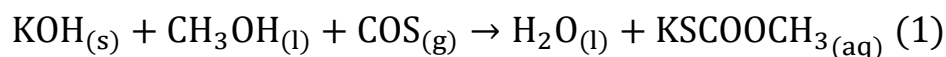
Note: the unit of all the above parameters is mg/L which is equivalent to ppm

*pH & true color are unitless

** Unit of Temperature is Centigrade

2.2.5 Spent caustic reaction

The primary reaction of spent caustic formation in potassium hydroxide/ methanol process (non-regenerative caustic processes) is shown in equation 1 (Mamrosh et al., 2017; Woodall et al., 1981):



Where CH_3OH : is methanol in the liquid phase

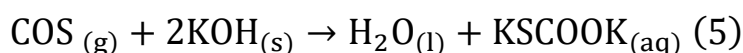
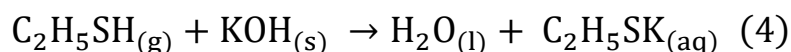
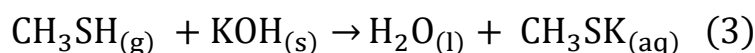
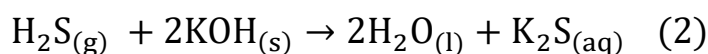
KOH : is the solid potassium hydroxide

COS : is carbonyl sulfide

H_2O : is water, a product from equation 1

KSCOOCH_3 : is another product from equation 1

As this process has the tendency to hydrogen sulfide and mercaptans removal in addition to carbonyl sulfide (Mamrosh et al., 2017), equations 2-5 shows the possible reactions of hydrogen sulfide, mercaptans and carbonyl sulfide (Banagas, 2010):



Where

H_2S : is hydrogen sulfide

K_2S : is potassium sulfide, a product from equation 2

CH_3SH : is methyl mercaptan

CH_3SK : is potassium methyl mercaptide, a product from equation 3

$\text{C}_2\text{H}_5\text{SH}$: is ethyl mercaptan

$\text{C}_2\text{H}_5\text{SK}$: is potassium ethyl mercaptide, a product from equation 4

KSCOOK : is a product from equation 5

2.2.6 Means of spent caustic handling

Handling of spent caustic varies based on its constituent concentrations. Some of the handling means were the following (C. M. De Graaff, 2012; Ketu, 2013):

1. Deep well injection.
2. Dilution and treatment in Wastewater Treatment Plant (WWTP).
3. Oxidization (details of this method application is discussed in the next section).
4. Exporting to paper and pulp mills and using it as lignin bonds breaker.
5. Other treatment means.

2.2.7 Spent caustic treatment methods, advantages and disadvantages

Due to the presence of organic matters, phenols, sulfur and mercaptans compounds, treatment of spent caustic is difficult. The most associated problems are the following (Pino-Cortés et al., 2020):

1. Strong unpleasant odour of mercaptans and sulfur compounds.
2. High phenol compounds concentrations are highly inhibiting compounds for biological activity.
3. High bio-refractory compounds concentrations such as naphthenic acid and cresylic. Those compounds are non-degradable, and naphthenic acids cause the foam to form.

Spent caustic treatment methods could be classified into five methods, namely: thermal method, chemical oxidation, biological, membrane filtration and electrochemical method. Thermal processes mainly rely

on high temperature and pressure conditions for the treatment. It is subclassified into incineration, wet air oxidation (WAO) and catalytic wet air oxidation (CWAO). The conditions of WAO reaches 120 – 320°C and 0.5 – 20 MPa with the presence of water vapor and an oxidizing agent. CWAO is similar to the WAO process with the addition of catalyst material which helps in reducing the required operating conditions. Acid neutralization, classical chemical oxidation, and advanced chemical oxidation processes are the main subcategories of the chemical oxidation process. An oxidizing agent is used to oxidize the organic and inorganic compounds (hydroxyl radical is formed in this process). The biological treatment is the treatment that utilizes micro-organisms. It is a practical operational method compared to other methods which require high operating conditions. However, it is not suitable in most cases due to the partial purification of Sulfide and other compounds. Membrane technology can give high quality purified effluent when a suitable membrane is used. Membrane types/filters are: reverse osmosis, nanofiltration, microfiltration and ultrafiltration. Lastly, the electrochemical methods, i.e. electrocoagulation and electro-Fenton processes, depend on applying electric currents for the purification (removal of soluble inorganic solids, oil, grease and suspended solids). They are very efficient for suspended solids, inorganic solids, oil and grease removal, and they produce less amount of sludge (Alipour & Azari, 2020). Pino-Cortés et al. (2020) summarized the possible treatment methods for different spent caustics types as shown in Fig.2. Table (5) compares the advantages and disadvantages of the treatment techniques.

Wet Air Oxidation	• Sulfidic spent caustic , Cresylic spent caustic, Naphthenic spent caustic & Mixed spent caustic
Biological process	• Sulfidic spent caustic, Cresylic spent caustic , Naphthenic spent caustic & Mixed spent caustic
Fenton reaction	• Sulfidic spent caustic & Naphthenic spent caustic
Acid neutralization	• Sulfidic spent caustic, Naphthenic spent caustic & Mixed spent caustic
Chemical precipitation	• Sulfidic spent caustic & Naphthenic spent caustic
Advance oxidation process	• Sulfidic spent caustic
Electrochemical	• Sulfidic spent caustic

Fig.2: Possible treatment methods with respect to spent caustic types

Table (5): Advantages and disadvantages of the treatment techniques

Method type	Method name	Advantages	Disadvantages	References
Thermal process	Incineration	• One of the oldest techniques. • Ability to convert high concentration pollutants to less environmentally dangerous materials.	• High operating cost (temperature and pressure). • Release of toxic substance.	(Alipour & Azari, 2020) (Ahmadi et al., 2019)
	Wet air oxidation	• It is usually used as a pre-treatment step for biological systems (because it has the ability to reduce COD). • Ability to alter the condition based on the required specification i.e. Low temperature conditions is good for sulfidic types, it will convert sulfide to thiosulfate and sulfate, at medium operating conditions, sulfide is oxidized to sulfate, and mercaptans are completely destroyed. While at high	• High operating cost (temperature, pressure, air, energy consumption and corrosion protection). • High initial investment cost. • Apply under strict operating condition. • Safety concerns during high pressure and high temperature conditions.	(Alipour & Azari, 2020) (Karimi et al., 2016) (Aldaghman, 2012) (Ahmadi et al., 2019) (Pino-Cortés et al., 2020)

Method type	Method name	Advantages	Disadvantages	References
		operating conditions sulfide, mercaptans, and other organic compounds is complete oxidized. • Ease of operation. • Equipment is highly resistance to corrosion. • Low maintenance cost. • No by-products are produced and no excess sulfur within off-gas stream.		
	Catalytic wet air oxidation	• Less operating cost compared to WAO. • High efficiency and ability to destroy multiple pollutants. • Ease recovery of iron catalyst. • Cheap catalyst (some types). • Ability to retrieve some type of catalyst.	• Cost associated with catalyst purchasing and replacement. • Low catalyst stability (some types).	(Ahmadi et al., 2019) (Alipour & Azari, 2020)

Method type	Method name	Advantages	Disadvantages	References
Chemical oxidation	Acid neutralization	• Low Operating Cost (Temperature and pressure) • Ability to capture and reuse compounds such as phenol because this process did not destroy the compounds.	• Difficult separation of volatile gases (high COD result) / complex separation steps. • Cost associated with chemical use. • Require multiple chemical feeds. • Safety concerns due to H₂S generation from neutralization process. • Equipment life reduction due to H₂S presence which is highly corrosive. • Odours Concerns.	(Aldaghman, 2012) (Ben Hariz et al., 2013) (Pino-Cortés et al., 2020) (Alipour & Azari, 2020)

Method type	Method name	Advantages	Disadvantages	References
	Classical chemical oxidation	• Need to be combined with neutralization process. • Ability to oxidize most of spent caustic.	• Difficulty in controlling the pH level. • Reaction is exothermic nature. • Possibility of side reactions of hydrogen peroxide to form weak radicals. • High operating cost. • High explosion risks. • Requires special handling (H_2O_2 is corrosive and degrades in heat).	(Ahmadi et al., 2019) (Aldaghman, 2012) (Alipour & Azari, 2020)

Method type	Method name	Advantages	Disadvantages	References
	Advanced chemical oxidation	• Ability to convert pollutants into water, carbon dioxide and inorganic products. • Low investment cost. • Relatively easy technology.	• High operating cost. • Spent caustic with carbonate and bicarbonate could affect hydroxyl radical production. • Most often leads to incomplete oxidation of the dissolved sulfide to thiosulfate $S_2O_3^{2-}$. • Difficulties with chemical handling.	(Ahmadi et al., 2019) (C. M. De Graaff, 2012) (Alipour & Azari, 2020) (C. M. De Graaff, 2012)
Membrane filtration technology	Reverse osmosis	• Easy operation. • Less initial investment cost compared to conventional types. • Low energy consumption.	• Fouling issue which reduces the flow. • Need to have high resistance and stable membrane material.	(Alipour & Azari, 2020)
	Nanofiltration			
	Microfiltration			
	Ultrafiltration			

Method type	Method name	Advantages	Disadvantages	References
		• High efficiency when suitable membrane is used.	• Cost associated with frequent membrane cleaning.	
Biological treatment		• Usually cheap due to lower operating cost since it can be operated around ambient temperatures and atmospheric pressure. • Eliminate heat and pressure needs (reduce energy costs).	• Often applied as pre-treatment step. • Cost associated with biological material.	(Karimi et al., 2016) (Qaisar et al., 2007) (Ahmadi et al., 2019) (Alipour & Azari, 2020)
Electrochemical	Electrocoagulation	• Has very high removal efficiency. • It provides active cations without the need for salts or coagulants. • No cost associated with chemicals. • Low sludge quantity generated.	• Cost associated with electricity use. • Cost associated with cells and electrodes provision.	(Ben Hariz et al., 2013) (Ahmadi et al., 2019)

Method type	Method name	Advantages	Disadvantages	References
		• No need for additional refinement method. • Simple equipment. • Easy operation.		
	Electro-Fenton	It utilizes electrical current instead of power source (clean energy and does not cause secondary pollution).	It is strongly affected by the electric current, pH, reaction time and hydrogen peroxide to iron ions.	(Ahmadi et al., 2019)

2.2.8 Spent caustic treatments

Studies about spent caustic treatment specifically generated from potassium hydroxide/methanol process (nonregenerative caustic processes) was limited, however extensive literature was found for spent caustics generated from generative processes (NaOH washing). Treatment varied from single to multiple components targeting. The following sub-sections provide an overview of researcher's work and findings categorized as per treatment process types:

1. Thermal process

Barge & Vaidya (2018) modelled cresylic spent caustic from gasoline refinery to find an alternative method for the usual high-cost approach (activated carbon adsorption). pH, BOD and TOC were the parameters of interest for treatment. They tested the Graphene oxide (GO) catalyst and their Nobel synthesized catalyst Graphene oxide with Ruthenium (GO/Ru). The primary outcome was in favor to GO/Ru catalyst: (1) it is an excellent TOC and BOD degrader, (2) very active catalyst compared to GO catalyst, (3) has high stability, i.e. more than 200°C, (4) has less recovery than GO catalyst, (5) its order of cresols degradation was: p-cresol>o-cresol>m-cresol and (6) its reaction could be described as two-step power type kinetic model. The highest achieved TOC conversions for p-cresol, o-cresol and m-cresol were 81.4%, 74.8% and 66.1%, respectively, while the maximum COD degradations were 75.3%, 70.2% and 60.7% for p-cresol, o-cresol and m-cresol respectively at 190°C and using Ru/GO catalyst (Barge & Vaidya, 2018).

As per Pino-Cortés et al. (2020) review, this field was the most studied field; it was applied and tested on a pilot, laboratory and real scales. As catalyst behaves differently with different efficiencies, much

research was performed to investigate the best catalyst type. Vanadium, copper, nickel, and ferrum-based catalysts are examples of the best catalyst for this method (Pino-Cortés et al., 2020).

2. Chemical oxidation process

Seyedin & Hassanzadeganroudsari (2018) studied the possibility of treating petrochemical spent caustic with the aim of eliminating its high toxic compounds, reducing neutralization and pH with minimum cost, producing usable products from the effluent, utilizing low-cost materials/ additives and feed, optimizing energy use, use new technologies with high added values, purify the spent caustic without environmental risks and protect the environment from the high alkalinity characteristics. They succeed by using advance oxidation techniques (wet air, ozone molecules, catalyst and UV radiation). Results were exceeding the design/ expected values, Na_2S content was less than 1 ppm (wt), and Na_2S conversion to Na_2SO_4 was 97%. Pre-treatment was proved to enhance the oxidation process leading to more efficient oxidation and potential elimination of secondary steps (Seyedin & Hassanzadeganroudsari, 2018).

Hawari et al. (2015) research was also investigating sulfidic spent caustic treatment. Samples from Qatar petroleum refinery were undergone neutralization, naturalization combined with classical oxidation and neutralization combined with advance oxidation using Fenton reagent to obtain the best treatment option and condition. Neutralization gives good results with respect to Sulfide and COD reduction but not to the desired level. Neutralization combined with classical oxidation (hydrogen peroxide) treatment was better than neutralization alone, Sulfide was totally removed, but COD was above the desired limit (above 1000 mg/L). Neutralization combined

with advance oxidation using Fenton reagent was the best option with total sulfide removal and 96.4% COD removal (at pH= 2.5 and hydrogen peroxide to ferrous sulfate ratio 7:1) (Hawari et al., 2015).

Yu et al. (2004) studied the feasibility of increasing hydroxyl radicals concentration on a laboratory scale using O_3 and H_2O_2 . Sulfidic spent caustic with 0.8 and 0.6 g/L of H_2O_2 and O_3 loads, respectively, resulted in only 76% COD removal (Yu et al., 2004).

3.Biological process

Gholipour et al. (2018) investigated the ability of fungi species derived from rich sulfur hot springs to oxidize sulfur compounds in sulfidic spent caustic. Among 17 different fungi, fungi from Sadat Mahale Hot spring water (SMHS-3) showed a great result in sulfur oxidizing. SMHS-3 is characterized by its high biomass production and fast growth at alkaline conditions (pH=8.96), which is unlike other fungi. Novel SMHS-3 reduced 55% of active sulfite and 16% of COD due to its high conversion (oxidation) ability. The study was proven on a small laboratory scale. The researcher suggested to studying this process at a larger scale to prove its effectiveness on an industrial scale (Gholipour et al., 2018).

Acidic sulfate-containing wastewater was also treated biologically by Zhou et al. (2018). Algal biofilm set-up was used in their research with the aim to remove sulfate only. They succeed in reducing sulfate with 35-46% efficiency (Zhou et al., 2018).

M. De Graaff et al. (2012) synthesized sulfidic spent caustic (pH = 9.7, NaOH = concentration 0.8 M) to study the feasibility of treating it biologically using two reactors placed in series and operated with aerobic conditions at 23°C. They succeed with the aforementioned set-

up; the first step converts Sulfide to thiosulfate while the second step converts the whole mixture (Sulfide and thiosulfate) to sulfate. The optimal reactor configuration was found mathematically; it shall be 60% biological and 40% abiotic volume (M. De Graaff et al., 2012).

M. de Graaff et al. in 2011 focused on using haloalkaliphilic sulfide oxidizing bacteria (Russian soda lakes sediments) for the treatment of sulfidic spent caustic. This type of bacteria is a special type that proved its efficiency to remove hydrogen sulfide in spent caustic treatment without the need for solution dilution, which reduces the need for influent dilution by three factors to lower the pH for biological treatment. The research also focused on benzene removal as it is characterized by its high-water solubility, high stability and carcinogenic nature. Removal of sulfide was 100% through its conversion to sulfate. Benzene's removal was also achieved. The percentage was 93% attributed to the high stripping condition and biodegradation characteristics of benzene (M. de Graaff et al., 2011).

4.Membrane filtration technology process

Membrane filtration application, in general, was applied a lot in multiple purification processes due to its low energy consumption and high efficiency compared to other methods; Anna et al. investigated the possibility of treating caustic and recovering the waste using Microfiltration, Ultrafiltration, Ultrafiltration/Nanofiltration, Ultrafiltration/Microfiltration. COD removal using Microfiltration and Microfiltration/Ultrafiltration membranes at 2bar were 47.75% and 75.26%, respectively, while using Ultrafiltration and Ultrafiltration/Nanofiltration membranes at 4bar were 63.83% and 99.7%, respectively (Alipour & Azari, 2020).

5. Electrochemical process

Luo et al. (2020) focused on sulfate reduction and elemental sulfur recovery using photoelectric microbial electrolysis cell method. They succeeded in recovering elemental sulfur at just 1.2V with a rate of conversion of $46.3\% \pm 7.9\%$ (Luo et al., 2020).

Ntagia et al. (2020) studied the feasibility of electrochemical treatment of the spent caustics from the petrochemical plant. They found that it was more economically efficient than the advance oxidation process due to the cost-saving from NaOH recovery and hydrogen peroxide (oxidizing agent) replacement cost. They synthesized spent caustic first to check the removal feasibility, then continued operation of 20 days with real spent caustic, which was used in divided electrolysis cell controlled galvanostatically at 300 Am^{-2} . The energy input for sulfur removal, wastewater treatment and NaOH recovery were $3.7 \frac{\text{kWh}}{\text{Kg S}}$, $75.3 \frac{\text{kWh}}{\text{m}^3}$ and $6.3 \frac{\text{kWh}}{\text{Kg}}$, respectively (Ntagia et al., 2020).

Abd & Li (2018) have simulated petrochemical industrial sulfidic spent caustic and studied the effect of basic anion exchange resin in removing sulfide ions. The results showed good sulfide removal (95.5%, from 35.5 mg/L to 1.5 mg/L) along with good moisture retention (60% at 60 °C) and COD removal (94.5%). No significant change was observed for the pH in this treatment (Abd & Li, 2018).

Davarnejad & Bakhshandeh (2018) also investigated the electro-fenton method for spent caustic treatment. They succeed in finding the optimum pH, reaction time, current density, $\text{H}_2\text{O}_2/\text{SCW}$ and $\text{H}_2\text{O}_2/\text{Fe}^{2+}$ ratios. The optimum operating pH was in the range of 2.96-2.87 at reaction time 70.67min-65.52min with current density in

the range of 58.85mA/cm²-55.47 mA/cm² at 1.59 ml/l-1.38 ml/l H₂O₂/SCW volume ratio and 3.47-3.21 H₂O₂/ Fe²⁺ molar ratios for COD and sulfide, respectively (Davarnajad & Bakhshandeh, 2018).

Ben Hariz et al. (2013) studied the possibility of sulfidic spent caustic treatment using electrocoagulation method. They chose electrocoagulation method as it is characterized by its simple equipment, ease of operation and decreased amount of sludge. They studied the effect of initial pH, type of electrode, density and set-up. Iron electrode showed better results in 60 minutes duration compared to aluminium electrode (84% and 58% of sulfide removal for iron and aluminium respectively) at initial spent caustic sulfide concentration of 34517 mg/L and COD concentration of 72450 mg/L. The optimum pH and density were at 9 and 21.2 mA cm²- respectively. The removal using a single electrocoagulation cell was 84% and 85% for sulfide and COD removal respectively and when using two parallel electrocoagulation cells, the removal was more than 98%. Metals removal were also observed in the aforementioned process (Ben Hariz et al., 2013).

6. Multiple techniques application

Rita et al. (2020) studied the possibility of treating naphthenic spent caustic (from MEROX process) using neutralization combined with Fenton oxidation and neutralization combined with liquid-liquid extraction on the laboratory scale. Samples were taken from Galp refinery located in Sines, Portugal. The main conclusion of their study was: the necessity of neutralization step where its importance lies in enhancing many contaminants removal and ease of the treatment process. Fenton oxidation and liquid-liquid extraction processes post to neutralization were effective to improve effluent quality and as per

their operational expenditure (OPEX) cost, both methods show substantial economic saving. By comparing the two processes, liquid-liquid extraction resulted in effluent with the highest removal percentage (96% for COD, 99% for polar oil and grease & 80% for COD and 95% for polar oil and grease for liquid-liquid extraction and Fenton oxidation, respectively) (Rita et al., 2020).

Microbial Fuel Cell (MFC) technology is a combined method of biological and electrochemical treatment methods that utilizes biomass energy to generate electrical energy. In this type of treatment, the constituent micro-organisms play a vital role in the oxidation and reduction reaction leading to energy generation and extraction. The main drawback is the need to separate toxic substances which could not be decomposed by the germs. This was the cost factor of this type of process (Alipour & Azari, 2020).

In 2019, Fazli et al. investigated the possibility of having MFC with a novel set-up of the bioelectrochemical cell (BeCC) integrated with Granular Activated Carbon (GAC). Sulfidic spent caustic from a petrochemical industry located on the east coast of Malaysia was used for this research. The optimum GAC dosage was 10g operated with BeCC leading to 97.56% COD removal, 96.25% sulfide removal and 583 mV Open Circuit Voltage (OCV) production. Among several tested bacteria, *Klebsiella oxytoca* was the dominant bacteria attached to the GAC, which is “an electrochemically active bacteria that contributed towards better BeCC performance”. This study was on a laboratory scale, which needs to be proven on a real scale (Fazli et al., 2019).

Fazli et al. in 2018, also studied the possibility of treating spent caustic from the petrochemical industry located in Gebeng, Kuantan using

MFC with altering Hydraulic retention time (HRT) and Mixed Liquor Suspended Solid (MLSS) factors. They wanted to prove MFC effectiveness in treating spent caustic in addition to their conventional use for sewage water, swine water and domestic wastewater. The outcome was promising; COD and sulfide removal was efficient. The best operating condition was found at HRT 9 days leading to 98% and 98.89% for COD and sulfide removal respectively and 82.1mV voltage generation. When the effect of MLSS was studied, the best results obtained with MLSS concentration 1500 mg/L, which led to 94.07% and 89.01% COD and sulfide removal efficiency, respectively (Fazli et al., 2018).

Karimi et al. (2016) compared three common widely used technologies for spent caustic treatment to choose the best method for their case study (WAO, biological and catalytic methods). Among the three types and based on the four comparison criteria: cost, availability, ability to scale-up and environmental impact, catalytic method dominant the list of preference and subsequent studies were based on the catalytic method. AHP technique for the best method selection was used. The catalytic air oxidation in batch bubble column and mixed precipitation reactor succeeded to recover 13.4% (by wt) of NaOH for an initial weight of 4% (by wt) at mild temperature and pressure conditions. Sulfide and COD reductions were 45% and 33%, respectively (81 to 36 g/L of Sulfide and 160 to 52 g/L of COD) (Karimi et al., 2016).

Ketu (2013) studied the feasibility of treating Tema's Oil Refinery (TOR)-Ghana spent caustic (NaOH based) using two stages, i.e. neutralization followed by WAO at high temperature (240-260 °C). The high operating condition oxidized all reduced sulfur compounds

and phenols, reduced most of COD, and also eliminated foaming tendency characteristics. Reduction percentage was 88.46%, 99.57%, 94.33%, 50.93%, 88.97%, 99.03%, 99.73% and 84.37% for H₂S, phenol, mercaptans, pH, COD, BOD, TDS and TSS, respectively (Ketu, 2013).

The problem of spent caustic generation could also be avoided/reduced from the beginning by changing the desulfurization philosophy/ techniques.

2.2.9 Summary of the frequently treatment techniques

Table (6) summarizes the most used techniques for spent caustic treatment as per the literature findings:

Table (6): Summary of the most used techniques for spent caustic treatment

	Paper title	Most used methods	Reference
1.	Electrochemical treatment of industrial sulfidic spent caustic streams for sulfide removal and caustic recovery	1. Biological treatment with chemical treatment. (either by neutralization, conventional and advance oxidation or combination) 2. Electrochemical based on their research-lab scale only	(Ntagia et al., 2020)
2.	Comparison of different strategies to treat challenging refinery spent caustic effluents	1. Incineration 2. Neutralization 3. Neutralization combined with other techniques such as Liquid-liquid extraction or Fenton process	(Rita et al., 2020)
3.	Characteristics and Treatment of Wastewater from the Mercaptan Oxidation Process: A Comprehensive Review	1. WAO 2. CWAO 3. Acid neutralization 4. AOP 5. Electrochemical process and MFC	(Pino-Cortés et al., 2020)

	Paper title	Most used methods	Reference
		6. Biological	
4.	Electrochemical cell (BeCC) integrated with Granular Activated Carbon (GAC) in treating spent caustic wastewater	1. Chemical oxidation 2. WAO 3. Biological	(Fazli et al., 2019)
5.	Biological treatment of toxic refinery spent sulfidic caustic at low dilution by sulfur-oxidizing fungi	1. Hydro-sulfurization 2. Extractive desulfurization 3. Oxidative desulfurization 4. Bio-desulfurization (BDS)	(Gholipour et al., 2018)
6.	Olefin plant spent caustic wastewater treatment using electro-Fenton technique	1. Neutralization 2. WAO 3. AOP (chemical oxidation, Fenton, and photo-Fenton processes, ultraviolet (UV)-based processes, photo-catalytic redox processes, supercritical water oxidation, sonolysis and electro beams) 4. Electro Fenton	(Davarnejad & Bakhshandeh, 2018)

	Paper title	Most used methods	Reference
7.	Preliminary study of sulphide removal using ion exchange resin	1. WAO 2. Chemical precipitation 3. Ion exchange resin	(Abd & Li, 2018)
8.	Microbial Fuel Cell (MFC) in treating spent caustic wastewater: Varies in Hydraulic Retention Time (HRT) and Mixed Liquor Suspended Solid (MLSS)	1. Chemical oxidation (using hydrogen peroxide) 2. WAO 3. MFC	(Fazli et al., 2018)
9.	Wet air oxidation of cresylic spent caustic A model compound study over graphene oxide (GO) and ruthenium/GO catalysts	1. WAO 2. CWAO	(Barge & Vaidya, 2018)
10.	The Efficient Process for Spent-caustic Wastewater Treatment	1. WAO 2. Direct acid neutralization 3. Biological	(Seyedin & Hassanzadeganroudsari, 2018)

	Paper title	Most used methods	Reference
		4. Incineration 5. Advance chemical oxidation	
11.	Investigation on new method of spent caustic treatment	Used methods 1. Biotreatment 2. Incineration 3. Acid neutralization 4. WAO 5. Catalytic oxidation 6. Peroxide oxidation Most 2 used methods: 1. Chemical oxidation & Neutralization 2. Dilution Treatment & WAO	(Roudsari et al., 2017)
12.	Regeneration and treatment of sulfidic spent caustic using analytic hierarchy process	1. Biological 2. Chemical 3. Thermal (incineration & oxidation)	(Karimi et al., 2016)

	Paper title	Most used methods	Reference
13.	A comparative study of the treatment of ethylene plant spent caustic by neutralization and classical and advanced oxidation	1. Chemical 2. Thermal 3. Biological 4. Neutralization	(Hawari et al., 2015)
14.	Treatment and disposal of spent caustic at TEMA oil refinery (TOR)	1. Neutralization followed by biological 2. WAO followed by biological	(Ketu, 2013)
15.	Treatment of petroleum refinery sulfidic spent caustic wastes by electrocoagulation	1. Neutralization 2. WAO 3. Chemical oxidation and precipitation 4. Combination of neutralization and Fenton or electro-Fenton 5. Biological 6. Electrochemical processes (e.g. electrocoagulation)	(Ben Hariz et al., 2013)
16.	Application of a 2-step process for the biological	Didn't give recommendations. It talks only about biological treatment.	(M. De Graaff et al., 2012)

	Paper title	Most used methods	Reference
	treatment of sulfidic spent caustics		
17.	Spent caustic treatment options	1. Chemical oxidation 2. Neutralization 3. Dilution treatment 4. Wet air oxidation	(Aldaghman, 2012)
18.	Biological treatment of refinery spent caustics under halo-alkaline conditions	1. Wet air oxidation 2. Chemical treatment (with hydrogen-peroxide) 3. Biological treatment	(M. de Graaff et al., 2011)
19.	Sources of sulfide in waste streams and current biotechnologies for its removal	1. Direct air stripping 2. WAO 3. Chemical precipitation 4. Oxidation (catalytic or non-catalytic) 5. Biological	(Qaisar et al., 2007)

2.2.10 Summary of literature review findings

Table (7) summarize the literature findings.

Table (7): Summary of literature review findings

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
1	Wet air oxidation of cresylic spent caustic-A model compound study over graphene oxide (GO) and ruthenium/GO catalysts	Aditti S. Barge Prakash D. Vaidya	2018	Treat cresylic spent caustic using Nobel catalyst (ruthenium/GO) to reduce cost associated with WAO and conventional carbon treatment method.	Cresylic	Experiment for synthesizing and testing the catalyst over different range of temperature, pressure and concentrations. Methods used were WAO & CWAQ treatments.	1. Conventional GO catalyst was good TOC & BOD degrader. 2. GO/Re give better degradation results. 3. GO/Re stability was better than GO at the same temperature. 4. Ease of GO catalyst recovery. 5. Order of degradation was found p-cresol > o-cresol > m-cresol.	1. Only applied using synthesized spent caustic. 2. Parameter of concern: TOC and COD.
2	Characteristics and Treatment of Wastewater from the	Ernesto Pino-Cortés Silvio Montalvo	2020	Carry-out comprehensive review on spent caustic types,	All	Literature review Using information	1. WAO Most applicable method, easy	1. WAO High initial investment cost,

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
	Mercaptan Oxidation Process: A Comprehensive Review	César Huiliñir Francisco Cubillos Juan Gacitúa		sources, characteristics, reactions and their treatment methods.		from reports, thesis, and research articles.	method, Safest method, proven technology. 2. CWAO Reduce the required operating condition for WAO, Fasten the reaction, High selectivity to removal of contaminant. 3. Acid neutralization Ability to capture and reuse contaminates, it does not destroy it, can reduce COD significantly, Best acid type is sulfuric acid, Foam formation enhance naphthenic acids removal. 4. AOP	High operational cost due to the requirement for P & T, High cost associated with materials of construction. 2. CWAO Difficult to have the suitable catalyst, Cost associated with catalyst purchasing and replacing. 3. Acid neutralization Foam formation at high temperature due to phenol presence.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
							Very good for high COD and low biodegradability spent caustic, low capital costs, relatively easy to install. 5. MFC Ability to use biological energy to introduce energy. 6. Biological Environmentally beneficial, economical method.	4. AOP Destroy the contaminates. 5. MFC have several limitations on a real scale. 6. Biological Cannot be used solely specially for high concentrations feeds.
3	The Efficient Process for Spent-caustic Wastewater Treatment	SayedHadi Seyedin Majid Hassanzadeganroudsari	2018	Treat the spent caustic to: 1. Eliminate high toxic compounds 2. Reduce neutralization	Sulfidic	Experiment using AOP treatment.	1. Reduction of sulfur materials and phenols. 2. Remove foaming tendency. 3. Reduction of COD.	1. Safety factor is an issue with the treatment using AOP. 2. Parameter of concern:

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
				and pH reduction costs. 3. Produce usable product from the effluent. 4. Utilize low cost materials/ additives and feeds. 5. Optimize energy use. 6. Use new technology. 7. Purify without environmental risks.			4. Production of biodegradable wastewater. 5. Recovering NaOH and Na₂CO₃ products.	phenol, sulfur and COD.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
4	A comparative study of the treatment of ethylene plant spent caustic by neutralization and classical and advanced oxidation	Alaa Hawari Hasanat Ramadan Ibrahim Abu-Reesh Mabrouk Ouederni	2015	To study different treatment methods on sulfidic spent caustic. Studied methods were: neutralization, classical oxidation and advance oxidation. Study to reduce COD and sulfide concentrations. Also, to investigate of the following parameters: pH, oxidants concentration, ratio of oxidant concentration to	Sulfidic	Experiment using neutralization, classical oxidation & advance oxidation treatments	1. Neutralization coupled with Classic oxidation reduced the sulfur significantly. 2. Neutralization coupled with AOP (Fenton) was the best for removal of sulfide and COD below the limits.	1. Neutralization alone did not reduce the parameters to the obligated limits. It only reduces sulfide content. 2. Neutralization could be used combined with other methods. 3. Neutralization coupled with classical oxidation reduce both COD and sulfide but still values were above the legal limits.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
				catalyst concentration.				4. Parameter of concern: COD, sulfide and pH.
5	UV-catalytic treatment of spent caustic from ethene plant with hydrogen peroxide and ozone oxidation	Zheng-zhe Yu De-zhi Sun Chang-hai Li Peng-fei Shi Xiao-dong Duan Guo-rong Sun Jun-xin Liu	2004	Enhance sulfidic spent caustic treatment by increasing hydroxyl concentration and use UV/H ₂ O ₂ , UV/O ₃ and UV/H ₂ O ₂ /O ₃ oxidation systems.	Sulfidic	Experiment using AOP treatment.	1. Removal of COD increase with increasing H ₂ O ₂ dosage for both UV/ H ₂ O ₂ and UV/O ₃ . 2. Ratio of BOD/ COD of the effluent increased. 3. Removal of COD in UV/ H ₂ O ₂ /O ₃ system was better than UV/O ₃ .	1. Parameter of concern: COD.
6	Biological treatment of toxic refinery spent sulfidic caustic at low	Sevan Gholipour Pouya Mehrkesh Ehsan Azin	2018	Treat sulfidic spent caustic biologically using fungi taken from high sulfur	Sulfidic	Experiment using biological treatment.	1. SMHS-3 has the highest sulfur oxidation activity. 2. Biologically it was proved the	1. pH reduction step is a must. 2. Parameters of concern: TDS,

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
	dilution by sulfur-oxidizing fungi	Hoda Nouri Abbas Abbas Rouhollahi Hamid Moghimi		containing environment.			reduction of TDS, COD and sulfide.	COD and active sulfide.
7	Treatment of acidic sulfate-containing wastewater using revolving algae biofilm reactors: Sulfur removal performance and microbial community characterization	Haoyuan Zhoua Yanqing Shenga Xuefei Zhaod Martin Grossd Zhiyou Wenb	2018	Evaluate revolving algal biofilm (RAB) reactor performance to treat acid mine drainage wastewater which is characterized by its low pH and high sulfate.	Acid mine drainage	Experiment using biological treatment.	1. RAB reactor is effective and efficient. Removal was range from 35-46%. 2. RAB also proved its effectiveness to remove ammonia, phosphorus and COD.	1. Applied using synthesized solution. 2. Need to assess and optimize RAB operational conditions. 3. Parameters of concern: COD.
8	Biological treatment of sulfidic spent caustics under haloalkaline conditions	Cornelis Maarten de Graaf	2012	Develop biotechnological process for sulfidic spent caustic without	Sulfidic	Experiment using biological treatment.	1. Biological treatment is cheaper and safer compared to other treatment methods.	1. Parameters of concern: sulfide and benzene.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
	using soda lake bacteria			using water dilution.			2. The used soda lake bacteria prove its efficiency to treat sulfidic spent caustic, it reduces sulfide through converting it to sulfate. 3. In addition to sulfide, benzene biodegrading took place.	
9	Biological treatment of refinery spent caustics under halo-alkaline conditions	Marco de Graaff Martijn F.M. Bijmans Ben Abbas Gert-J.W. Euverink Gerard Muyzer Albert J.H. Janssen a,d	2011	Treat sulfidic spent caustic biologically to reduce sulfide.	Sulfidic	Experiment using biological treatment.	1. Biological treatment is cheaper and safer compared to other treatment methods. 2. soda lake bacteria (genus Thioalkalivibrio) was effective to sulfide conversion.	1. Biological treatments are not designed to handle large amounts of complex spent caustic. 2. Biological treatments are affected by pH changes, salt

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
							3. Benzene was removed in addition to sulfide.	concentrations and toxic compounds. 3. Parameters of concerns: sulfide & benzene.
10	Regeneration of spent caustic and acidic cleaning baths using a pilot membrane system	Anna Kowalik-Klimczak Maciej Życki, Paulina Rajewska	2019	To evaluate the performance of membrane process for spent caustic generated as a result of daily industry washing technology.	Generated from industry caustic washing technology	Experiment using membrane treatment.	1. MF type proves its effectiveness in reducing the contaminates level. 2. MF/UF was more effective than MF. 3. UF also proves its effectiveness for acidic cleaning bath. 4. UF/ NF system was crucial to regenerate acidic cleaning baths.	1. Applied using synthesized spent caustic and acid solution. 2. Parameters of concern: total bound nitrogen, total phosphorous, COD and TOC.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
11	Sulfate reduction and elemental sulfur recovery using photoelectric microbial electrolysis cell	Haiping Luo Jiamin Bai Jiajia He Guangli Liu Yaobin Lu Renduo Zhang Cuiping Zeng	2020	Treat synthesized sulfate rich wastewater and recover sulfur using photoelectricity microbial electrolysis cell & to optimize the external voltage for elemental sulfur recovery and energy consumption.	Synthesized sulfate rich wastewater	Experiment using microbial electrolysis cell.	1. Sulfate was reduced with just 1.7V. reduction of sulfate was in the form of elemental sulfur (S^0), sulfide (S^{2-}), and S_2O_3. 2. The results confirmed that the PMEC is able to convert solar energy and therefore it can reduce electric energy consumption.	1. Applied using synthesized spent caustic. 2. Parameter of concern: sulfate.
12	Electrochemical treatment of industrial sulfidic spent caustic streams for	Eleftheria Ntagia Erika Fiset Linh Truong Cong Hong Eleni Vaiopoulou	2020	Treat synthesized and real sulfidic spent caustic using electrochemical treatment.	Sulfidic	Experiment using electrochemical treatment.	1. Testing real spent caustic with 2 compartment electrochemical cells and with 20 days operation was proved to be	1. High investment cost for anode and membrane provision. 2. Requirement for regular

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
	sulfide removal and caustic recovery	Korneel Rabaey					economically viable for HS⁻ removal. 2. The cell voltage and anode potentials during the 20 days period with continuous operation was stable with 80% efficiency for HS⁻ conversion to sulfur. 3. Recovery was achieved. It reduces the cost of fresh/ new caustic purchasing and transportation. 4. Pollutant was removed with low energy input and NaOH recover	electrode replacement and the lack of resource recovery. 3. Cost associated with cost of energy required for electrochemical cell. 4. Parameters: of concern sulfide and NaOH.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
							achieved with moderate energy input. 5. Assessment showed it is very cost efficient due to the recovery of NaOH and replacing H₂O₂ oxidizing agent.	
13	Preliminary study of sulphide removal using ion exchange resin	Syarifah Abd Rahim Kai Li Teo	2018	Treat synthesized sulfidic spent caustic using ion exchange resin. Treatment target sulfide and COD.	Sulfidic	Experiment using ion exchange resin treatment.	1. Efficiency of ion exchange resin was proved to remove sulfide and COD.	1. Applied using synthesized spent caustic. 2. pH value remains constant which means this method did not reduce pH. 3. Parameters of concern: pH,

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
								COD and sulfide.
14	Olefin plant spent caustic wastewater treatment using electro-Fenton technique	Reza Davarnejad Malihe Bakhshandeh	2018	Treat synthesized and real olefin spent caustic using electro-Fenton method. And to find the optimum condition for maximum sulfide and COD removal.	Sulfidic	Experiment using electro-Fenton treatment.	1. The method was proved experimentally and statistically to remove sulfide and COD. 2. The optimum operating conditions and settings were also studied and found.	1. Effect of other parameters which might exist were not studied. 2. Parameters of concern: sulfide and COD.
15	Treatment of petroleum refinery sulfidic spent caustic wastes by electrocoagulation	Ichrak Ben Hariz Ayed Halleb Nafaa Adhoum Lotfi Monser	2013	Treatment of synthesized and real refinery spent caustic using electrocoagulation. Treatment target sulfide and organic compounds.	Sulfidic	Experiment using electrocoagulation.	1. Very effective for sulfide, organic compounds (Represented by COD) and metals heavy metals removal.	1. Parameters of concern: sulfide and organic compounds.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
				Also, it optimizes the conditions for maximum removal.			2. Sacrifice anode like Fe was found better than Al. 3. 2 cells in parallel gave better results and reduce sulfide and organic compounds by 98%.	
16	Comparison of different strategies to treat challenging refinery spent caustic effluents	A.I. Rita C.S.D. Rodrigues M. Santos S. Sanches L.M. Madeira	2020	Treat synthesized and real spent caustic using neutralization combined with Fenton oxidation and neutralization combined with liquid-liquid extraction.	Naphthenic spent caustic	Experiment using neutralization combined with Fenton oxidation and neutralization combined with liquid-liquid extraction treatments.	1. Neutralization step was proven to be important as pre-treatment. 2. Fenton oxidation and LLE proved their efficiency to treat the spent caustic. 3. As per the conducted OPEX, both methods are considered	1. Did not carry-out the CAPEX. 2. Parameters of concerns: TOC, COD, pH, sulfide, Phenolic, Sulphates and O&G.

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
				Target contaminant is organic load. Also, it performs cost treatment analysis to choose the best option.			economically since it will save money of disposal charging. 4. Comparing OPEX of the two methods, neutralization followed by LLE was found more preferable.	
17	Bioelectrochemical cell (BeCC) integrated with Granular Activated Carbon (GAC) in treating spent caustic wastewater	Norsafiah Fazli NoorSabrina Ahmad Mutamim ChanYung Shem SyarifahAbd Rahim	2019	Treat real spent caustic using novel BeCC cell integrated with GAC.	Sulfidic	Experimental using MFC treatment.	1. This configuration proves its efficiency to treat the spent caustic 2. It produces clean energy.	1. Parameters of concern: Sulfide and COD.
18	Microbial Fuel Cell (MFC) in treating spent	Norsafiah Fazli	2018	Treat real spent caustic and generate clean	Sulfidic	Experimental using MFC.	1. MFC proved its efficiency to treat spent caustic by	1. Parameters of concern:

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
	caustic wastewater: Varies in Hydraulic Retention Time (HRT) and Mixed Liquor Suspended Solid (MLSS)	Noor Sabrina Ahmad Mutamim Nur Maizatul Azwani Jafri Nurul Aisyah Mohd Ramli		energy using MFC.			reducing COD and sulfide. 2. In addition to the treatment, energy was generated.	Sulfide and COD.
19	Regeneration and treatment of sulfidic spent caustic using analytic hierarchy process	Asadollah Karimi Esmaeil Fatehifar Reza Alizadeh Iraq Ahadzadeh	2016	To choose the best treatment option using AHP and carry-out experiments for the best option.	Sulfidic	AHP and experiment using CWAQ.	1. Alternatives were: WAO, biological and catalytic methods. 2. Criteria were: cost, scale-up, availability, environmental impact. 3. Weights of cost: 40.9%. 4. Weights of scale-up: 27.9%.	1. AHP model was based on 3 alternatives and 4 criteria only. 2. The experiment was based on CWAQ as per the results best treatment results. 3. Parameters of concern:

	Article title	Researcher (s) names	Year	Objective	Type of spent caustic	Methodology	Outcome	
							Strengths	Weaknesses
							5. Weight of availability 8%. 6. Weight of environmental requirement 27.9%. 7. CWAO dominate the list among the 3 criteria (45,4%), followed by WAO 31.8% and lastly biological method 22.7%.	sulfide, COD and NaOH.
20	Treatment and disposal of spent caustic at TEMA oil refinery (TOR)	Ketu, Jonathan	2013	Treat real spent caustic in two stages using neutralization and WAO.	Cresylic	Experiment using neutralization and WAO methods.	1. Results proved reduction of multiple parameters below the regulated limits.	1. Parameters of concern: pH, BOD, COD, TDS, TSS, hydrogen sulfide, mercaptan and phenol.

Based on the above literature review, there were no researches found for non-regenerative process spent caustic treatment. However, research for the treatment of regenerative processes spent caustic were found a lot.

AHP method for the best treatment option selection was used once by Karimi et al. (2016) with a limited number of criteria and alternatives. Criteria of their model include cost, scale-up, availability, environmental impact. While the alternatives were: WAO, biological and catalytic methods. Moreover, emission dispersion modelling for environmental and health impact assessments was not found applied in any of the above literature.

This research uses APHA for the wastewater analysis and Karimi et al. methodology for the best treatment option investigation (AHP).

2.3 Research Hypotheses

1. Treatment of Bahrain's gas treatment plant spent caustic is feasible and lowering its hazardous parameters to the acceptable levels is possible.
2. Hydrogen sulfide concentration in the air is hazardous to employees/ neighbours.
3. Hydrogen sulfide concentration in the air is in agreement with Bahraini air quality standards.

Chapter Three

Methods and Procedures

- 3.1 Introduction**
- 3.2 Research Study Methodology**
- 3.3 Research Study Tools**
- 3.4 Data Collection and Procedures**

Chapter Three

Methods and Procedures

3.1 Introduction

This chapter includes details of the research design type (clause 3.1), the study methodology (clause 3.2), study tools (clause 3.3) and data collection and procedures (clause 3.4).

The research design type on the basis of time was cross-sectional because it was conducted during a short and specific time period. On the basis of nature, it was applied/action i.e. it aimed to solve an immediate problem facing an organization (Bahrain gas treatment plant). On the basis of purpose, it was exploratory. It aims to gain formality with a phenomenon to achieve new insights into it to serve the purpose and also to test the hypothesis of a causal relationship between variables. On the basis of intervention implemented in research, it was observational research because there was no control on the variables, and there was no intervention. On the basis of evidence, it was conceptual and empirical because it relates data derived from literature, data analysis and case modelling. On the basis of environment, it was set in a simulated environment. GRAMM/GRAL software was used to model the conditions. On the basis of the level of investigation, it was analytical since it depends on analyzing the available information to draw a critical evaluation of interest. On the basis of the analysis approach adopted in this research, it was a quantitative approach (C.R. Kothari, 1990).

The used data type in this research was secondary data which were the following:

- Data from literature

- Data from the case study company records (process description, equipment data sheets, process flow diagrams, spent caustic analysis reports, etc.)
- Metrological data from the ministry of transportation and telecommunication- metrological directorate.

3.2 Research Study Methodology

The methodology of this research was based on the following:

1. Analytical Hierarchy Process (AHP) Questionnaire for the best treatment option selection.
2. GRAL modelling for the air dispersion modelling. The model aims to determine the concentrations of hydrogen sulfide at different levels above the ground at both desulfurization and wastewater discharge locations.
3. American Public Health Association (APHA) wastewater analysis for the wastewater analysis. This tool aims to analyze the wastewater to determine the type and concentrations of the contaminants.

Details of each method and assumptions are discussed in the following sections.

3.3 Research Study Tools

The used tools in this research were the following:

1. Desk study, i.e. theoretical literature review through the published researches, studies and documents found in the case study company records such as procedures, previous analysis reports and studies.

2. AHP Questionnaire for the best treatment option.
3. APHA for the wastewater analysis.
4. GRAMM/GRAL software for air dispersion modelling (GRAL-GUI version 20.9.0.2).
5. Google map for maps and coordinates obtaining (for GRAMM/GRAL software).
6. Microsoft (MS) Word and MS Excel for data collection, compilation, organization, processing and analyzing.
7. Mendeley reference manager to organize references and citations.

1. AHP Questionnaire

AHP is one of the Multi-Criteria Decision Making (MCDM) methods that uses a hierarchal structure model to break down complex, unstructured situations/ case into its components and assigns weights to those components. Obtained weights represent the component importance or priority which enlightens the decision-makers about the degree of component influence or priority compared to another component” (Brunelli & Matteo, 2015; Karimi et al., 2016; OĞUZTİMUR, 2011; Saaty R.W., 1987).

AHP rating is based on common Saaty scale from 1-9; table (8) presents the scale along with each scale explanation:

Table (8): Saaty AHP scale of relative importance and explanation

Intensity of importance/ scale	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgment slightly favor one over the other.
5	Much more important	Experience and judgment strongly favor one over the other.
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate value	When compromise is needed.

While comparing two criteria with each other, one criterion shall be rated as per the aforementioned scale and the other will have the reciprocal values of the assigned rating ($a_{ji} = 1/a_{ij}$). In other words, suppose element A (i) and element B (j) are two criteria that are being compared. If it was decided that A is very much more important than B, hence a_{ij} (criterion i compared with j) is rated as seven and a_{ji} (criterion j compared with i) will be $1/7$. In the same way, the matrix is completed for all criteria. Following that step, relative weights (eigenvector) and the consistency ratio (CR) are calculated as shown

in Equation 7 and 8 below. CR calculation is important to measure the judgment/ rating consistency. The accepted value for CR is 10%, and so if calculated CR exceed 0.1, judgments are untrustworthy, and the exercise is considered valueless, meaning it must be repeated (Brunelli & Matteo, 2015; Coyle, 2004; Saaty R.W., 1987).

The comparison matrix between criteria is a n x n dimensional square matrix. The diagonal take value of 1 because at the diagonal, the criterion is compared with itself. Equation (6) shows the format of the comparison matrix (OĞUZTİMUR, 2011):

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (6)$$

$$\text{Consistency Index (CI)} = \frac{\lambda_{\max} - n}{n - 1} \quad (7)$$

Where $\lambda_{\max}$ is the maximum eigenvalue.

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}} \quad (8)$$

The random index (RI) is an estimation of the average CI obtained from a large enough set of randomly generated matrices of size n. RI values for the n matrix are shown in table (9).

Table (9): Random index table (Brunelli & Matteo, 2015; Coyle, 2004; Saaty R.W., 1987)

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41

After computing the above calculation and checking the inconsistency, the aggregated value is calculated by averaging the

valid responses. Also, the global weights are calculated by multiplying the local weight by its respective criteria weight. Equation (9) presents the global weight formula.

Global weight = alternative local weight $\times$ criteria weight (9)

2.GRAMM/GRAL software for air emission dispersion

Graz Lagrangian Model (GRAL) was used to compute the air dispersions. The software is free software that was developed in 1999, and now it is widely used in regulatory and scientific studies/assessment. The software is characterized by its ability to deal with frequent low-wind speed conditions, i.e. less than 1.5 m/s for up to 90% of the time. It can model emissions from stack sources, buildings, transportations, vegetations, lines, area sources and point sources. GRAMM/GRAL modelling is based on Reynolds-Averaged Navier–Stokes equations (RANS) and mass transfer algorithm equations solutions (Internal Combustion Engines and Thermodynamics, 2014).

3.APHA wastewater analysis method

APHA method is a standard testing method for water and wastewater analysis. It is an old standard that originated back in 1895 when bacteriologists faced a dilemma with analyzing bacteria in water. Bacteriologists asked for a standard procedure that unifies the results with particular reference to differentiate species. APHA established the first standard in 1897, which was widely accepted. The latest standard (edition 23rd/ 2017) consists of ten parts, each with a detailed method procedure for the constituents such as the physical and aggregate properties analysis, metals analysis, inorganic non-metallic constituent analysis etc. This method was explicitly requested from the third-party laboratory to test the wastewater samples (Hydrology Project - Technical Assistance, 1999).

3.4 Data Collection and Procedures

1.AHP Questionnaire

Fig.1 in chapter 2 shows AHP structural model used in this study. A total of five comparison criteria were used for six alternatives. The considered comparison criteria were the most affected criteria for any treatment facility selection:

- 1- Initial investment cost: refers to the cost associated with the needed capital expenditures such as machinery, shipment, tools and installation etc. (Jan, 2019).
- 2- Operational cost: it is associated with the maintenance and administration cost of a business on a day-to-day basis. Examples of these costs are rent expenses, maintenance, raw materials, chemicals etc. (MURPHY, 2020).
- 3- Environmental impact and safety concerns: refers to the environmental impact caused by using the technique and the degree of the required safety requirements.
- 4- Materials availability refers to the availability of raw materials/ equipment.
- 5- Treatment benefits: refers to the gained benefit such as electricity generation, new product formation, recovered substance etc.

The chosen alternatives were: WAO, CWAQ, AOP, biological, MFC and pre-treatment technologies. These alternatives were the most applied techniques found in the literature.

The questionnaire consists of 8 pages. The first page includes brief information about the research and the researcher as well. The second page includes instructions and guides on how to attempt the survey, along with a brief definition of the treatment methods (Alternatives).

The pairwise comparison starts from the third page onward. Each pairwise comparison is on a separate page. Total pairwise comparison questions which were required to attempt were 25.

The questionnaire targeted experts in wastewater, treatment, industrial and environmental fields as the subject requires knowledge about the wastewater treatment methods. The distribution sampling type was non-probability sampling. The questionnaire was sent to at least one person from the target fields (environmental and technical personnel from the case study company, supreme council for environment–Bahrain, environment specialists from private treatment/ recycling companies and specialist academics). A list of the targeted personnel is attached in appendix A2-1.

MS word was used to structure the questionnaire, and it was distributed as a soft copy through emails. The distribution commenced in November 2021 and lasted up to January 2022. Prior to distributing the final version of the questionnaire, the questionnaire was tested for validity through a pilot study. Comments were received and addressed. The pilot respondents were exempted from participation in the final distribution.

Upon responses receipts, data were compiled using MS excel and processed as per the described theory in section 3.3. Some of the responders were asked to revise their answers as their results were marked as invalid at the beginning due to exceeding the CR value.

Sample of AHP weight calculation

Sample of the carried calculation is presented below. The same calculations were introduced in MS excel.

Step1: getting the matrix based on the responder rating (A).

$$A = \begin{bmatrix} 1 & 3 & 4 & 2 & 5 \\ \frac{1}{3} & 1 & 2 & 2 & 6 \\ \frac{1}{4} & \frac{1}{2} & 1 & \frac{1}{2} & 7 \\ \frac{1}{2} & \frac{1}{2} & 2 & 1 & 3 \\ \frac{1}{5} & \frac{1}{6} & \frac{1}{7} & \frac{1}{3} & 1 \end{bmatrix}$$

Step 2: getting the sum of each column

Example:

$$1 + \frac{1}{3} + \frac{1}{4} + \frac{1}{2} + \frac{1}{5} = 2.3$$

The sum of each column will equal to $\Sigma = [2.3 \ 5.2 \ 9.1 \ 5.8 \ 22]$

Step 3: getting the normalized matrix.

Example: Column 1 normalized

$$\frac{1}{2.3} = 0.438$$

$$\frac{\frac{1}{3}}{2.3} = 0.146$$

$$\frac{\frac{1}{4}}{2.3} = 0.109$$

$$\frac{\frac{1}{2}}{2.3} = 0.219$$

$$\frac{\frac{1}{5}}{2.3} = 0.088$$

After carrying the same calculation for the other columns, the normalized matrix will equal to:

$$\begin{bmatrix} 0.438 & 0.581 & 0.438 & 0.343 & 0.227 \\ 0.146 & 0.194 & 0.219 & 0.343 & 0.273 \\ 0.109 & 0.097 & 0.109 & 0.086 & 0.318 \\ 0.219 & 0.097 & 0.219 & 0.171 & 0.136 \\ 0.088 & 0.032 & 0.016 & 0.057 & 0.045 \end{bmatrix}$$

Step 4: ensuring normalization was carried correctly by summing the columns and ensure it equal to 1.

Step 5: calculating the priority vector. It is the average of each row

Example: $\frac{0.438+0.581+0.438+0.343+0.227}{5} = 0.405$

The result of averaged each row gives the priority vector (X)

$$X = \begin{bmatrix} 0.405 \\ 0.235 \\ 0.144 \\ 0.168 \\ 0.048 \end{bmatrix}$$

Step 6: calculating AX which is the multiplication of matrix A by matrix X

$$A \times X = \begin{bmatrix} 1 & 3 & 4 & 2 & 5 \\ \frac{1}{3} & 1 & 2 & 2 & 6 \\ \frac{1}{4} & \frac{1}{2} & 1 & \frac{1}{2} & 7 \\ \frac{1}{2} & \frac{1}{2} & 2 & 1 & 3 \\ \frac{1}{5} & \frac{1}{6} & \frac{1}{7} & \frac{1}{3} & 1 \end{bmatrix} \times \begin{bmatrix} 0.405 \\ 0.235 \\ 0.144 \\ 0.168 \\ 0.048 \end{bmatrix}$$

Example:

$$1 \times 0.405 + 3 \times 0.235 + 4 \times 0.144 + 2 \times 0.168 + 5 \times 0.048 = 2.26$$

The resulted AX will equal to

$$\begin{bmatrix} 2.26 \\ 1.28 \\ 0.780 \\ 0.919 \\ 0.245 \end{bmatrix}$$

Step 7: calculating the $\lambda_{\max} \{AX|X\}$

$$\begin{bmatrix} 2.26 \\ 0.405 \\ 1.28 \\ 0.235 \\ 0.78 \\ 0.144 \\ 0.919 \\ 0.168 \\ 0.245 \\ 0.048 \end{bmatrix} = \begin{bmatrix} 5.57 \\ 5.45 \\ 5.42 \\ 5.45 \\ 5.13 \end{bmatrix}$$

The average of the matrix $\lambda_{\max} = \frac{5.57+5.45+5.42+5.45+5.13}{5} = 5.4$

Sep 8: calculating CI

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{5.4 - 5}{5 - 1} = 0.10$$

Step 9: getting RI. From the table RI = 1.12

Step 10: calculating CR = $\frac{CI}{RI} = \frac{0.1}{1.12} = 0.09$

Since CR < 0.1(this means that contribution is valid)

Sample of the distributed questionnaire and received feedback is illustrated in appendix A2-2.

2.GRAMM/GRAL data

GRAL was used in this study to compute the weathering pits as area sources and the drain pot discharge points as stack sources.

The made assumptions to run the software were the following:

Point or area sources at flat terrain with no buildings.

GRAL general settings were the following:

Dispersion time: 3600s

Particles per second: 100s

Surface roughness: 0.1m

Latitude of the GRAL area: 47 degree

Start with dispersion simulation: 1

Result file compression: 2

GRAL concentration grid settings were the following:

Horizontal grid resolution: 2.5m

Vertical dimensions of concentration layers: 3m

Number of horizontal slices: 3

Height above the ground: 1.8m, 3m and 6m

Values were the recommended values for the model computation. The domain area was selected large enough to visualise the dispersion in the nearby critical locations. Heights above the ground were: 1.8m to account for personnel at the site (person height), 3m and 6m account for personnel in the offices, which are either at first or second story building.

The metrological data were requested from the most reliable sources in Bahrain for the metrological data, i.e. metrological directorate in the Kingdom of Bahrain. The sample was for three years, i.e. from 1st January 2017 up to 31st December 2019. The data were electronically received in MS excel sheets (hourly data). The recorded metrological data were from Bahrain International Airport weather station at Lat 26 16N Long 50 39E Height 2m. It was screened, compiled, tabulated and analyzed using MS excel prior to processing in GRAMM/GRAL software. The metrological data included the date, time, wind speed (meters per second (m/s)), wind direction and the stability class. The file was arranged for work in the software, then converted to a CVS file, then to a met file. Manipulations that took place for the data arranging includes converting the temperature from degree Celsius (°C) to Kelvin (K), converting the wind speed from Knots to m/s, converting the hourly solar radiation from W/m² to Langley/m² (Ly/m²).

The stability class was calculated based on the Pasquill method based on time, wind speed, cloud cover, and solar radiation.

Google map was mainly used to get the geographical pictures and distances of the weathering pits and the desulfurization unit location along with their coordinate's details.

Emission rates (unit mass/ unit time) were one of the inputs for the dispersion modelling. The used models and equations for emission rates calculation are as follow:

1. Hydrogen sulfide emission rate from the weathering pits

WATER9 model equation was used for hydrogen sulfide emissions calculation from the open bonds/ weathering pits. This model is based on Henry's law constant, liquid and gas mass transfer coefficient, which was calculated using Springer et al. (1984) and Mackay and Matsugu (1973) equations (Bader Trading & Contracting, 2013b, 2013a; Beghia et al., 2012; EPA, 2016b; Jr et al., 2016; Prata et al., 2016).

$$E = K_L A C_L \quad (10)$$

Where K_L is the overall mass transfer coefficient (m/s)

A is the surface area (m^2)

C_L is the component concentration (kg/m^3)

The overall mass transfer coefficient is calculated by the following equation:

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{H_c k_G} \quad (11)$$

Where H_c is Henry's law constant (dimensionless)

k_L is the mass transfer coefficient in the liquid phase (m/s)

k_G is the mass transfer coefficient in the gas phase (m/s)

The mass transfer coefficient in the gas phase (k_G) was given by Mackay and Matsugu (1973).

$$k_G = 4.82 \times 10^{-3} U_{10}^{0.78} Sc_G^{-0.67} d_e^{-0.11} \quad (12)$$

Where U_{10} is wind velocity (m/s)

Sc_G is Schmidt number for the compound in the gas phase and its equation

$$Sc_G = \nu_G / D_G \quad (13)$$

ν_G the kinematic viscosity of air (m²/s)

D_G the molecular diffusivity of the compound in air (m²/s)

d_e is the effective diameter (m)

k_L is the mass transfer coefficient in the liquid phase, it was calculated using Springer et al. (1984), they gave total of 3 equations for this parameter based on the wind velocity U_{10} and F/D ratio.

F is fetch (m), D is the depth (m)

Table (10): Springer et al. (1984) Liquid phase mass transfer coefficient equations

Table SM1. Equations for the calculation of the mass transfer coefficients in the liquid and gas phases according to the WATER9 model.					1 2
Reference	Expression	ID	Conditions		
			F/D	U_{10}	
Mackay and Yeun (1983)	$k_L = 1 \times 10^{-6} + 144 \times 10^{-4} U_*^{2.2} Sc_L^{-0.5}$	SM1	F/D < 14	$U_{10} > 3.25 \text{ m s}^{-1}$	U^*
Mackay and Yeun (1983)	$k_L = 1 \times 10^{-6} + 34.1 \times 10^{-4} U_* Sc_L^{-0.5}$	SM2	F/D < 14	$U_{10} > 3.25 \text{ m s}^{-1}$	U^*
Springer et al. (1984)	$k_L = 2.78 \times 10^{-6} (D_L/D_{L,ether})^{-2/3}$	SM3	All F/D	$0 < U_{10} < 3.25 \text{ m s}^{-1}$	
Springer et al. (1984)	$k_L = 2.605 \times 10^{-9} (F/D) + 1.277 \times 10^{-7} U_{10}^2 (\frac{D_L}{D_{L,ether}})^{2/3}$	SM4	$14 < F/D < 51,2$	$U_{10} > 3.25 \text{ m s}^{-1}$	
Springer et al. (1984)	$k_L = 2.61 \times 10^{-7} U_{10}^2 (\frac{D_L}{D_{L,ether}})^{2/3}$	SM5	F/D > 51,2	$U_{10} > 3.25 \text{ m s}^{-1}$	
Mackay and Matsugu (1973)	$k_G = 4.82 \times 10^{-3} U_{10}^{0.78} Sc_G^{-0.67} d_e^{-0.11}$	SM6	All F/D	All U_{10}	

Where D_L is the molecular diffusivity of the compound in water (m^2/s)

$D_{L,ether}$ is molecular diffusivity of ethyl ether in water

Weathering pit-II emission rate calculation

CGP-II dimensions:

Length $L = 32.6 \text{ m}$ and the width $W = 29 \text{ m}$

$$d_e = 2 \sqrt{\frac{LW}{\pi}} = 2 \sqrt{\frac{32.6 \times 29}{\pi}} = 34.69 \text{ m}$$

F based on USEPA (2001) it is equal to the effective diameter

$F = 34.69 \text{ m}$, $D = 1.5 \text{ m}$

$$\frac{F}{D} = \frac{34.69 \text{ m}}{1.5 \text{ m}} = 23.13$$

$v_G = 1.54 \times 10^{-5} \text{ m/s}$ from table SM3

$D_G = 1.76 \times 10^{-5} \text{ m}^2/\text{s}$ from table SM2

$$Sc_G = \frac{1.54 \times 10^{-5} \text{ m/s}}{1.76 \times 10^{-5} \text{ m}^2/\text{s}} = 0.875 \text{ m}^{-1}$$

$$Sc_L = v_L/D_L$$

$$u_L = 8.93 \times 10^{-7} \text{ m/s}, D_L = 1.61 \times 10^{-9} \text{ m}^2/\text{s}$$

$$Sc_L = \frac{8.93 \times 10^{-7} \text{ m/s}}{1.61 \times 10^{-9} \text{ m}^2/\text{s}} = 554.65 \text{ m}^{-1}$$

The friction velocity U^* (m/s) is calculated using the following Smith (1980) equation

$$U^* (\text{m/s}) = U_{10} \times 0.01 \times (6.1 + 0.63 \times U_{10})^{0.5}$$

U_{10} vary based on the hourly metrological data, therefore MS excel was used for the calculation of the liquid mass transfer coefficient (k_L).

The suitable equation was chosen among equations SM1 to SM5 based on each case i.e. based on the U_{10} , F/D ratio and U^* .

The overall k_G equation is as follow:

$$k_G = 4.82 \times 10^{-3} U_{10}^{0.78} (0.875 \text{ m}^{-1})^{-0.67} (30.98 \text{ m})^{-0.11}$$

Henry's law constant for hydrogen sulfide was found equal to 4.03×10^{-1}

Using

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{H_c k_G}$$

And the averaged value of k_G , surface area 945.4 m^2 and $5.45 \frac{\text{mg}}{\text{L}}$ H_2S concentration,

$$E = 2.71 \times 10^{-5} \text{ kg/s} = 9.77 \times 10^{-2} \text{ kg/h}$$

Similarly, with the difference in weathering pit-I dimensions and H_2S concentration ($L = 29 \text{ m}$, $W = 26 \text{ m}$ and $5.95 \frac{\text{mg}}{\text{L}}$), the emission rate of weathering pit-I was found:

$$E = 5.3 \times 10^{-5} \text{ kg/s} = 1.91 \times 10^{-1} \text{ kg/h}$$

2. Hydrogen sulfide emission rate from desulfurization unit (drain pots)

The Heel method was used for hydrogen sulfide emission rates released from the desulfurization unit (drain pots depressurization). The heel method depends on the liquid fraction remain in the vessel prior to purging. Assumptions made for this method were the following (Bahrain national gas company, 1979; Banagas, 2010; Chemical book, 2017; Chevron phillips chemical company, 2019; Engineering ToolBox, 2003; National library of medicine, 2021e, 2014, 2021d, 2021a, 2021c, 2021b; RTI International, 2011; SIGMA-ALDRICH, 2006):

- 1- The liquid mass in the tank overwhelms the quantity of contaminants in the headspace.
- 2- The heel fraction range is between 0.1 to 1 percent based on multiple factors (liquid viscosity, vessel internals surface areas and the drainage locations).

The mixture specific gravity was calculated and the obtained results are shown in Table (11).

The maximum liquid volume in the vessel was $0.21 \frac{\text{m}^3}{\text{day}}$ and with 0.5% assumption for the heel fraction, the total liquid volume in the vessel equal to $0.21 \frac{\text{m}^3}{\text{day}} \times 0.005 = 0.00105 \frac{\text{m}^3}{\text{day}}$.

With 1.09 specific gravity and $0.44 \frac{\text{kg H}_2\text{S}}{\text{kg total}}$ hydrogen sulfide composition in the drained mixture, the amount of hydrogen sulfide emission is equal to:

$$0.00105 \frac{\text{m}^3}{\text{day}} \times 1.09 \times 1000 \frac{\text{kg}}{\text{m}^3} \times \frac{1\text{day}}{24\text{hours}} \times 0.44 \frac{\text{kg H}_2\text{S}}{\text{kg total}}$$

$$= 0.02 \frac{\text{kg}}{\text{hour}}$$

Similarly, the calculation was carried for all drain pots. Results are summarized in Table (11). Material balance results and detailed calculation are in appendix-A1-1 & A1-2.

Table (11): Mixture specific gravity and emissions rate - drain pots

		Specific gravity	H₂S composition (mass%)	Emissions ($\frac{\text{kg}}{\text{h}}$)
CGP-I	C3	1.091	0.44	0.02
	C4	0.88	0.00	0.00
CGP-II	C3	1.096	0.47	0.02
	C4	0.87	0.88	0.00

3.APHA analysis

The research population for the spent caustic/ wastewater was Bahrain's gas treatment plant. Samples were taken from the only gas treatment plant in Bahrain, which is Bahrain National Gas company (Banagas). A formal request was issued for a list of approved laboratories in the Kingdom of Bahrain, specifically requesting APHA analysis (Physiochemical, organic, non-organic and biological characteristics) since those parameters are the legally obligated parameters. Intranational laboratories was awarded for the sampling and analysis activity, the order was placed, and samples were taken on 5th October 2020. Reports were received on 13th October 2020.

Samples were taken from the two open bonds separately on the same day. The sampling type was random sampling. Each total sample volume was 5 litres which were stored in a labelled glass canister. The used sampling tool was a simple water sampler, as is shown in Fig.3 (Singh, 2015). International laboratories analysed the wastewater as requested using the Inductively Coupled Plasma mass spectrometry (ICP) method. The activity was witnessed by the researcher, operation and security personnel. Test lab analysis results are illustrated in appendix A3-1.

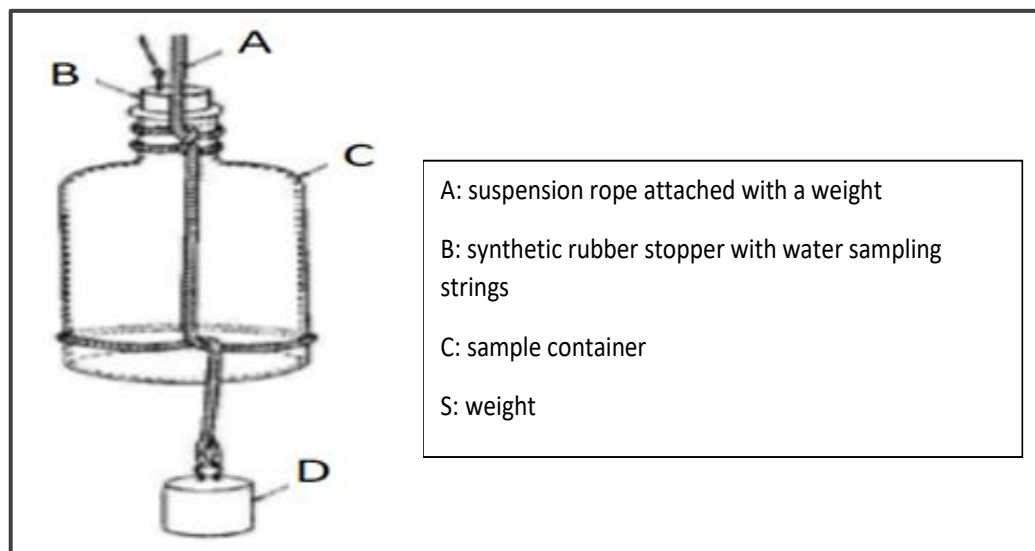


Fig.3: Simple water sampler (Singh, 2015)

General Background about the case study company

Banagas was established in 1979 and was inaugurated by His Highness late Amir of Bahrain Shaikh Isa bin Salman Al-Khalifa. The company is located in Alsakhir (about 20km from the capital Manama). Its main objective was to use the associated gas that is extracted and vented from Bahrain oil fields and produce marketable and high specification products. It also aimed to supply residue gas for internal company use and local industries and provide employment opportunities to Bahraini nationals. The company

underwent several expansions in 1990, 2003, 2013 and 2018. The current total throughput quantity is 170 Million Standard Cubic Feet per Day (MMSCFD), 150 MMSCFD and 350 MMSCFD for train I, train II and train III, respectively (Banagas, 2009; Operation department, 2019).

Process wise, Banagas process associated gas from Bahrain oil field and Refinery Off Gas (ROG) from Bahrain Petroleum Company (BAPCO) to Liquefied Petroleum Gas (Propane, Butane), Naphtha and residue gas. The overall operation units are three, namely (Operation department, 2019):

- 1- Compressor Station (CS) units
- 2- Central Gas Plant (CGP) units
- 3- Sitra Storage and product shipping units

CGP-I&II are further sub-classified into four units:

- 1- Condensation/ Separation unit
- 2- Dehydration/ Absorption unit
- 3- Fractionation unit
- 4- Treatment and Intermediate storage unit

Fig.4 shows Banagas's overall process operation diagram.

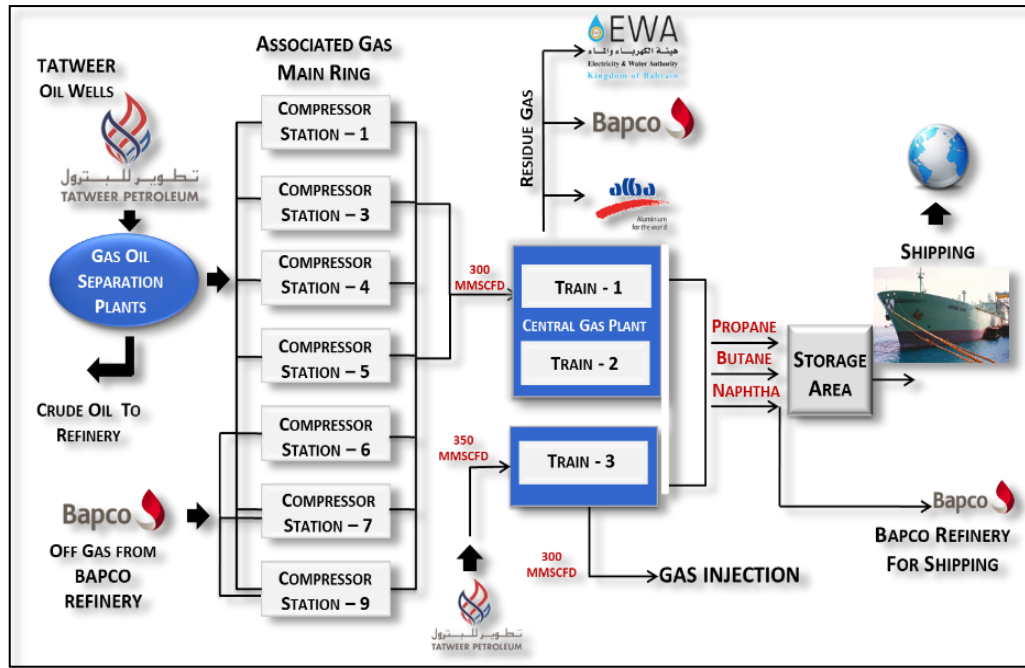


Fig.4: Banagas overall process operation diagram (Banagas, 2009; Operation department, 2019)

Potassium hydroxide/ methanol spent caustic, which is the main focus of this study, is generated from CGP train I and train II processing activities, and it is sent through the sewer along with other process wastewater to the weathering pits. Both subject of interest weathering pits located in the field next to CGP-I and CGP-II trains. Fig.5 and Fig.6 show the location of both weathering pits and the desulfurization unit, respectively (Alsaeg, 2014; Banagas, 1994b, 1994a, 1996, 2014).

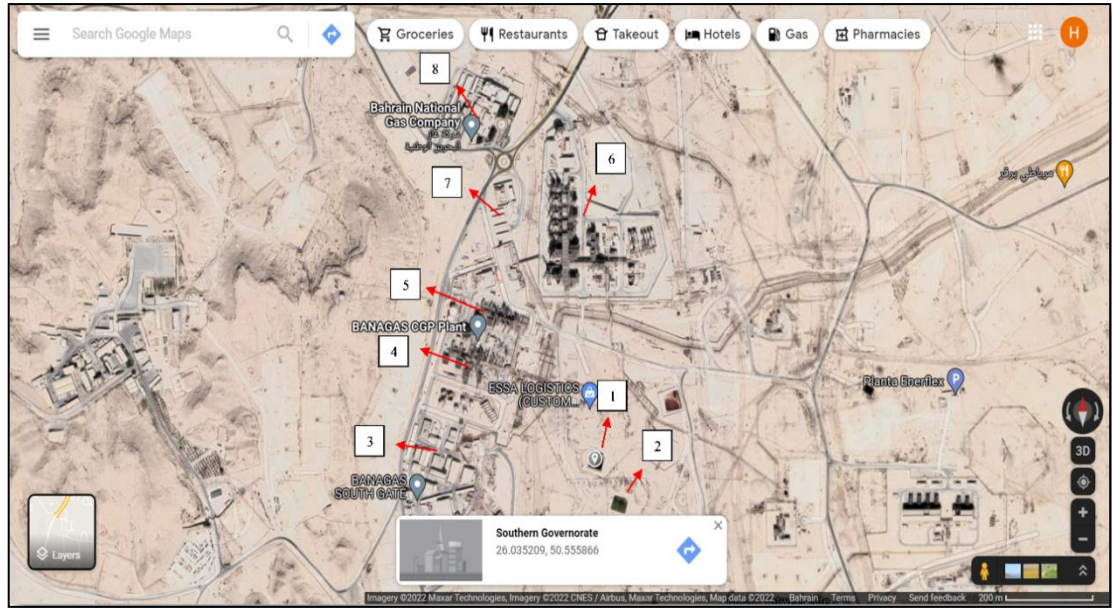


Fig.5: Geographical map for the weathering pits and nearby locations

[1: Weathering pit I, 2: Weathering pit II, 3: South side offices, 4: CGP-I, 5: CGP-II, 6: CGP-III, 7: north side offices, 8: main offices]

Approximate distance from weathering pit I, II and nearby locations are shown below in table (12).

Table (12): Approximate distance from weathering pit I, II and nearby locations

	Weathering pit I	Wreathing pit II
South side offices	286m	316m
CGP-I	285m	363m
CGP-II	313m	395m
CGP-III	361m	436m
Main office	693m	794m
North side offices	400m	484m

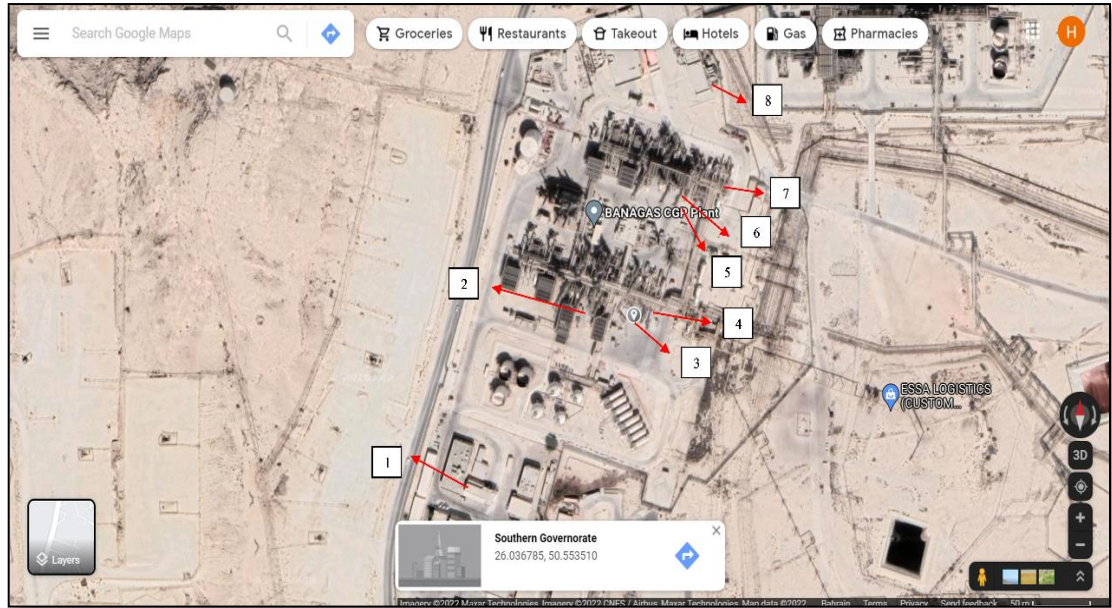


Fig.6: Geographical map for desulfurization unit (KOH treaters) and nearby locations

[1: south side offices, 2: CGP-I butane KOH treater, 3: CGP-I propane KOH treater, 4: CGP-I, 5: CGP-II propane KOH treater, 6: CGP-II butane KOH treater, 7: CGP-II, 8: North side offices]

Approximate distance from desulfurization units and nearby locations are shown below in table (13).

Table (13): Approximate distance from desulfurization units and nearby locations

	CGP-II desulfurization unit	CGP-I desulfurization unit
South side offices	247m	131m
CGP-III	143m	264m
North side offices	81m	193m

Chapter Four

Results, Discussion, and Recommendations

4.1 Results and Discussion

4.2 Conclusion, Recommendations and Future work

Chapter Four

Results, Discussion, and Recommendations

4.1 Results and Discussion

1.APHA wastewater analysis

Table (14) shows the analysis result of both wastewater weathering pits for 2014 and 2020. Bahrain's limits are also listed next to each parameter in the seventh and eighth columns.

Table (14): APHA wastewater analysis results

Parameter	Unit	Analysis results				Bahrain’s standards	
		CGP- Pit-I	CGP-Pit-II	CGP- Pit-I	CGP-Pit-II		
		December 2014	December 2014	October 2020	October 2020	Average monthly	Maximum
Physical							
Floating particles	mg/L	Nil	Nil	Nil	Nil	Nil	
PH @ 25	—	10.62	12.96	12.01	12.14	6-9	
Temperature (as received)	°C	28.2	28	34.1	34.2	3± (ΔT)	3± (ΔT)
Total Suspended solids (TSS)	mg/L	38	49	89	67.4	20	30
Turbidity	NTU	29	21	40.3	18.6	25	50
Chemical/ inorganic							
Ammoniacal Nitrogen as N	mg/L	12.75	8.9	4.8	3.4	1	3
Nitrate as NO ₃ – N	mg/L	24.2	45	36.3	21.8	10	10
Nitrite as NO ₂ – N	mg/L	18.4	20	32.1	17.2		
Sulfide as H ₂ S	mg/L	5.6	6.8	6.3	4.1	0.5	1
Chlorine residual	mg/L	1.4	1.8	Nil	Nil	0.5	1
Cyanide, CN ⁻	mg/L	<0.01	<0.01	<0.01	<0.01	0.05	0.1

Parameter	Unit	Analysis results				Bahrain's standards	
		CGP- Pit-I	CGP-Pit-II	CGP- Pit-I	CGP-Pit-II		
		December 2014	December 2014	October 2020	October 2020	Average monthly	Maximum
Total phosphate	mg/L	19.6	43.2	27.6	14.1	1	2
Organic pollutants							
Biochemical Oxygen Demand, BOD 5 days	mg/L	5220	7280	8855	5030	15	25
Chemical Oxygen Demand, COD	mg/L	4960	7588.8	9100	5200	100	150
Total Kjeldhal Nitrogen	mg/L	110	380	49.4	12.9	5	10
Total Organic Carbon, TOC	mg/L	1210	860	2690	785	50	50
Fluorescent Petroleum Matter	mg/L	<0.001	<0.001	<0.02	<0.02		
Oil & Grease	mg/L	<1	<1	<1	<1	8	10
Phenol	mg/L	<0.01	<0.01	<0.01	<0.01	0.2	0.2
Trace metals							
Aluminium (Al)	mg/L	<0.001	1.416	0.082	0.044	1	5
Cadmium (Cd)	mg/L	<0.001	0.36	0.301	0.23	0.01	0.05
Total chromium (Cr)	mg/L	<0.001	<0.001	0.63	0.29	0.1	1

Parameter	Unit	Analysis results				Bahrain's standards	
		CGP- Pit-I	CGP-Pit-II	CGP- Pit-I	CGP-Pit-II		
		December 2014	December 2014	October 2020	October 2020	Average monthly	Maximum
Copper (Cu)	mg/L	<0.001	<0.001	0.32	0.07	0.2	0.5
Iron (Fe)	mg/L	0.085	0.132	0.9	0.5	1	2
Lead (Pb)	mg/L	<0.001	<0.001	0.144	0.118	0.1	0.5
Mercury (Hg)	mg/L	<0.001	<0.001	<0.002	<0.002	0.001	0.001
Nickle (Ni)	mg/L	0.195	2.622	0.124	0.004	0.1	0.5
Zinc (Zn)	mg/L	0.4	0.876	0.8	0.05	0.5	1
Arsenic (As)	mg/L	<0.001	<0.001	<0.01	<0.01	0.05	0.1
Other parameters							
Total coliforms	CFU 100 ml And MPN	70 CFU/ 100 ml	Nil	81 MPN	72 MPN	1000	2500

Based on the above analysis result for both weathering pits in 2014 and 2020, most of the parameters were found to exceed the maximum limit set by Bahrain's regulation. The pH, TSS, ammoniacal nitrogen as N, nitrate as $\text{NO}_3 - \text{N}$, sulfide as H_2S , chlorine residual (in 2014 only), total phosphate, BOD, COD, total Kjeldhal nitrogen, TOC, Cd (except CGP-I weathering pit in December 2014) and Ni (only for CGP-II weathering pit in October 2020), were the parameters that exceeded the threshold limits. See table (14) and appendix A3-1.

H_2S concentration in the wastewater varies in both pits from 2014 and 2020. It increased by 12.5% in the first pit and reduced by 39.7% in the second weathering pit. The average concentrations were 5.95mg/L and 5.45mg/L for weathering pit I and weathering pit II respectively. The difference from the maximum set value and the measured values was 460% and 530% for weathering pit I in December 2014 and October 2020, respectively & 580% and 310% for weathering pit II in December 2014 and October 2020, respectively.

The only explanation for the parameter's massive variation in 2014 and 2020 and also the difference between the pits is the frequent company attempt to balance the wastewater levels in both weathering pits. These attempts were to avoid wastewater overflow issues. They used to transfer the wastewater from one pit to the other or even by utilizing the other weathering pits located in the compressor stations. From the above outcomes, the analysis proved the need of finding suitable treatment options for the wastewater since conventional disposal in water media/ landfill sites is impossible with these parameter values.

2. AHP Questionnaire

Of 13 target participants, nine only responded to the questionnaire, representing a 69.23% response rate. Out of the nine responses, three responses were valid, i.e. results were found consistent as per the Saaty consistency test. Therefore, there were 33.3% and 66.7%, respectively, valid and invalid response rates. Out of the six invalid responses, 2 participants only fully completed the questionnaire (33.3%), and the remaining 4 participants (66.7%) regret completing the questionnaire as they found the subject beyond their field expertise. Table (15) summarizes the response numbers and rates.

Table (15): Questionnaire response details

Total expected respondents	13
Replied responses number	9
No responses number	4
Response rate	69.2%
No response rate	30.8%
Valid responses	3
Valid responses rate	33.3%
Invalid responses	6
Invalid responses rate	66.7%
Invalid responses due to CR>0.1	2
Invalid responses due to other reasons	4
Invalid responses rate due to CR>0.1	33.3%
Invalid responses rate due to other reason	66.7%

AHP method is a quality-based method that did not specify a minimum number of responses or response rate due to the requirement of having experts in the subject field. Therefore, the received response rate was found acceptable.

Table (16) shows the local weights, global weights and rankings for each criterion and alternative. AHP model criteria are in the first column while its weights and ranking are in the second and third columns respectively. Alternatives with their local weights, local weights ranking and global weights are in the fourth, fifth, sixth and seventh columns respectively. Fig.7 present the alternatives local weights with respect to the criteria. The global weights results are the aggregated results for all valid responses. Detailed participants' answers and the calculation results are illustrated in appendix A2-3 & A2-4.

Table (16): Summary of criteria and alternatives weights and ranking of AHP method

Criteria	Criteria Local weights	Ranking	Alternatives	Alternatives Local weights	Local weights Ranking	Alternatives Global weights
Initial investment cost	0.292	1	WAO	0.170	3	0.049
			CWAO	0.105	5	0.031
			AOP	0.111	4	0.033
			Biological treatment	0.329	1	0.096
			MFC	0.231	2	0.067
			Pre-treatment technology	0.053	6	0.015
Operational cost	0.273	2	WAO	0.207	2	0.057
			CWAO	0.116	4	0.031
			AOP	0.100	6	0.027
			Biological treatment	0.284	1	0.077
			MFC	0.189	3	0.052
			Pre-treatment technology	0.105	5	0.029
Environmental impact and safety concerns	0.176	3	WAO	0.136	4	0.024
			CWAO	0.094	6	0.017
			AOP	0.183	3	0.032
			Biological treatment	0.258	1	0.046
			MFC	0.207	2	0.037

Criteria	Criteria Local weights	Ranking	Alternatives	Alternatives Local weights	Local weights Ranking	Alternatives Global weights
			Pre-treatment technology	0.122	5	0.022
Materials availability	0.137	4	WAO	0.248	1	0.034
			CWAO	0.105	5	0.014
			AOP	0.101	6	0.014
			Biological treatment	0.223	2	0.031
			MFC	0.213	3	0.029
			Pre-treatment technology	0.109	4	0.015
Treatment benefit	0.122	5	WAO	0.107	5	0.013
			CWAO	0.111	4	0.014
			AOP	0.107	6	0.013
			Biological treatment	0.128	3	0.016
			MFC	0.276	1	0.034
			Pre-treatment technology	0.272	2	0.033



Fig.7: Alternatives local weights with respect to the criteria

Figure 8 presents the criteria weights. The top two criteria were the initial investment and operational costs with only a 7% difference. The weight of the initial investment cost was 0.29 while the operational cost weight was 0.27. Following the cost factors, environmental impact and safety concerns showed up in third place (0.18), followed by the materials availability (0.14) and treatment benefit (0.12).

Costs are usually the main drivers in the prioritization list for any treatment method selection or investment. Our results were in agreement with Karimi et al.'s (2016) AHP results (rank wise), where the cost also dominant their list of criteria with 40.9 weight percent. Following the cost, environmental impact was in the second place with 27.9% weight and materials availability in the third place with 8% weight. This research subdivided the cost into initial investment and operational cost. The combined weight of both criteria was 56% which is a 27% difference from Karimi et al.'s results. The percentage of difference for the environmental impact and materials availability were 35.4% and 42.8%, respectively.

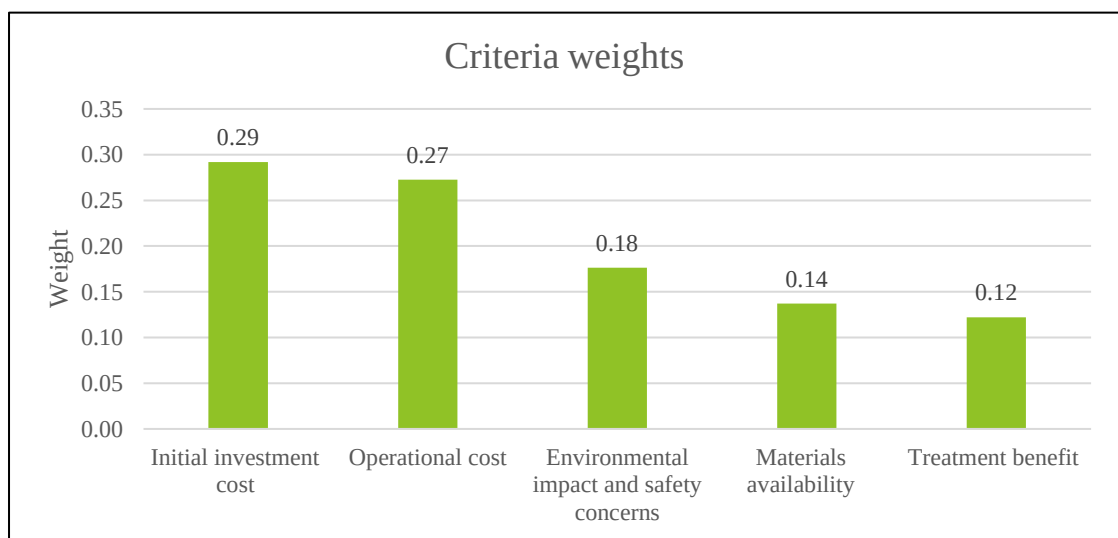


Fig.8:Overall criteria weights obtained by analysis of questionnaire

When comparing the alternatives with each other with respect to the criteria as mentioned earlier, results vary. Fig.9 shows the local weights of the six AHP model alternatives with respect to the initial investment cost. Biological treatment leads the list with 0.329 weight followed by MFC (0.231), WAO (0.170), AOP (0.111), CWAO (0.105) and lastly pre-treatment technology/ philosophy (0.053).

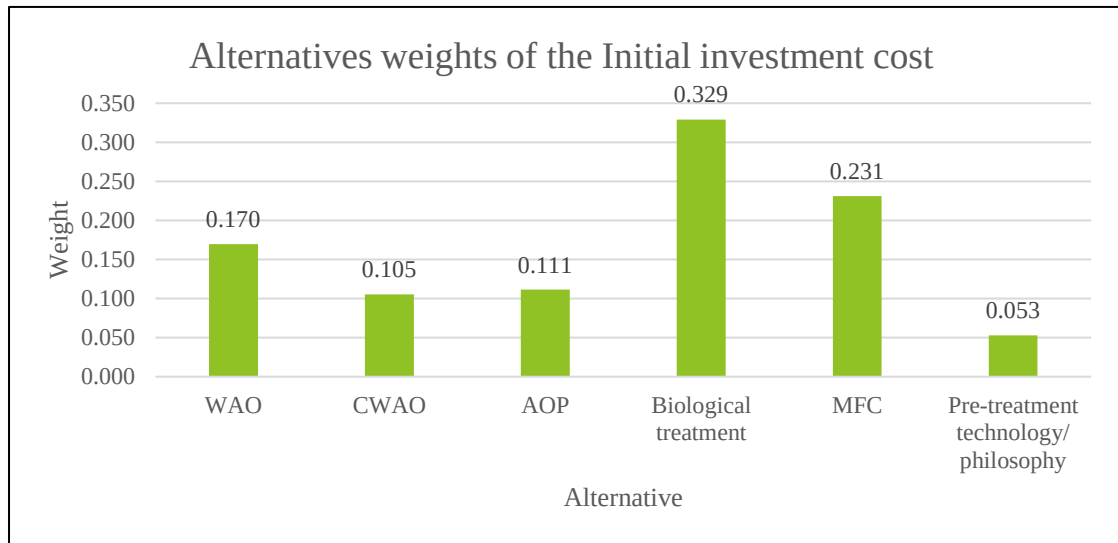


Fig.9: Alternatives weights of the Initial investment cost

Fig.10 demonstrates the alternative local weights with respect to the operational cost criteria. Again, biological treatment leads the list with 0.284 weight, followed by WAO (0.207), then MFC (0.189), CWAO (0.116), pre-treatment technology/ philosophy (0.105) and lastly AOP (0.1).

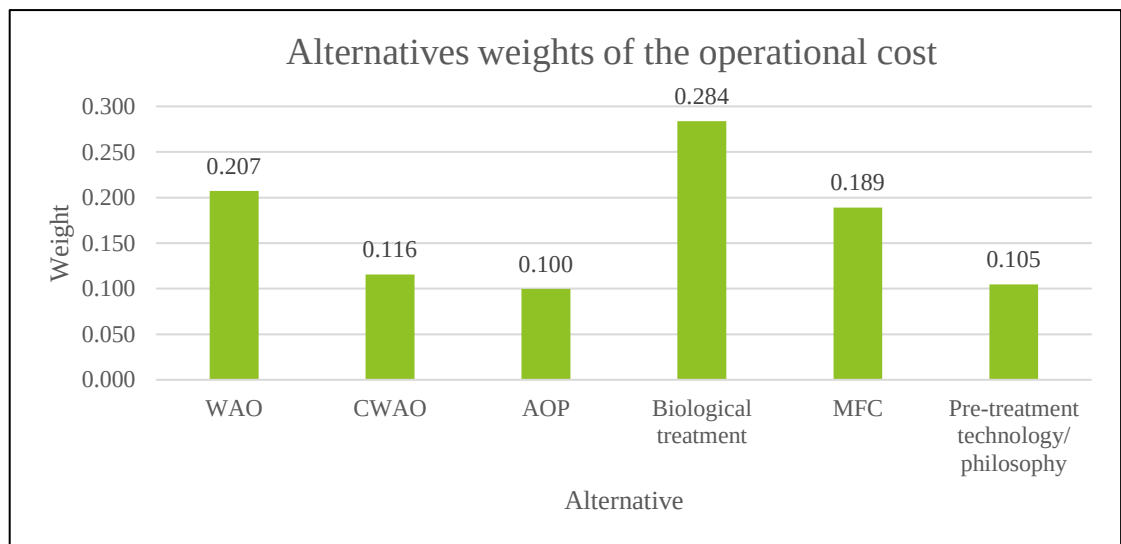


Fig.10: Alternatives weights of the operational cost

These results were unlike Karimi et al.'s results since biological treatment in their study was the least preferable method compared to WAO and CWAQ treatments. However, these results match the literature review findings concerning the cost of biological treatment. Biological treatment usually operates at ambient conditions with less expenditure, i.e. there is no cost associated with high pressure, high temperature and air/ oxygen provision. In contrast, other technologies require unique/ high resistant material of constructed equipment (e.g. WAO), additional chemicals/ catalyst (CWAQ/ AOP), electrochemical cells (MFC), or even process/ engineering modification (Pre-treatment technology).

Similarly, the biological treatment also leads the environmental impact and safety concerns criteria with 25.8 weight percent. MFC comes in the second place with 0.207 weight followed by AOP (0.183), WAO (0.136), Pre-treatment technology/ philosophy (0.122) and CWAQ (0.094) see Fig.11.

These results agree with the literature findings. Biological and MFC are economical, safe and environmentally friendly methods. These methods operate at ambient conditions with micro-organism only. Hence, there are no risks of explosions due to severe operating conditions or exothermic reactions, no risks associated with hazardous materials transporting and handling (e.g. hydrogen peroxide handling), and there are no wastes generated (e.g. toxic/hazardous emissions, effluent and/or spent catalyst).

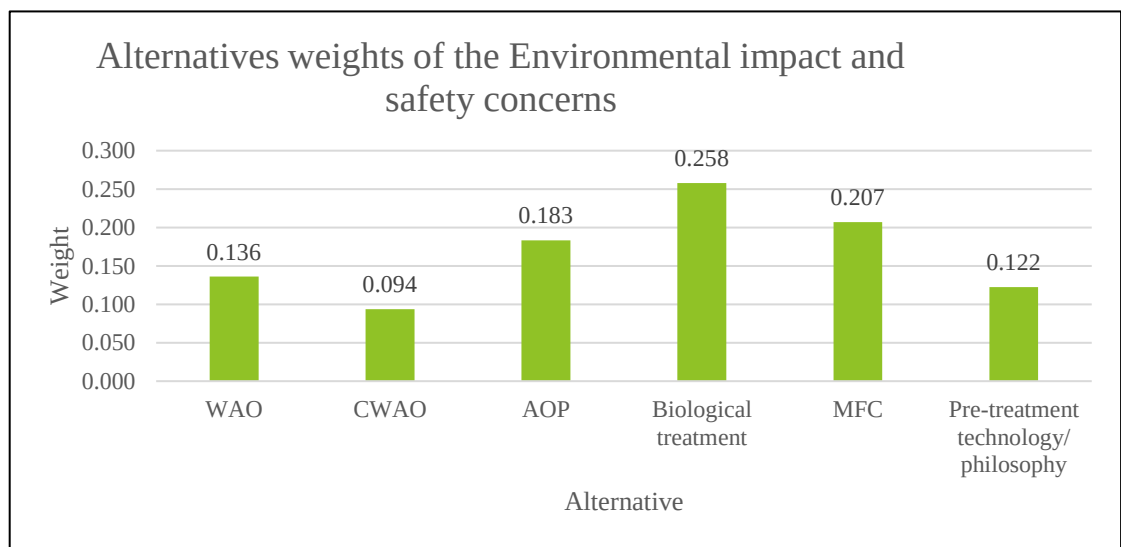


Fig.11: Alternatives weights of the Environmental impact and safety concerns

Unlike other pairwise comparisons, for the availability of the materials, weights of WAO, biological and MFC were close to each other with only 10% and 14% difference, respectively. The weight of WAO was 0.248, while the weights of biological and MFC were 0.223 and 0.213. The weight of the remaining methods was 0.11 each. Fig.12 shows the alternative local weights with respect to the materials availability criteria.

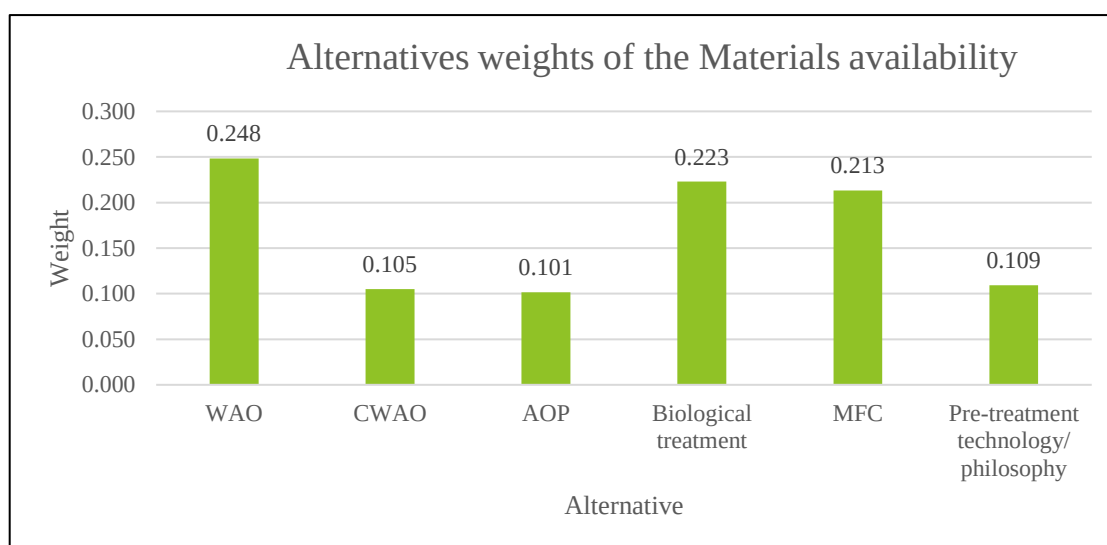


Fig.12: Alternatives weights of the Materials availability

Again, the results of the materials availability pairwise comparison were as expected. Temperature, pressure, air or oxygen are required for WAO operation, which is easy to obtain materials. Also, the required materials for operation are relatively obtainable for biological and MFC methods compared to the other methods (suitable micro-organisms at normal operating conditions). CWAQ, AOP and pre-treatment technology/ philosophy were weighted less due to their need for chemicals, catalysts and/or special conditions or arrangements.

The treatment benefits criterion was led by MFC (0.276) and Pre-treatment technology/ philosophy (0.272). Biological method weight 0.128, CWAQ weight 0.111, WAO weight 0.107 and AOP weight 0.107. Fig.13 illustrates the alternative local weights with respect to the treatment benefit criteria.

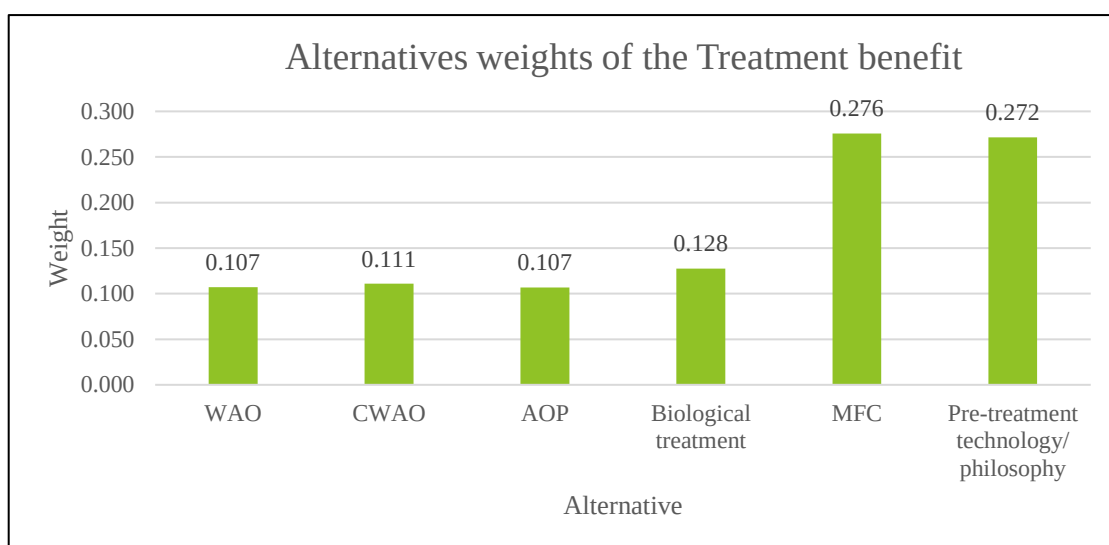


Fig.13: Alternatives weights of the Treatment benefit

MFC produces electricity from micro-organisms energy which is a great benefit in addition to the spent caustic treatment. That is why MFC dominates the list among other methods which mainly treat the waste. Changing the total philosophy and pre-treat the stream prior to processing once it is feasible can add significant value in terms of avoiding the generation of the spent caustic effluent and/ or producing new contaminate products.

All in all, the dominant criteria for prioritizing is the cost (initial investment and operational cost) followed by the environmental impact and safety concerns. The leading ten alternatives based on the global weights in descending order is as follows: initial investment cost for biological treatment, the operational cost for biological treatment, initial investment cost for MFC, the operational cost for WAO, the operational cost for MFC, initial investment cost for WAO, environmental impact and safety concerns for biological treatment, environmental impact and safety concerns for MFC, materials availability for WAO and treatment benefit for MFC.

3.GRAL software air dispersion

General model results

- Windrose

Fig.14 shows the data windrose, the dominant windrose was in the north west direction (17%), at 6 m/s speed or more.

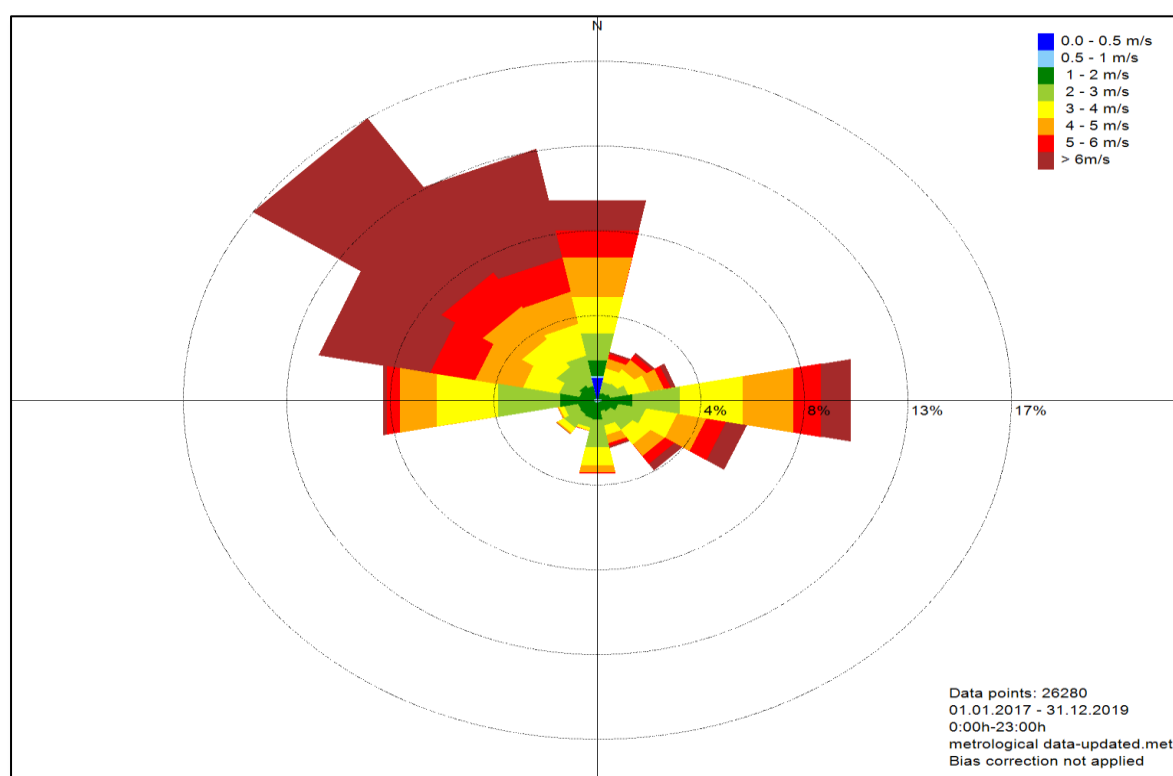


Fig.14: Windrose result

- Frequency distribution wind class

Fig.15 presents the frequency distribution of the wind class; the dominant class was those of 6 m/s speed and above.

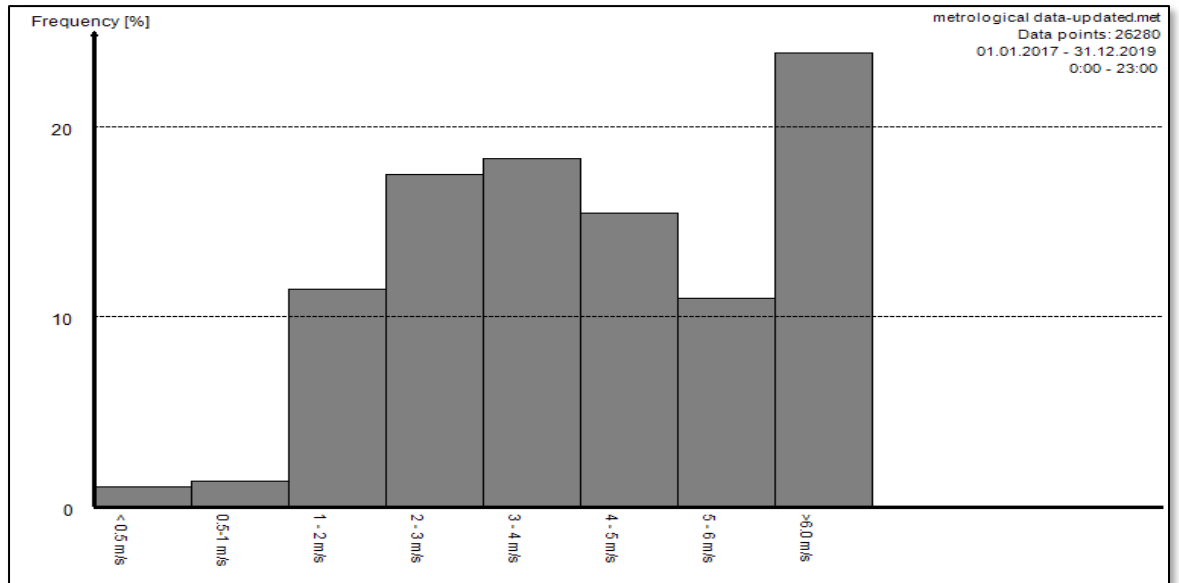


Fig.15: Frequency distribution wind class result

- Stability class

Fig.16 shows the model stability class; the dominant stability class of the used date was neutral (40%).

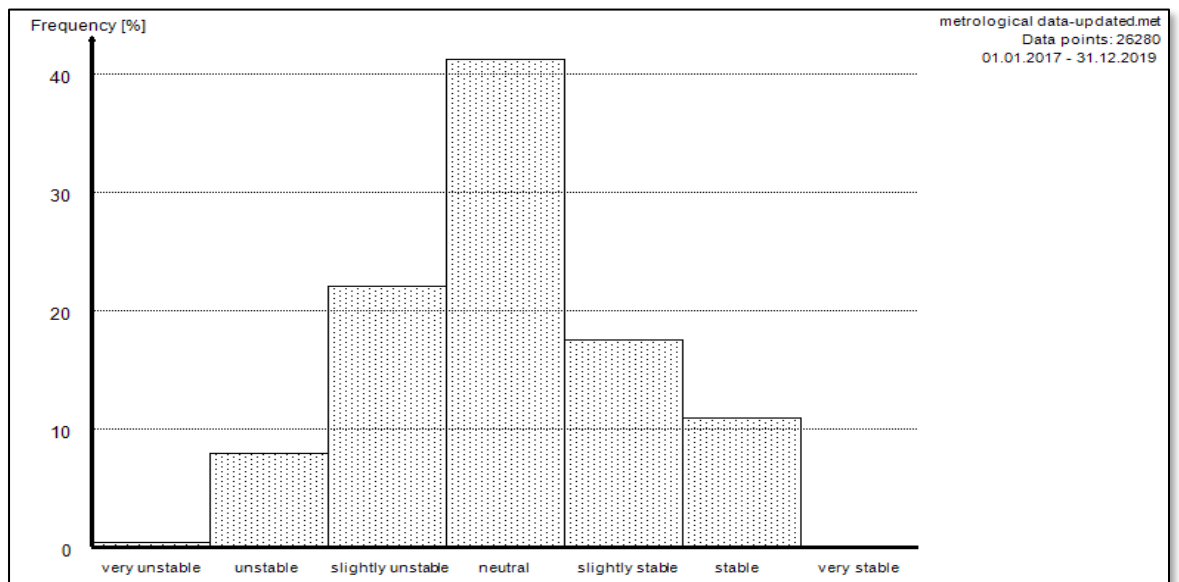


Fig.16: Stability class result

Generally, the dominant windrose of the used metrological date from 01/01/2017 to 31/12/2019 was in the northwest direction (17%) at a 6 m/s or more speed.

The modelling classes were calculated using the Pasquill equation based on time, wind speed, cloud cover, and solar radiation. It was 42% of the period neutral, 29% stable to slightly stable and 29% unstable to slightly unstable.

Weathering pits air dispersion

Fig.17 to Fig.25 show H_2S mean concentrations ($\mu g/m^3$), daily maximum and maximum contours at 1.8m, 3m and 6m heights above the ground for the weathering pits emissions. Contours are shown on the geographical map. Table (17) summarizes the obtained results.

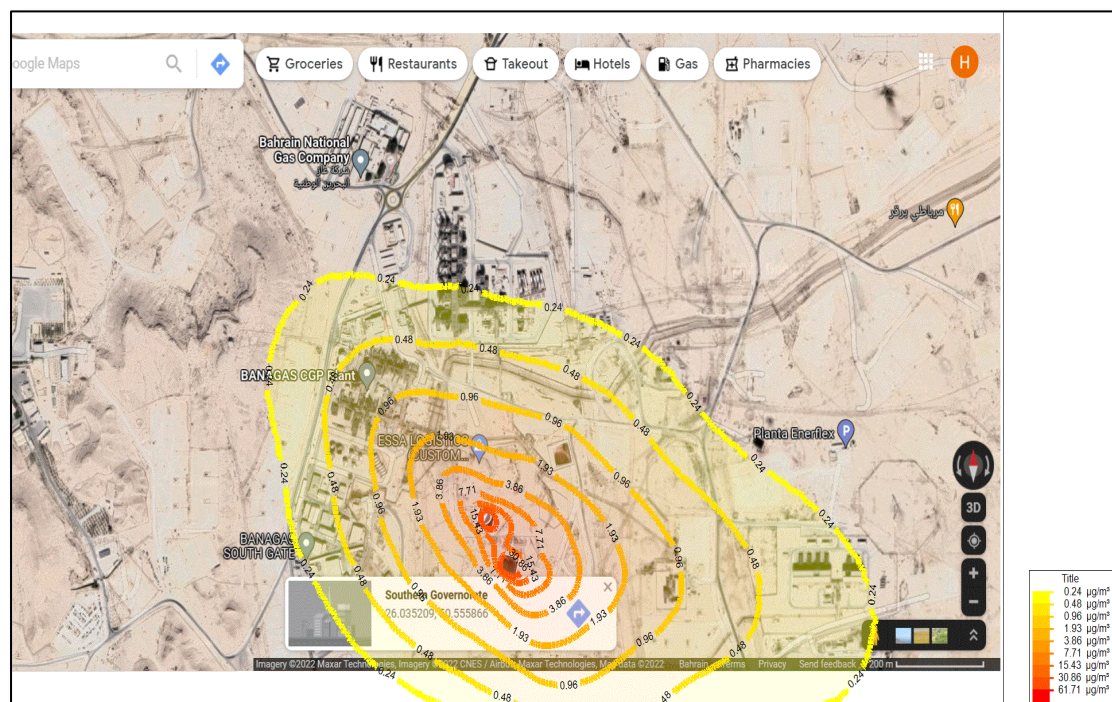


Fig.17: Contours of H_2S mean concentrations ($\mu g/m^3$) at 1.8 meters height above the ground-weathering pit

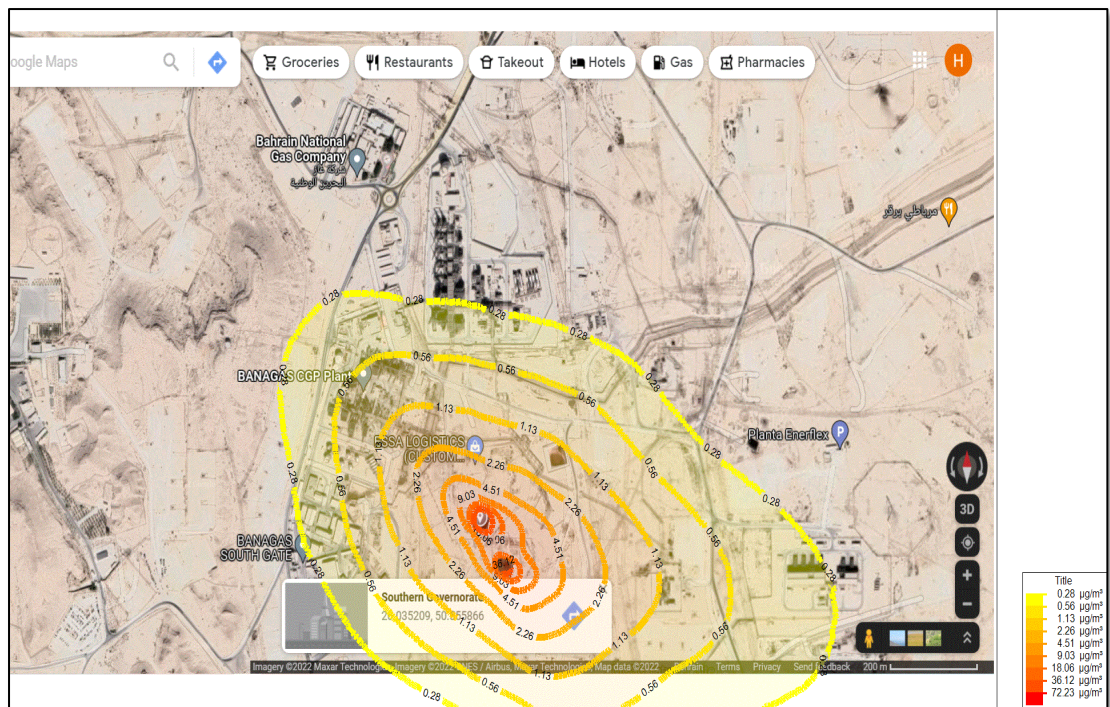


Fig.18: Contours of H₂S mean concentrations ($\mu\text{g}/\text{m}^3$) at 3 meters height above the ground-weathering pits

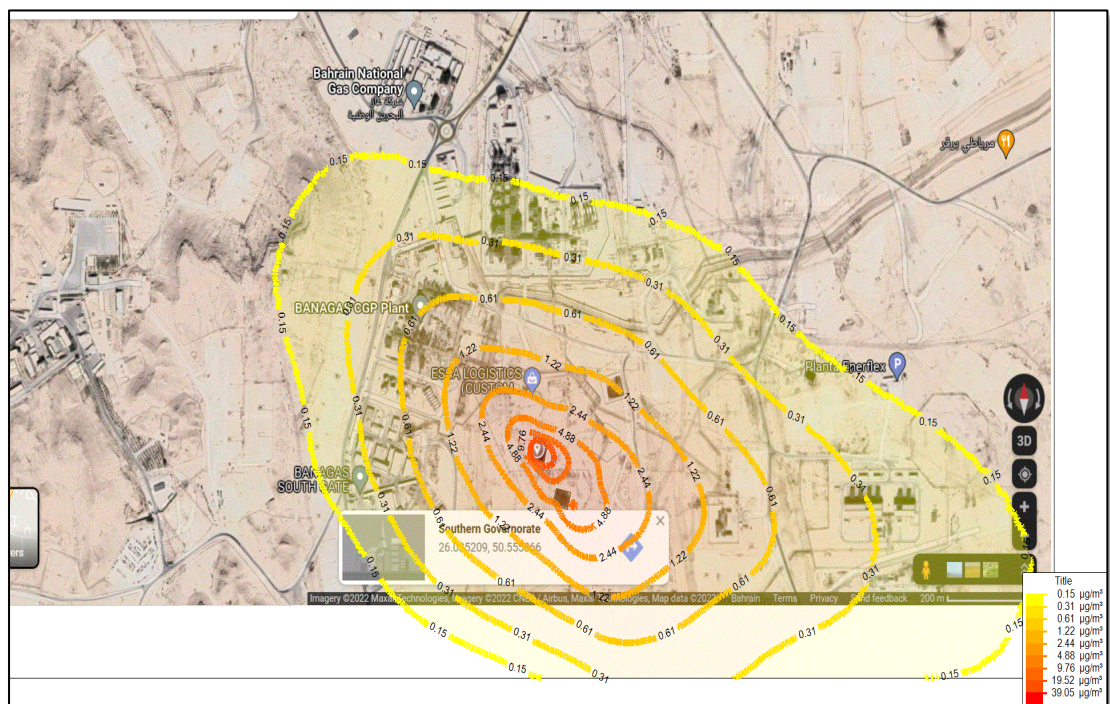


Fig.19: Contours of H₂S mean concentrations ($\mu\text{g}/\text{m}^3$) at 6 meters height above the ground-weathering pits

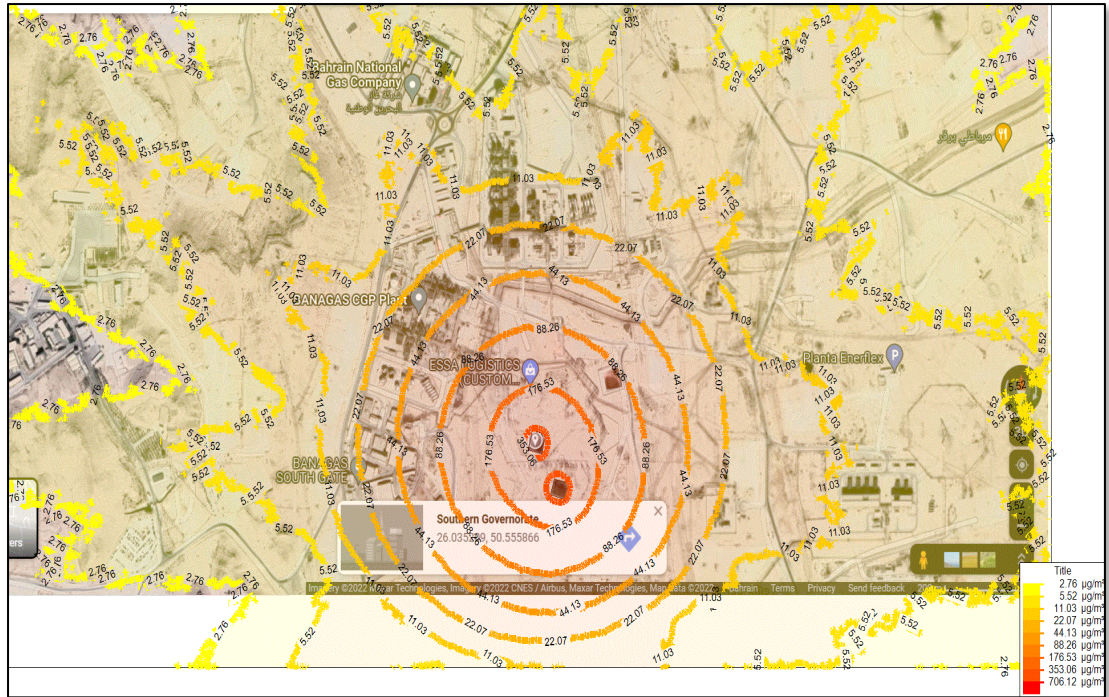


Fig.20: Contours of H₂S maximum concentrations (µg/m³) at 1.8 meters height above the ground-weathering pits

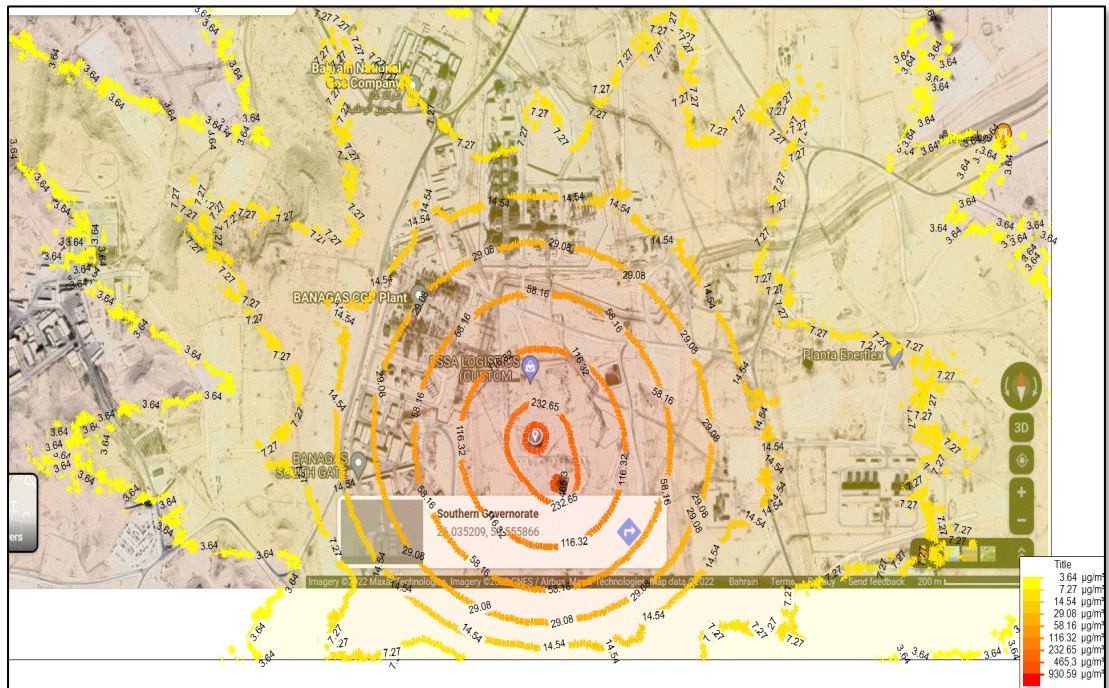


Fig.21: Contours of H₂S maximum concentrations (µg/m³) at 3 meters height above the ground-weathering pits

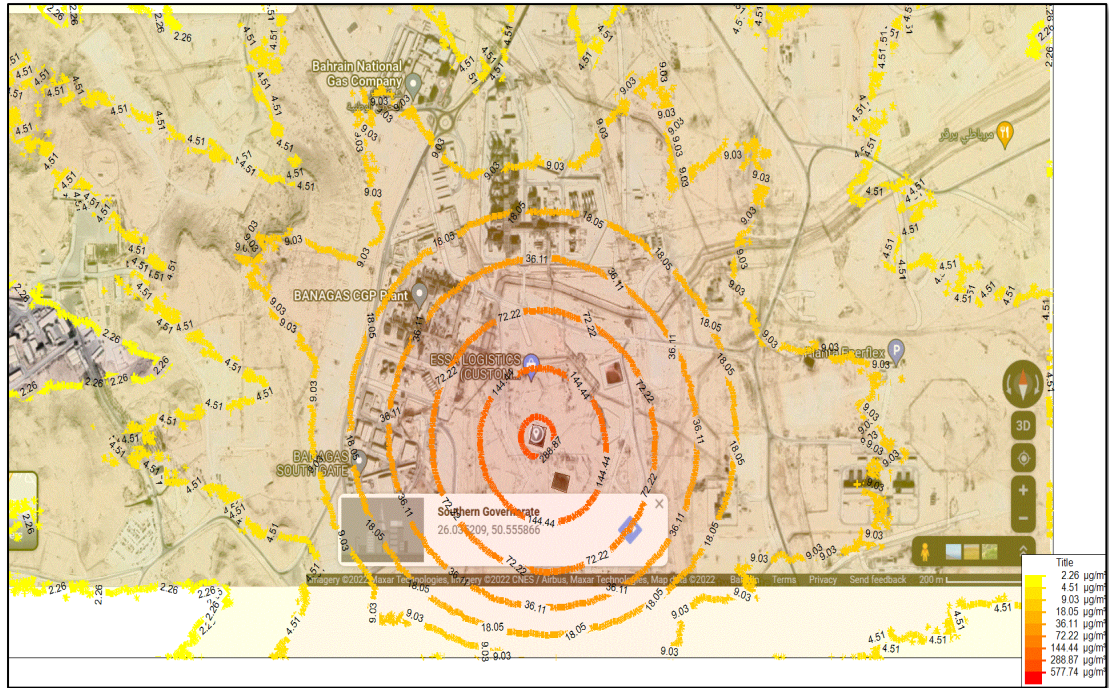


Fig.22: Contours of H₂S maximum concentrations (µg/m³) at 6 meters height above the ground-weathering pits

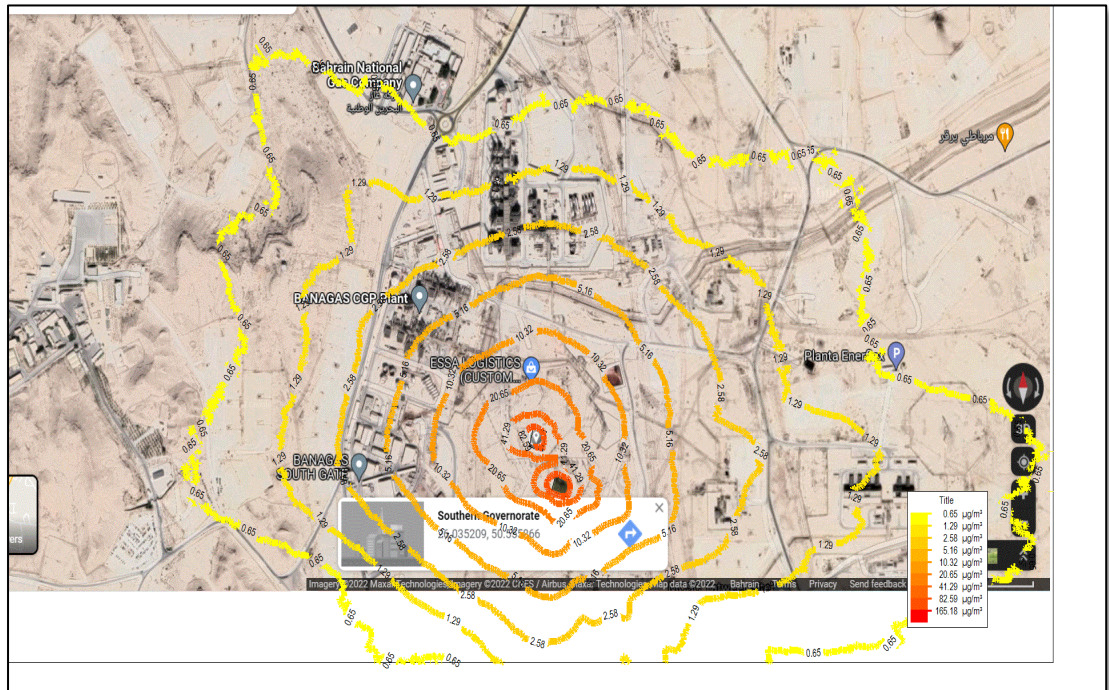


Fig.23: Contours of H₂S daily maximum concentrations (µg/m³) at 1.8 meters height above the ground-weathering pits

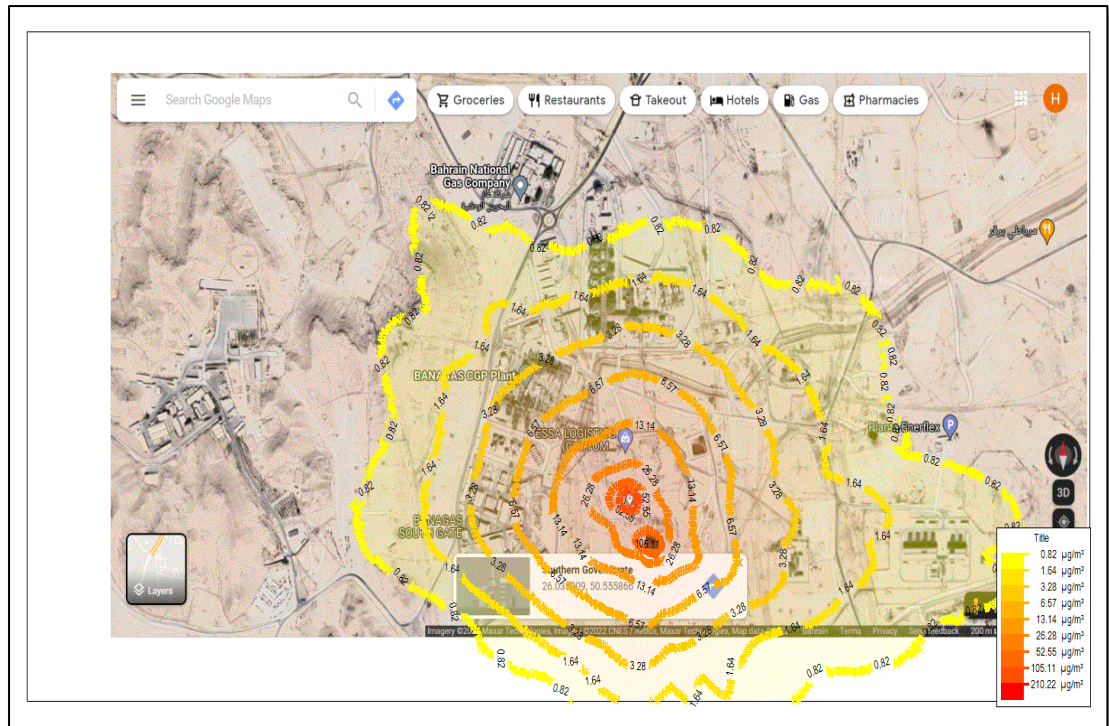


Fig.24: Contours of H₂S daily maximum concentrations ($\mu\text{g}/\text{m}^3$) at 3 meters height above the ground-weathering pits

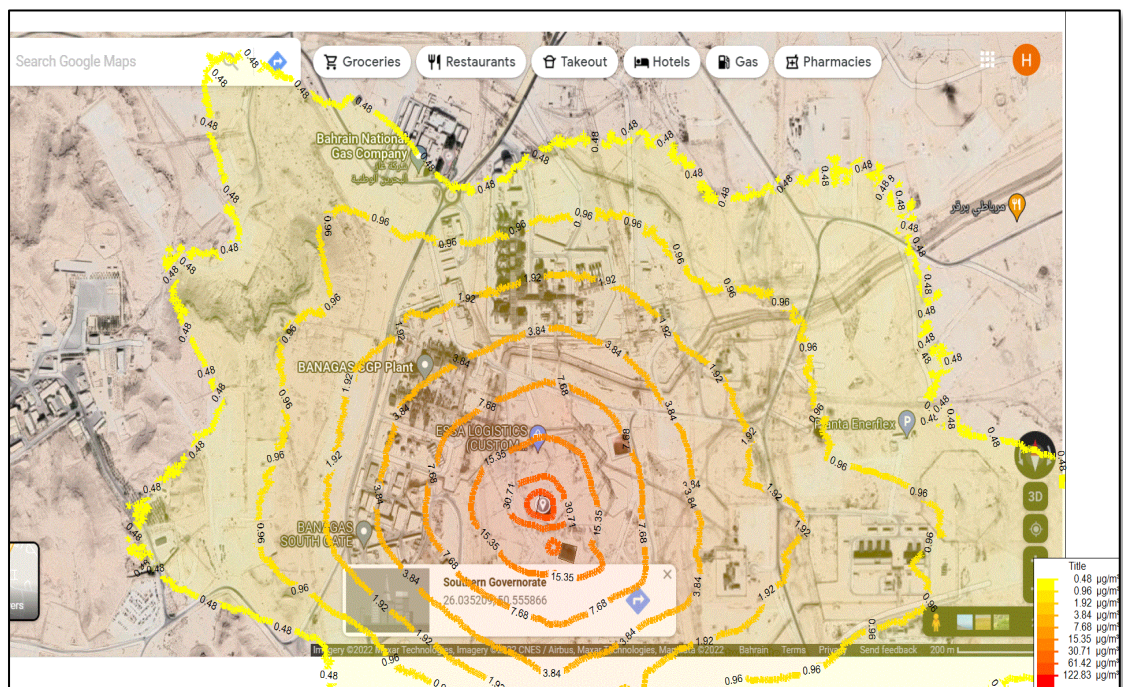


Fig.25: Contours of H₂S daily maximum concentrations ($\mu\text{g}/\text{m}^3$) at 6 meters height above the ground-weathering pits

Table (17): Summary of computation results of H₂S concentrations at different heights above the ground for weathering pit I and II

		Weathering pit I	Weathering pit II
Mean values	Height above the ground (m)	Highest concentration value	
	1.8 m	30.86 μg/m ³	30.86 μg/m ³
	3 m	18.06 μg/m ³	36.12 μg/m ³
	6 m	19.51 μg/m ³	9.76 μg/m ³
		Distance between the source in meters and respective zone	
	1.8 m	21 m	27 m
		Zone:15.43 μg/m ³	Zone:15.43 μg/m ³
	3 m	20.2 m	14.8 m
		Zone:9.03 μg/m ³	Zone:9.03 μg/m ³
	6 m	19.9 m	11.3 m
		Zone:9.76 μg/m ³	Zone:4.88 μg/m ³
		Weathering pit I	Weathering pit II
Daily maximum values	Height above the ground (m)	Highest concentration value	
	1.8 m	82.59 μg/m ³	82.59 μg/m ³
	3 m	105.11 μg/m ³	105.11 μg/m ³
	6 m	61.42 μg/m ³	30.71 μg/m ³
		Distance between the source in meters and respective zone	

	1.8 m	64.3 m	34.4 m
		Zone:41.29 µg/m³	Zone:41.29 µg/m³
	3 m	42 m	16 m
		Zone:52.55 µg/m³	Zone:52.55 µg/m³
	6 m	35 m	48 m
		Zone:30.71µg/m³	Zone:15.35 µg/m³
		Weathering pit I	Weathering pit II
Maximum values	Height above the ground (m)	Highest concentration value	
	1.8 m	353.06 µg/m³	353.06 µg/m³
	3 m	465.3 µg/m³	465.3 µg/m³
	6 m	288.8 µg/m³	144.4 µg/m³
		Distance between the source in meters and respective zone	
	1.8 m	17.6 m	65.7 m
		Zone:176.53 µg/m³	Zone:176.53 µg/m³
	3 m	62 m	31.6 m
		Zone:232.65 µg/m³	Zone:232.65 µg/m³
	6 m	130 m	65.5 m
		Zone:144.4 µg/m³	Zone:144.4 µg/m³

- Bahrain's legal mean concentration for H₂S is 15 µg/m³.

Based on the computed concentrations for weathering pits I and II, the legal mean value was over the limit in all cases except for the mean concentration around weathering pit II at 6m height above the ground case.

The mean computed concentrations were between 9.76 µg/m³ to 30.86µg/m³ covering zones from 11.3m to 27m from the source. The percentage of the difference between each computed mean concentration value with respect to the legal 24-hour mean value is presented in table (18) below.

Table (18): Percentage of mean concentration values difference-weathering pits

	Height above the ground	Weathering pit I percentage	Weathering pit II percentage
Percentage of mean value difference	1.8 m	105.7%	105.7%
	3 m	20.4%	140.8%
	6 m	30.1%	-34.9%

The highest daily maximum and maximum contoured concentration values were 105.11µg/m³ and 465.3 µg/m³ respectively around weathering pit I and II at 3 meters height above the ground. The zones of the highest daily maximum concentrations were from 16 to 42 meters distance, while the zones of the highest maximum computed concentrations were from 31.6 to 62 meters.

Comparing the concentrations as mentioned earlier with the occupational safety and health administration limits, values were below the harmful exposure levels and the impact is limited to the

smell impact. i.e. the area will smell rotten eggs only with no occupational health impact.

Drain pots air dispersion

Figures 26-34 show H₂S mean, daily maximum and maximum concentration ($\mu\text{g}/\text{m}^3$) contours at 1.8m, 3m and 6m heights above the ground for the drain pots emissions. Contours are shown on the geographical maps. Also, table (19) summarizes the obtained results.



Fig.26: Contours of H₂S mean concentrations ($\mu\text{g}/\text{m}^3$) at 1.8 meters height above the ground- drain pots



Fig.27: Contours of H₂S mean concentrations ($\mu\text{g}/\text{m}^3$) at 3 meters height above the ground- drain pots

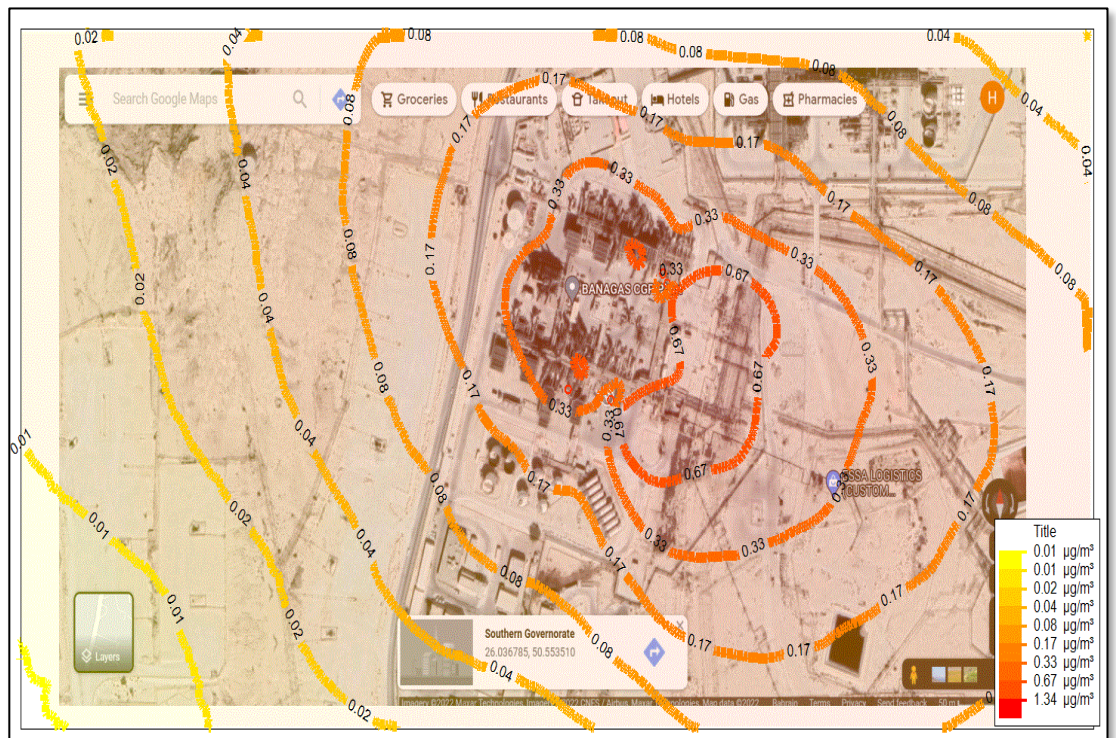


Fig.28: Contours of H₂S mean concentrations ($\mu\text{g}/\text{m}^3$) at 6 meters height above the ground- drain pots



Fig.29: Contours of H₂S daily maximum concentrations (µg/m³) at 1.8 meters height above the ground- drain pots

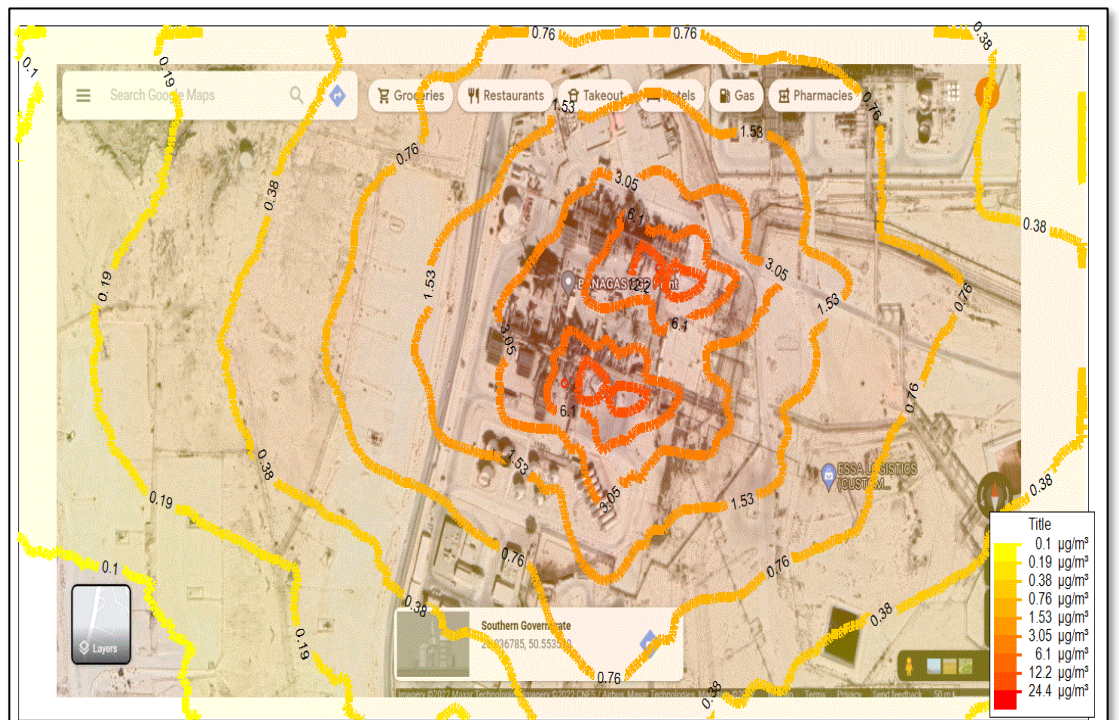


Fig.30: Contours of H₂S daily maximum concentrations (µg/m³) at 3 meters height above the ground- drain pots



Fig.31: Contours of H₂S daily maximum concentrations ($\mu\text{g}/\text{m}^3$) at 6 meters height above the ground- drain pots

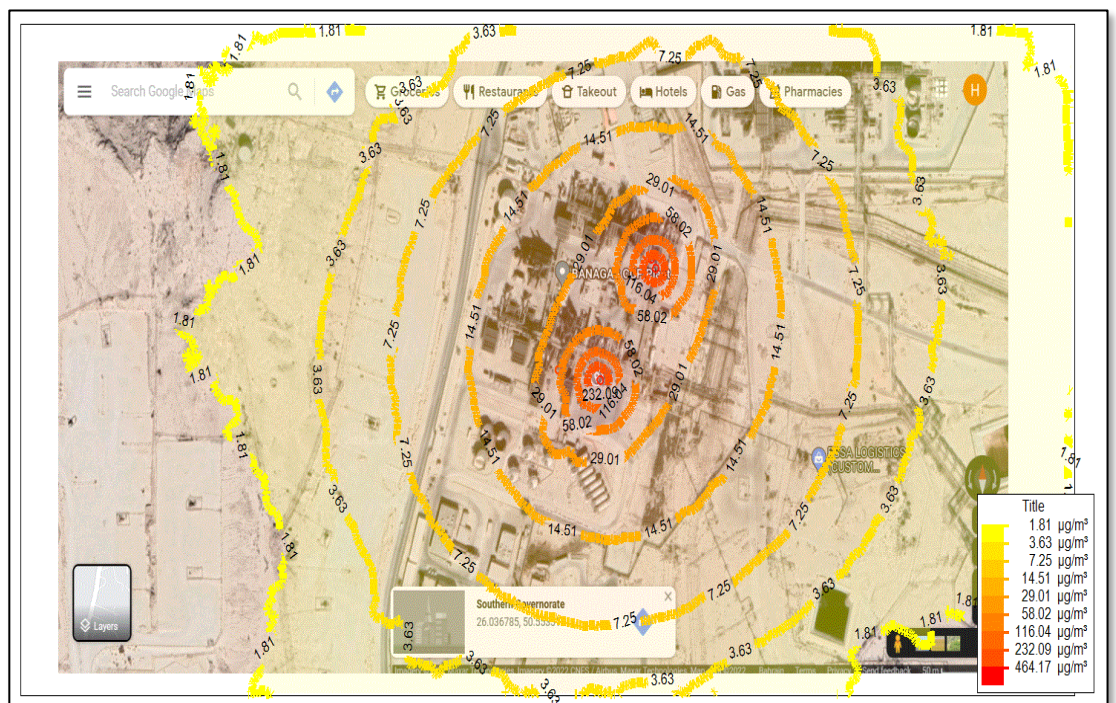


Fig.32: Contours of H₂S maximum concentrations ($\mu\text{g}/\text{m}^3$) at 1.8 meters height above the ground- drain pots

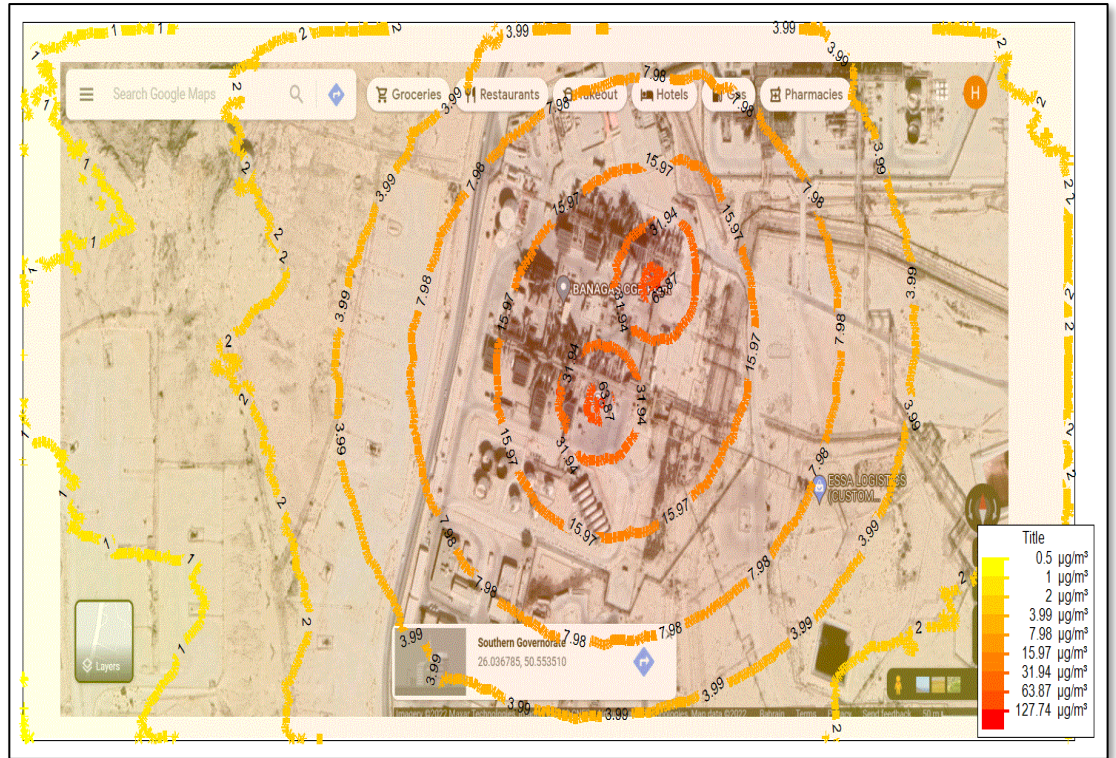


Fig.33: Contours of H_2S maximum concentrations ($\mu g/m^3$) at 3 meters height above the ground- drain pots

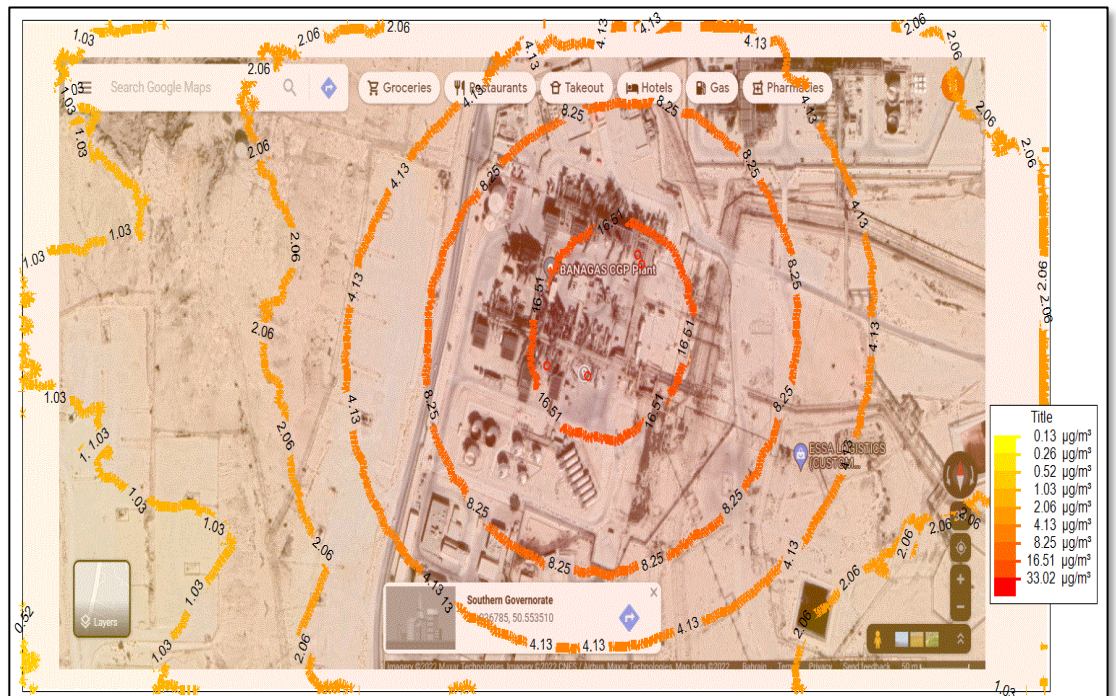


Fig.34: Contours of H_2S maximum concentrations ($\mu g/m^3$) at 6 meters height above the ground-drain pots

Table (19): Summary of computation results of H₂S concentrations at different heights above the ground for the drain pots

Mean	Height above the ground (m)	Highest detected concentration value	
	1.8 m	16.09 µg/m ³	
	3 m	3.69 µg/m ³	
	6 m	0.67 µg/m ³	
		Distance between the source in meters and respective zone	
		CGP-II C3	CGP-I C3
	1.8 m	7 m	6.4 m
		Zone:4.02 µg/m ³	Zone:8.05 µg/m ³
	3 m	9 m	12.2 m
		Zone:1.85 µg/m ³	Zone:0.92 µg/m ³
Daily maximum	6 m	11.4 m	8.7 m
		Zone:0.67 µg/m ³	Zone:12.7 µg/m ³
	Height above the ground (m)	Highest detected concentration value	
	1.8 m	42.96 µg/m ³	
	3 m	12.2 µg/m ³	
	6 m	2.48 µg/m ³	
		Distance between the source in meters and respective zone	
		CGP-II C3	CGP-I C3
	1.8 m	4.6 m	7 m
		Zone:21.48 µg/m ³	Zone:21.48 µg/m ³

	3 m	20.4 m	17.8 m
		Zone:6.1 µg/m ³	Zone:6.1 µg/m ³
	6 m	105.5 m	63.8 m
		Zone: 1.24 µg/m ³	Zone: 1.24 µg/m ³
Maximum	Height above the ground (m)	Highest detected concentration value	
	1.8 m	232 µg/m ³	
	3 m	63.87 µg/m ³	
	6 m	16.51 µg/m ³	
		Distance between the source in meters and respective zone	
		CGP-II C3	CGP-I C3
	1.8 m	7.9 m	15.3 m
		Zone:116 µg/m ³	Zone:116 µg/m ³
	3 m	33.6 m	32.2 m
		Zone:31.94 µg/m ³	Zone:31.94 µg/m ³
	6 m	149.6 m	126.2 m
		Zone:8.25 µg/m ³	Zone:8.25 µg/m ³

Unlike the weathering pits case, the computed mean concentrations for the drain pots at 3 meters and 6-meters heights above the ground were well below the regulated value. However, at 1.8 meters above the ground and around both propane drains pots, the concentration was $16.09 \mu\text{g}/\text{m}^3$, which is slightly higher than Bahrain's obligated values ($15 \mu\text{g}/\text{m}^3$). The percentage of the difference between each computed mean concentration value with respect to the obligated 24-hour mean value is presented in table (20) below.

Table (20): Percentage of mean concentration values difference-weathering pits

	Height above the ground	Percentage
Percentage of mean value difference	1.8m	7.3%
	3m	-75.4%
	6m	-95.5%

The highest contoured value for the maximum daily concentrations at 3m and 6m heights above the ground were below the mean obligated value. However, at 1.8m height above the ground, the highest computed value was 186.4% higher than the obligated value. The zone of the breached limit from the sources extends from 4.6 to 7 meters.

The highest maximum contoured concentrations were all above the regulated value. Values were between $16.51 \mu\text{g}/\text{m}^3$ to $232 \mu\text{g}/\text{m}^3$. The zones of breached limits extend from 7.9m to 149.6m from the source.

Again, at those concentrations and as per the occupational safety and health administration limits, there will be no health impact on personnel except the odor effect.

The above results were as expected as the concentrations were generally reducing as the height above the ground increased. This is due to hydrogen sulfide's high density, which makes it accumulate near the ground level (H_2S gas density = 1.426 kg/m^3 and air density = 1.225 kg/m^3) (Airgas, 2017).

Since the results show very low concentration values, especially around drain pots (below odor threshold value $1.95 \times 10^6 \mu\text{g/m}^3$), the only explanation for the strong odor around the desulfurization unit is routed to the organic sulfur compounds, which have similar characteristics to hydrogen sulfide. Organic sulfur compounds are heavier than air, colorless, explosive, toxic to human health if inhaled and smell like a rotten egg (Airgas, 2017; National library of medicine, 2021d, 2021e).

4.2 Conclusion, Recommendations and Future work

1. Conclusion

The intended research outcomes were achieved. Biological treatment is the best option for Bahrain's old gas treatment plant spent caustic. That is due to its low initial investment cost, low operational cost, low environmental impact and fewer safety-related concerns and requirements.

The air dispersion for the weathering pits emissions contained override hydrogen sulfide concentrations in all cases except around weathering pit II at 6 meters height above the ground. At the same

time, the air dispersion of the desulfurization unit showed slight override only at 1.8 meters above the ground case. The health impact of all emission dispersion cases was limited to the unpleasant odor at the site and neighboring places.

2.Recommendations

Below is a list of recommendations to consider about the subject:

- Concentrate on organic sulfur compounds for the odor root investigation and assessment.
- Carry-out pilot plant study for biological treatment and apply it as it is the preferred treatment method.

3.Future work

For future works, suggestions are as follow:

- Use multiple dispersion software and compare the results of each.
- Include the complex terrain effect.
- Use advance emission dispersion software that can account for chemical reactions.
- Verify the obtained results from modelling using real-time measurements.
- Target more international experts in the wastewater treatment and environmental fields for the best treatment method selection.

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Appendices

Appendix 1:

A1-1 Material balance calculation around KOH treaters (desulfurization unit)

The following mass balance was obtained based on the data from the case study company. Reference PFDs and P&IDs were D-40-1220-105, D-40-1220-106, D-50-1220-105, D-50-1220-106, (19)-BNA-A-7064-(Rev.8)-Model, (22)-BNA-A-7067 (Rev.9)-Model, (51)-D-50-1220-213(Rev.10)-Model, (52)-D-50-1220-214(Rev.10)-Model (JGC CORPORATIONS, 1978a, 1978b, 1988a, 1988b; JGC gulf international Go. Ltd., 2012, 2014b, 2014a, 2014c).

The following figure represent summary of the streams around the KOH treater:

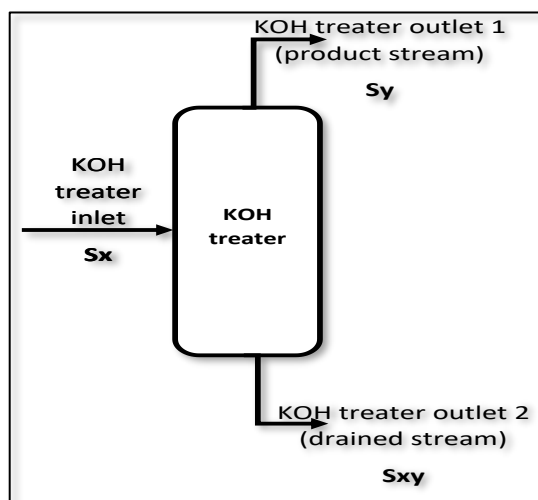
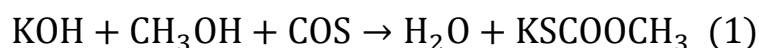


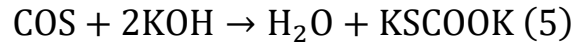
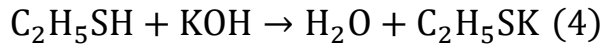
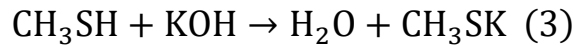
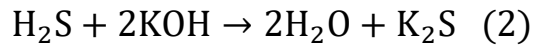
Fig.35: Stream summary around KOH treater

1- CGP-I – propane KOH treater material balance

To obtain the amount of hydrogen sulfide drained, total material balance was carried around the KOH treater.

As aforementioned, the reactions which takes place in the treater and resulted the spent caustic generation are the following:





The total material balance equation is equal:

$$\text{Accumulation}_i = \text{in}_i - \text{out}_i \pm \sum v_i f_i$$

By assuming steady state condition, accumulation will be zero.

Therefore, the equation will equal to:

$$\text{out}_i = \text{in}_i \pm \sum v_i f_i$$

➤ H_2S balance:

$$n_{\text{H}_2\text{S out}} = n_{\text{H}_2\text{S in}} - \int_2$$

From the given data,

$$n_{\text{H}_2\text{S in}} = 0.97 \text{ lbmol/h}$$

So

$$n_{\text{H}_2\text{S out}} = 0.97 - \int_2$$

Also given that in the outlet product stream, the maximum allowed hydrogen sulfide concentration (as product specification) is 5ppm and the flow rate of the same stream is 3.3 MMSCFD.

By this, the flow rate of H_2S in the product can be calculated as follow:

$$\begin{aligned} & 3.3 \times 10^6 \frac{\text{ft}^3}{\text{day}} \times \frac{1 \text{ day}}{24 \text{ hour}} \times \frac{0.028 \text{ m}^3}{1 \text{ ft}^3} \times 5 \text{ ppm H}_2\text{S} \times \frac{1.5 \frac{\text{mg}}{\text{m}^3} \text{ H}_2\text{S}}{1 \text{ ppm H}_2\text{S}} \\ & \quad \times \frac{\text{gmol H}_2\text{S}}{34.1 \text{ g H}_2\text{S}} \times \frac{0.0022 \text{ lbmol}}{\text{gmol}} \\ & = 1.86 \times 10^{-3} \text{ lbmol/hour} \end{aligned}$$

$n_{\text{out,H}_2\text{S}}$ equal to the summation of the top and bottom values from the KOH treater, therefore: $n_{\text{out,H}_2\text{S}} = n_{\text{top,H}_2\text{S}} + n_{\text{bottom,H}_2\text{S}}$

$$n_{\text{out,H}_2\text{S}} = 1.86 \times 10^{-3} \text{ lbmol/hour} + n_{\text{bottom,H}_2\text{S}}$$

$$\int_2 = \frac{n_{\text{out,H}_2\text{S}}}{n_{\text{in,H}_2\text{S}}} = \frac{1.86 \times 10^{-3} \text{ lbmol/hour} + n_{\text{bottom,H}_2\text{S}}}{0.97}$$

Now substituting the last two equations in hydrogen sulfide balance equation and solving for n_{bottom} will give the drained amount of hydrogen sulfide.

$$n_{\text{H}_2\text{S out}} = 0.97 - \int_2$$

$$n_{\text{out,H}_2\text{S}} = 0.97 - \int_2 = 1.86 \times 10^{-3} + n_{\text{bottom,H}_2\text{S}}$$

$$= 0.97 - \frac{1.86 \times 10^{-3} + n_{\text{bottom,H}_2\text{S}}}{0.97}$$

$$1.86 \times 10^{-3} - 0.97 + \frac{1.86 \times 10^{-3}}{0.97}$$

$$= -n_{\text{bottom,H}_2\text{S}} + \frac{-n_{\text{bottom,H}_2\text{S}}}{0.97}$$

$$-0.966 = -2.03 \times n_{\text{bottom,H}_2\text{S}}$$

$$\therefore n_{\text{bottom,H}_2\text{S}} = 0.47 \text{ lbmol/h}$$

$$n_{\text{bottom,H}_2\text{S}} = 0.475 \frac{\text{lbmol}}{\text{h}} \times 34.1 \frac{\text{lbm}}{\text{lbmol}} \times \frac{1 \text{ kg}}{2.204 \text{ lbm}} = 7.349 \frac{\text{kg}}{\text{h}}$$

$$\therefore \int_2 = \frac{1.86 \times 10^{-3} + 0.47}{0.97} = 0.49$$

Since the water will be accumulated at the bottom and it is generated as a result of the reactions, we carry-out also water material balance

$$\text{out}_i = \text{in}_i \pm \sum v_i \int_i$$

$$n_{\text{H}_2\text{O,out}} = n_{\text{H}_2\text{O,in}} + \int_1 + 2\int_2 + \int_3 + \int_4 + \int_5$$

The extents of reactions are found by carrying out components balance.

➤ COS balance

$$\text{out}_{\text{COS}} = \text{in}_{\text{COS}} \pm \sum v_{\text{COS}} \int_{\text{COS}}$$

$$n_{\text{cos,out}} = n_{\text{cos,in}} - \int_1 - \int_5$$

$n_{\text{cos,in}} = 0$. This means that no reaction takes place.

$$\int_1 = 0$$

$$\int_5 = 0$$

➤ CH_3SH balance

$$\text{out}_{\text{CH}_3\text{SH}} = \text{in}_{\text{CH}_3\text{SH}} \pm \sum v_{\text{CH}_3\text{SH}} \int_{\text{CH}_3\text{SH}}$$

$$n_{\text{CH}_3\text{SH},\text{out}} = n_{\text{CH}_3\text{SH},\text{in}} - \int_3$$

$$n_{\text{CH}_3\text{SH},\text{out}} = 0.11 - \int_3$$

Assuming all CH_3SH is adsorbed, i.e. no CH_3SH at the top stream of the KOH treater

$$n_{\text{CH}_3\text{SH},\text{out}} = n_{\text{CH}_3\text{SH},\text{out,top}} + n_{\text{CH}_3\text{SH},\text{out,bottom}}$$

$$n_{\text{CH}_3\text{SH},\text{out}} = n_{\text{CH}_3\text{SH},\text{out,bottom}}$$

And

$$n_{\text{CH}_3\text{SH},\text{out}} = 0.11 - \int_3$$

$$n_{\text{CH}_3\text{SH},\text{out,bottom}} = 0.11 - \int_3$$

$$\int_3 = \frac{n_{\text{CH}_3\text{SH},\text{out}}}{n_{\text{CH}_3\text{SH},\text{in}}} = \frac{n_{\text{CH}_3\text{SH},\text{out,bottom}}}{n_{\text{CH}_3\text{SH},\text{in}}} = \frac{n_{\text{CH}_3\text{SH},\text{out,bottom}}}{0.11}$$

Now solving the equations for $n_{\text{CH}_3\text{SH},\text{out,bottom}}$

$$n_{\text{CH}_3\text{SH},\text{out,bottom}} = 0.01 \frac{\text{lbmol}}{h}$$

$$\int_3 = \frac{0.01}{0.11} = 0.09$$

➤ $\text{C}_2\text{H}_5\text{SH}$ balance

$$\text{out}_{\text{C}_2\text{H}_5\text{SH}} = \text{in}_{\text{C}_2\text{H}_5\text{SH}} \pm \sum v_{\text{C}_2\text{H}_5\text{SH}} \int_{\text{C}_2\text{H}_5\text{SH}}$$

$$n_{\text{C}_2\text{H}_5\text{SH},\text{out}} = n_{\text{C}_2\text{H}_5\text{SH},\text{in}} - \int_4$$

$n_{\text{C}_2\text{H}_5\text{SH},\text{in}} = 0$, this means again no reaction takes place and hence

$$\int_4 = 0$$

Going back to water balance equation,

$$n_{H_2O,out} = n_{H_2O,in} + \int_1 + 2\int_2 + \int_3 + \int_4 + \int_5$$

$$n_{H_2O,out} = 0 + 2 \times 0.49 + 2 \times 0 + 0.09 + 0 + 0 = 1.07 \text{ lbmol/h}$$

➤ Velocity calculation

For the velocity calculation (required for software modelling), the amount of water drained was used.

$$n_{H_2O,out} = 1.07 \frac{\text{lbmol}}{h}$$

$$\rho = \frac{m}{V}$$

$$V = \frac{1.07 \frac{\text{lbmol}}{h} \times 18 \frac{\text{lbm}}{\text{lbmol}} \times \frac{0.453 \text{ kg}}{\text{lbm}} \times \frac{1 h}{3600 s}}{1000 \frac{\text{kg}}{\text{m}^3}}$$

$$= 2.42 \times 10^{-6} \text{ m}^3/\text{s}$$

$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} (0.101)^2 = 7.85 \times 10^{-3} \text{ m}^2$$

$$\therefore v = \frac{2.42 \times 10^{-6} \text{ m}^3/\text{s}}{7.85 \times 10^{-3} \text{ m}^2} = 3.08 \times 10^{-4} \text{ m/s}$$

2- CGP-II – propane KOH treater material balance

Similar reaction which happen in CGP-I propane KOH treater is happening in CGP-II propane KOH treater, therefore, the same calculation is carried with the difference in streams flow rate.

➤ H_2S balance:

$$n_{H_2S out} = n_{H_2S in} - \int_2$$

From the given data,

$$n_{H_2S in} = 0.94 \text{ lbmol/h}$$

So

$$n_{H_2S out} = 0.94 - \int_2$$

Also given that in the outlet product stream, the maximum allowed hydrogen sulfide concentration (as product specification) is 5ppm. The flow rate of the same stream is 3.3 *MMSCFD*.

By this, the flow rate of H_2S in the product could be calculated as follow:

$$\begin{aligned}
 & 3.3 \times 10^6 \frac{ft^3}{day} \times \frac{1day}{24hour} \times \frac{0.028m^3}{1ft^3} \times 5ppm H_2S \\
 & \times \frac{1.5 \frac{mg}{m^3} H_2S}{1 ppm H_2S} \times \frac{gmol H_2S}{34.1 g H_2S} \times \frac{0.0022lbmol}{gmol} \\
 & = 1.86 \times 10^{-3} lbmol/hour
 \end{aligned}$$

n_{out,H_2S} equal to the summation of the top and bottom values from the KOH treater, therefore: $n_{out,H_2S} = n_{top,H_2S} + n_{bottom,H_2S}$

$$\begin{aligned}
 n_{out,H_2S} &= 1.86 \times 10^{-3} lbmol/hour + n_{bottom,H_2S} \\
 \int_2 &= \frac{n_{out,H_2S}}{n_{in,H_2S}} = \frac{1.86 \times 10^{-3} lbmol/hour + n_{bottom,H_2S}}{0.94}
 \end{aligned}$$

Now substituting the last two equations in hydrogen sulfide balance equation and solving for n_{bottom} will give the drained amount of hydrogen sulfide.

$$\begin{aligned}
 n_{H_2S out} &= 0.94 - \int_2 \\
 n_{out,H_2S} &= 0.94 - \int_2 = 1.86 \times 10^{-3} + n_{bottom,H_2S} \\
 &= 0.94 - \frac{1.86 \times 10^{-3} + n_{bottom,H_2S}}{0.94} \\
 1.86 \times 10^{-3} - 0.94 &+ \frac{1.86 \times 10^{-3}}{0.94} \\
 &= -n_{bottom,H_2S} + \frac{-n_{bottom,H_2S}}{0.94} \\
 -0.936 &= -2.06 \times n_{bottom,H_2S} \\
 \therefore n_{bottom,H_2S} &= 0.45
 \end{aligned}$$

$$n_{bottom,H_2S} = 0.45 \frac{lbmol}{h} \times 34.1 \frac{lbm}{lbmol} \times \frac{1kg}{2.204 lbm} = 6.975 \frac{kg}{h}$$

$$\therefore \int_2 = \frac{1.86 \times 10^{-3} + 0.45}{0.94} = 0.48$$

Since the water will be accumulated at the bottom and it is generated as a result of the reactions, we carry-out also water material balance

$$out_i = in_i \pm \sum v_i \int_i$$

$$n_{H_2O,out} = n_{H_2O,in} + \int_1 + 2\int_2 + \int_3 + \int_4 + \int_5$$

The extents of reactions are found by carrying out other component balance

➤ COS balance

$$out_{COS} = in_{COS} \pm \sum v_{COS} \int_{COS}$$

$$n_{COS,out} = n_{COS,in} - \int_1 - \int_5$$

$n_{COS,in} = 0$. This means that no reaction takes place.

$$\int_1 = 0$$

$$\int_5 = 0$$

➤ CH_3SH balance

$$out_{CH_3SH} = in_{CH_3SH} \pm \sum v_{CH_3SH} \int_{CH_3SH}$$

$$n_{CH_3SH,out} = n_{CH_3SH,in} - \int_3$$

$$n_{CH_3SH,out} = 0.106 - \int_3$$

Assuming all CH_3SH is adsorbed, i.e. no CH_3SH at the top stream of the KOH treater

$$n_{CH_3SH,out} = n_{CH_3SH,out,top} + n_{CH_3SH,out,bottom}$$

$$n_{CH_3SH,out} = n_{CH_3SH,out,bottom}$$

And

$$n_{CH_3SH,out} = 0.106 - \int_3$$

$$n_{CH_3SH,out,bottom} = 0.106 - \int_3$$

$$\int_3 = \frac{n_{CH_3SH,out}}{n_{CH_3SH,in}} = \frac{n_{CH_3SH,out,bottom}}{n_{CH_3SH,in}} = \frac{n_{CH_3SH,out,bottom}}{0.106}$$

Now solving the equations for $n_{CH_3SH,out,bottom}$

$$n_{CH_3SH,out,bottom} = 0.01 \frac{lbmol}{h}$$

$$\int_3 = \frac{0.01}{0.94} = 0.01$$

➤ C_2H_5SH balance

$$out_{C_2H_5SH} = in_{C_2H_5SH} \pm \sum v_{C_2H_5SH} \int_{C_2H_5SH}$$

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,in} - \int_4$$

$n_{C_2H_5SH,in} = 0$, this means again no reaction takes place and hence

$$\int_4 = 0$$

Going back to water balance equation,

$$n_{H_2O,out} = n_{H_2O,in} + \int_1 + 2\int_2 + \int_3 + \int_4 + \int_5$$

$$n_{H_2O,out} = 0 + 2 \times 0.48 + 2 \times 0 + 0.01 + 0 + 0 = 0.97 \text{ lbmol/h}$$

➤ Velocity calculation

For the velocity calculation (required for software modelling), the amount of water drained was used.

$$n_{H_2O,out} = 0.97 \frac{lbmol}{h}$$

$$\rho = \frac{m}{V}$$

$$V = \frac{0.97 \frac{lbmol}{h} \times 18 \frac{lbm}{lbmol} \times \frac{0.453kg}{lbm} \times \frac{1h}{3600s}}{1000 \frac{kg}{m^3}}$$

$$= 2.197 \times 10^{-6} \text{ m}^3/s$$

$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} (0.101)^2 = 7.85 \times 10^{-3} \text{ m}^2$$

$$\therefore v = \frac{2.197 \times 10^{-6} \text{ m}^3/\text{s}}{7.85 \times 10^{-3} \text{ m}^2} 2.79 \times 10^{-4} \text{ m/s}$$

3- CGP-I- Butane KOH treater material balance

Again, the same set of reactions happens in this treater with the exception of the streams flow rate.

➤ H_2S balance:

$$n_{H_2S \text{ out}} = n_{H_2S \text{ in}} - \int_2$$

From the given data,

$$n_{H_2S \text{ in}} = 0 \text{ lbmol/h}$$

This means this reaction did not take place, $\int_2 = 0$

➤ COS balance

$$out_{COS} = in_{COS} \pm \sum v_{COS} \int_{COS}$$

$$n_{COS, out} = n_{COS, in} - \int_1 - \int_5$$

$n_{COS, in} = 0$. This means this reaction did not take place, $\int_1 = 0$ and

$$\int_5 = 0$$

➤ CH_3SH balance

$$out_{CH_3SH} = in_{CH_3SH} \pm \sum v_{CH_3SH} \int_{CH_3SH}$$

$$n_{CH_3SH, out} = n_{CH_3SH, in} - \int_3$$

$$n_{CH_3SH, out} = 0.124 - \int_3$$

Assuming all CH_3SH is adsorbed, i.e. no CH_3SH at the top stream of the KOH treater

$$\text{➤ } n_{CH_3SH, out} = n_{CH_3SH, out, top} + n_{CH_3SH, out, bottom}$$

$$n_{CH_3SH, out} = n_{CH_3SH, out, bottom}$$

And

$$n_{CH_3SH, out} = 0.124 - \int_3$$

$$n_{CH_3SH, out, bottom} = 0.124 - \int_3$$

$$\int_3 = \frac{n_{CH_3SH,out}}{n_{CH_3SH,in}} = \frac{n_{CH_3SH,out,bottom}}{n_{CH_3SH,in}} = \frac{n_{CH_3SH,out,bottom}}{0.124}$$

Now solving the equations for $n_{CH_3SH,out,bottom}$

$$n_{CH_3SH,out,bottom} = 0.013 \frac{lbmol}{h}$$

$$\int_3 = \frac{0.013}{0.124} = 0.105$$

➤ C_2H_5SH balance

$$out_{C_2H_5SH} = in_{C_2H_5SH} \pm \sum v_{C_2H_5SH} \int_{C_2H_5SH}$$

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,in} - \int_4$$

$$n_{C_2H_5SH,out} = 0.0016 - \int_4$$

Assuming all C_2H_5SH is adsorbed, i.e. no C_2H_5SH at the top stream of the KOH treater

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,out,top} + n_{C_2H_5SH,out,bottom}$$

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,out,bottom}$$

And

$$n_{C_2H_5SH,out} = 0.0016 - \int_4$$

$$\int_4 = \frac{n_{C_2H_5SH,out}}{n_{C_2H_5SH,in}} = \frac{n_{C_2H_5SH,bottom}}{n_{C_2H_5SH,in}} = \frac{n_{C_2H_5SH,bottom}}{0.0016}$$

Now solving the equations for $n_{C_2H_5SH,out,bottom}$

$$n_{C_2H_5SH,out,bottom} = 2.55 \times 10^{-6} \frac{lbmol}{h}$$

$$\int_4 = \frac{2.55 \times 10^{-6}}{0.0016} = 1.59 \times 10^{-3}$$

➤ Water balance

$$out_i = in_i \pm \sum v_i \int_i$$

$$n_{H_2O,out} = n_{H_2O,in} + \int_1 + 2\int_2 + \int_3 + \int_4 + \int_5$$

$$n_{H_2O,out} = 0 + 0 + 2 \times 0 + 0.105 + 1.59 \times 10^{-3} = 0.106 \frac{lbmol}{h}$$

4- CGP-II- Butane KOH treater material balance

Again, the same set of reactions happens in this treater with the exception of the streams flow rate

➤ H_2S balance:

$$n_{H_2S\ out} = n_{H_2S\ in} - \int_2$$

From the given data,

$$n_{H_2S\ in} = 0\ lbmol/h$$

This means this reaction did not take place, $\int_2 = 0$

➤ COS balance

$$out_{COS} = in_{COS} \pm \sum v_{COS} \int_{COS}$$

$$n_{COS,out} = n_{COS,in} - \int_1 - \int_5$$

$n_{COS,in} = 0$. This means this reaction did not take place, $\int_2 = 0$

and $\int_5 = 0$

➤ CH_3SH balance

$$out_{CH_3SH} = in_{CH_3SH} \pm \sum v_{CH_3SH} \int_{CH_3SH}$$

$$n_{CH_3SH,out} = n_{CH_3SH,in} - \int_3$$

$$n_{CH_3SH,out} = 0.126 - \int_3$$

Assuming all CH_3SH is adsorbed, i.e. no CH_3SH at the top stream of the KOH treater

➤ $n_{CH_3SH,out} = n_{CH_3SH,out,top} + n_{CH_3SH,out,bottom}$

$$n_{CH_3SH,out} = n_{CH_3SH,out,bottom}$$

And

$$n_{CH_3SH,out} = 0.126 - \int_3$$

$$n_{CH_3SH,out,bottom} = 0.126 - \int_3$$

$$\int_3 = \frac{n_{CH_3SH,out}}{n_{CH_3SH,in}} = \frac{n_{CH_3SH,out,bottom}}{n_{CH_3SH,in}} = \frac{n_{CH_3SH,out,bottom}}{0.126}$$

Now solving the equations for $n_{CH_3SH,out,bottom}$

$$n_{CH_3SH,out,bottom} = 0.014 \frac{lbmol}{h}$$

$$\int_3 = \frac{0.014}{0.126} = 0.11$$

➤ C_2H_5SH balance

$$out_{C_2H_5SH} = in_{C_2H_5SH} \pm \sum v_{C_2H_5SH} \int_{C_2H_5SH}$$

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,in} - \int_4$$

$$n_{C_2H_5SH,out} = 0.0016 - \int_4$$

Assuming all C_2H_5SH is adsorbed, i.e. no C_2H_5SH at the top stream of the KOH treater

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,out,top} + n_{C_2H_5SH,out,bottom}$$

$$n_{C_2H_5SH,out} = n_{C_2H_5SH,out,bottom}$$

And

$$n_{C_2H_5SH,out} = 0.0016 - \int_4$$

$$\int_4 = \frac{n_{C_2H_5SH,out}}{n_{C_2H_5SH,in}} = \frac{n_{C_2H_5SH,bottom}}{n_{C_2H_5SH,in}} = \frac{n_{C_2H_5SH,bottom}}{0.0016}$$

Now solving the equations for $n_{C_2H_5SH,out,bottom}$

$$n_{C_2H_5SH,out,bottom} = 2.55 \times 10^{-6} \frac{lbmol}{h}$$

$$\int_4 = \frac{2.55 \times 10^{-6}}{0.0016} = 1.59 \times 10^{-3}$$

➤ Water balance

$$out_i = in_i \pm \sum v_i \int_i$$

$$n_{H_2O,out} = n_{H_2O,in} + \int_1 + 2\int_2 + \int_3 + \int_4 + \int_5$$

$$n_{H_2O,out} = 0 + 0 + 2 \times 0 + 0.11 + 1.59 \times 10^{-3} = 0.11 \frac{lbmol}{h}$$

Below tables summarize the obtained results.

A1-2 Material balance results around KOH treaters

➤ CGP-I- C3 drain pot

Table (21): CGP-I C3 drain pot calculated results

	Unit	Molar mass	124 mass flow	124 X mass	124 mole flow (lbmol/h)	Drained stream flow rate lbmol/h	SG	Drain stream composition (mol%)	Mole% * Mi	Drain stream composition (mass%)	Composition x SG
Hydrogen	lb/hr		0			0			0	0	
Nitrogen	lb/hr		0			0			0	0	
H ₂ S	lb/hr	34.1	33.1	0.002	0.970674	0.475	1.207	0.305074	10.40302	0.450248	0.54345
CO ₂	lb/hr	44.01	0.2	0.000	0.004544	0			0	0	
H ₂ O	lb/hr	18	0			1	1	0.688504	12.39306	0.536378	0.536378
Teglycol	lb/hr		0			0			0	0	
Methane	lb/hr		0			0			0	0	
Ethane	lb/hr	30.07	173.1	0.011	5.756568	0			0	0	
Propane	lb/hr	44.1	15316	0.952	347.3016	0			0	0	

I-Butane	lb/hr	58.12	459	0.029	7.897454	0			0	0	
N-Butane	lb/hr	58.12	100.9	0.006	1.736063	0			0	0	
I-pentane	lb/hr	72.15	0.2	0.000	0.002772	0			0	0	
N-Pentane	lb/hr	72.15	0.1	0.000	0.001386	0			0	0	
N-Hexane	lb/hr		0			0			0	0	
N-Octane	lb/hr		0			0			0	0	
N-noane	lb/hr		0			0			0	0	
N-Decane	lb/hr		0			0			0	0	
N-C11	lb/hr		0			0			0	0	
C-C12	lb/hr		0			0			0	0	
Oxygen	lb/hr		0			0			0	0	
1-butene	lb/hr	56.106	0	0.000	0	0			0	0	
Propene	lb/hr		0			0			0	0	
Ammonia	lb/hr		0			0			0	0	

COS	lb/h r		0			0			0	0	
M-mercaptan	lb/h r	48.11	5.3	0.00 0	0.11016 4	0.01	0.87 5	0.006423	0.30899 2	0.013373	0.011702
E-mercaptan	lb/h r	62.14	0	0.00 0	0	0			0	0	
Dim-Sulphide	lb/h r		0			0			0	0	
Mercaptan	lb/h r		0			0			0	0	
2C3Mercaptan	lb/h r		0			0			0	0	
M-e-sulphide	lb/h r		0			0			0	0	
Thiophene	lb/h r		0			0			0	0	
Die-sulphide	lb/h r		0			0			0	0	
Dimdisulphide	lb/h r		0			0			0	0	
N-Heptane	lb/h r		0			0			0	0	
Total	lb/h r		16087. 9			1.557		1		1	1.09153
								Mixture molar mass	23.1050 7		

➤ CGP-II- C3 drain pot

Table (22): CGP-II C3 drain pot calculated results

		Molar mass	224 mass flow	224 X mas s	224 mole flow (lbmol/ h)	Draine d stream flow rate (lbmol/ h)	SG	Drain stream compositi on (mol%)	Mole% * Mi	Drain stream compositi on (mass%	Compositi on x SG
Hydrogen	lb/h r		0			0			0	0	
Nitrogen	lb/h r		0			0			0	0	
H ₂ S	lb/h r	34.1	32.2	0.00 2	0.9442 82	0.475	1.20 7	0.32646	11.1323	0.474463	0.572677
CO ₂	lb/h r	44.01	0.2	0.00 0	0.0045 44	0			0	0	
H ₂ O	lb/h r	18	0			1	1	0.666667	12	0.511445	0.511445
Teglycol	lb/h r		0			0			0	0	
Methane	lb/h r		0			0			0	0	
Ethane	lb/h r	30.07	168.5	0.01 1	5.6035 92	0			0	0	
Propane	lb/h r	44.1	15108 .7	0.95 2	342.60 09	0			0	0	
I-Butane	lb/h r	58.12	463.7	0.02 9	7.9783 21	0			0	0	

N-Butane	lb/hr	58.12	94.1	0.006	1.619064	0			0	0	
I-pentane	lb/hr	72.15	0.1	0.000	0.001386	0			0	0	
N-Pentane	lb/hr	72.15	0			0			0	0	
N-Hexane	lb/hr		0			0			0	0	
N-Octane	lb/hr		0			0			0	0	
N-noane	lb/hr		0			0			0	0	
N-Decane	lb/hr		0			0			0	0	
N-C11	lb/hr		0			0			0	0	
C-C12	lb/hr		0			0			0	0	
Oxygen	lb/hr		0			0			0	0	
1-butene	lb/hr	56.106	0			0			0	0	
Propene	lb/hr		0			0			0	0	
Ammonia	lb/hr		0			0			0	0	
COS	lb/hr		0			0			0	0	

M-mercaptan	lb/hr	48.11	5.1	0.000	0.106007	0.01	0.875	0.006873	0.330653	0.014093	0.012331
E-mercaptan	lb/hr	62.14	0			0			0	0	
Dim-Sulphide	lb/hr		0			0			0	0	
Mercaptan	lb/hr		0			0			0	0	
2C3Mercaptan	lb/hr		0			0			0	0	
M-e-sulphide	lb/hr		0			0			0	0	
Thiophene	lb/hr		0			0			0	0	
Die-sulphide	lb/hr		0			0			0	0	
Dimdisulphide	lb/hr		0			0			0	0	
N-Heptane	lb/hr		0			0			0	0	
Total	lb/hr		15872.7			1.455		1	23.46296	1	1.096452
									Mixture molar mass		

➤ CGP-I- C4 drain pot

Table (23): CGP-I C4 drain pot calculated results

		Molar mass	125 mass flow	125 X masses	125 mole flow (lbmol/h)	Drained stream flow rate (lbmol/h)	SG	Drain stream composition (mol%)	Mole% * Mi	Drain stream composition (mass%)	Composition x SG
Hydrogen	lb/hr		0						0	0.0	
Nitrogen	lb/hr		0						0	0.0	
H ₂ S	lb/hr	34.1	0	0.000	0		1.207	0	0	0.0	0
CO ₂	lb/hr	44.01	0	0.000	0				0	0.0	
H ₂ O	lb/hr		0			0.11	1	0.890737	0	0.0	0
Teglycol	lb/hr		0						0	0.0	
Methan	lb/hr		0						0	0.0	
Ethane	lb/hr	30.07	0	0.000	0				0	0.0	
Propane	lb/hr	44.1	201.7	0.009	4.573696	0.00			0	0.0	
I-Butane	lb/hr	58.12	8315.5	0.357	143.0747	0.00			0	0.0	
N-Butane	lb/hr	58.12	14498	0.623	249.4494	0.00			0	0.0	
I-pentane	lb/hr	72.15	229.4	0.010	3.179487	0.00			0	0.0	
N-Pentane	lb/hr	72.15	37.2	0.002	0.515593	0.00			0	0.0	
N-Hexane	lb/hr		0						0	0.0	

N-Octane	lb/hr		0						0	0.0	
N-noane	lb/hr		0						0	0.0	
N-Decane	lb/hr		0						0	0.0	
N-C11	lb/hr		0						0	0.0	
C-C12	lb/hr		0						0	0.0	
Oxygen	lb/hr		0						0	0.0	
1-butene	lb/hr	56.10 6	1.2	0.00 0	0.0213 88	0.00			0	0.0	
Propene	lb/hr		0						0	0.0	
Ammonia	lb/hr		0						0	0.0	
Cos	lb/hr		0						0	0.0	
M-mercaptan	lb/hr	48.11	6	0.00 0	0.1247 14	0.013	0.87 5	0.109241	5.255602	1.0	0.875
E-mercaptan	lb/hr	62.14	0.1	0.00 0	0.0016 09	2.55E-06			0	0.0	
Dim-Sulphide	lb/hr		0						0	0.0	
Mercaptan	lb/hr		0						0	0.0	
2C3Mercaptan	lb/hr		0						0	0.0	
M-e-sulphide	lb/hr		0						0	0.0	
Thiophene	lb/hr		0						0	0.0	
Die-sulphide	lb/hr		0						0	0.0	
Dimdisulphide	lb/hr		0						0	0.0	
N-Heptane	lb/hr		0						0	0.0	
Total	lb/hr		23289 .2			0.119002 55		1	5.255602	1	0.875
									Mixture molar mass		

➤ GP-II- C4 drain pot

Table (24): CGP-II C4 drain pot calculated results

		Molar mass	225 mass flow	225 X masses	225 mole flow lbmol/h	Drained stream flow rate lmbol/h	SG	Drain stream composition (mol%	Mole% * Mi	Drain stream composition (mass%	Composition x SG
Hydrogen	lb/hr		0						0	0.0	
Nitrogen	lb/hr		0						0	0.0	
H ₂ S	lb/hr	34.1	0				1.207	0	0	0.0	0
CO ₂	lb/hr	44.01	0						0	0.0	
H ₂ O	lb/hr		0			0.11	1	0.890737	0	0.0	0
TEGlycol	lb/hr		0						0	0.0	
Methane	lb/hr		0						0	0.0	
Ethane	lb/hr	30.07	0						0	0.0	
Propane	lb/hr	44.1	198.8	0.009	4.507937	0.00			0	0.0	
i-Butane	lb/hr	58.12	7892.1	0.363	135.7897	0.00			0	0.0	
n-Butane	lb/hr	58.12	13415.4	0.617	230.8224	0.00			0	0.0	
I-Pentane	lb/hr	72.15	201	0.009	2.785863	0.00			0	0.0	
n-Pentane	lb/hr	72.15	30.4	0.001	0.421344	0.00			0	0.0	
n-Hexane	lb/hr		0						0	0.0	
n-Octane	lb/hr		0						0	0.0	
n-noane	lb/hr		0						0	0.0	

n-Decane	lb/hr		0						0	0.0	
n-C11	lb/hr		0						0	0.0	
c-C12	lb/hr		0						0	0.0	
Oxygen	lb/hr		0						0	0.0	
1-Butene	lb/hr	56.10 6	1.1	0.00 0	0.0196 06	0.00			0	0.0	
Propene	lb/hr		0						0	0.0	
Ammonia	lb/hr		0						0	0.0	
COS	lb/hr		0						0	0.0	
M-Mercaptan	lb/hr	48.11	6.1	0.00 0	0.1267 93	0.013	0.87 5	0.109241	5.255602	1.0	0.875
E-Mercaptan	lb/hr	62.14	0.1	0.00 0	0.0016 09	2.55E-06			0	0.0	
diM-Sulphide	lb/hr		0						0	0.0	
nPMercaptan	lb/hr		0						0	0.0	
2C3Mercaptan	lb/hr		0						0	0.0	
M-E-Sulphide	lb/hr		0						0	0.0	
Thiophene	lb/hr		0						0	0.0	
diE-sulphide	lb/hr		0						0	0.0	
diMdiSulphide	lb/hr		0						0	0.0	
n-Heptane	lb/hr		0						0	0.0	
Total	lb/hr		21745			0.119002 55		1	5.255602	1	0.875
									Mixture molar mass		

Appendix 2:

A2-1 List of questionnaire respondents

Table (25): List of personnel for the questionnaire

Sr. No.	Expert field	Company	Respond status √ or ×	Valid/ Invalid Comment/ reason
1.	Environment field-case study company	Banagas	√	Valid response
2.		Banagas	√	Valid response
3.	Technical field- case study company	Banagas	√	Invalid Beyond respondent experience
4.		Banagas	√	Valid response
5.		Banagas	√	Invalid - CR>0.1 (1 st matrix) Beyond respondent experience + did not complete metrics
6.		Banagas	√	Invalid CR>0.1 (1 st matrix) Beyond respondent experience + did not complete metrics
7.	Environmental specialist- private company	Worley	√	Invalid - CR >0.1
8.	Environmental engineer- GPIC	GPIC	×	No reply
9.	SCE	SCE	×	No reply
10.		SCE	×	No reply
11.	Engineer – private treatment company	MERCO	×	No reply
12.	Academe- chemical engineering collage	UOB	√	Invalid Beyond respondent experience
13.	Academe- science collage	UOB	√	Invalid CR >0.1

A2-2 Questionnaire sample:

University of Bahrain

College of science



Subject: Questionnaire to select the best treatment method for potassium hydroxide/ methanol spent caustic

Introduction:

This questionnaire is part of M.Sc. dissertation requirement for the Environment and Sustainable Development (ESD) program in the University of Bahrain (UOB). The topic of interest is "Assessing the methods of spent caustic effluent treatment from liquid petroleum gas (LPG) Sulphur purification process", the main aim is to find the best solution for the spent caustic wastewater treatment and also to assess its impact on both human health and the environment.

This questionnaire is designed to target experts in wastewater treatment, industrial and environmental fields.

This questionnaire utilizes Analytical Hierarchy Process (AHP) to determine the best wastewater treatment solution. It is very effective tool based on comparing multiple criteria and alternatives with each other. Through that, weights are obtained that represent the criteria priority or importance.

The questionnaire will take about 25 to 45 minutes to complete. I kindly request your valuable feedback on the same as soft copy in order to be able to assess the treatment methods.

In case of ambiguity, please do not hesitate to contact me via the following contacts:

Phone: 39060754 or Email: haifamarjan@gmail.com

Thank you very much in advance for your participation.

Haifa Abdulaziz Eid Marjan

M.Sc. in Environment and Sustainable Development (ESD) program

Supervisor: Dr. Suad Ahmed rashdan

Co.Supervisour: Prof. Elamin M ElKanzi

How to attempt the pairwise comparisons:

You will see a table similar to the one below example where criterion (i) is in left side and criterion (j) is in the right side. Between the criteria, rating from 1 to 9 for each criterion side. You need to choose the preferred rating for the criterion in its side. For example, suppose criterion (i) is very strongly important than criterion (j), hence, the chosen rating will be number 7 to the left side/ red cell. Likewise, if criterion (j) is strongly important than criterion (i), then the chosen rating will be 5 from the right side/ blue. If both i and j criteria are equally important, rating will be 1/ the black cell.

	Extremely important		Very strong important		Strong important		Moderate important		Equal important		Moderate important		Strong important		Very strong important		Extremely important	
Criteria (i)	9	8	7 √	6	5	4	3	2	1 √	2	3	4	5 √	6	7	8	9	Criteria (j)

The aforementioned evaluation will be repeated six times for five different alternatives namely: Wet Air Oxidation, Catalytic Wet Air Oxidation, Advance chemical oxidation, Biological, Microbial Fuel Cell techniques and pre-treatment technology/ philosophy.

Here's summary of each technique for the ease of understanding and reference as required:

- Wet Air Oxidation: The principle of this technique relies on forming free radicals to attach organic compounds. The main reaction is oxidation reaction using air or oxygen at high temperature and pressure conditions.
- Catalytic Wet Air Oxidation: this technique is similar to Wet Air Oxidation technique with the exception of additional catalyst which helps in reducing the required operating condition for operation.
- Advance chemical oxidation: This technique is one of the best treatment techniques, it bases on forming hydroxyl radicals which break down resistant and hard molecules. Liquid Hydrogen peroxide is usually employed for this technique.
- Biological treatment: this technique usually take place at ambient temperature and pressure conditions; it utilize biological material for contaminants treatment.
- Microbial Fuel Cell: This technology combines biological and electrical techniques, basically it uses biomass energy to treat the wastewater and generate electrical energy.
- Pre-treatment technology/ philosophy: it is the philosophy which base on treating the gas from the beginning i.e. prior fractionation stage.

Beginning of the questionnaire

Pairwise comparisons

This part assesses initial capital cost, operational cost, environmental impact and safety concerns, materials availability and treatment benefit with each other.

Example for row 1: You may ask yourself to what extent initial investment cost is important than operational cost?

#1	Extremely important		Very strong important		Strong important		Moderate important		Equal important		Moderate important		Strong important		Very strong important		Extremely important	
Initial investment cost	9	8	7	6	5	4	3 √	2	1	2	3	4	5	6	7	8	9	Operational cost
Initial investment cost	9	8	7	6	5	4	3 √	2	1	2	3	4	5	6	7	8	9	Environmental impact and safety concerns
Initial investment cost	9	8	7	6	5	4	3	2 √	1	2	3	4	5	6	7	8	9	Materials availability
Initial investment cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Treatment benefit
Operational cost	9	8	7	6	5	4	3	2 √	1	2	3	4	5	6	7	8	9	Environmental impact and safety concerns
Operational cost	9	8	7	6	5	4	3	2 √	1	2	3	4	5	6	7	8	9	Materials availability
Operational cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Treatment benefit
Environmental impact and safety concerns	9	8	7	6	5	4	3	2	1	2 √	3	4	5	6	7	8	9	Materials availability
Environmental impact and safety concerns	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Treatment benefit
Materials availability	9	8	7	6	5	4	3 √	2	1	2	3	4	5	6	7	8	9	Treatment benefit

Considering initial investment cost only, the following comparison is for the five different alternatives.

Example for row 1: when comparing initial investment cost, to what extent Wet Air Oxidation technique is important compared to Catalytic Wet Air Oxidation?

Initial investment cost	Extremely important		Very strong important		Strong important		Moderate important		Equal important		Moderate important		Strong important		Very strong important		Extremely important	
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Catalytic Wet Air Oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Microbial Fuel Cell	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy

Considering Operational cost only, the following comparison is for the five different alternatives.

Example for row 1: when comparing operational cost, to what extent Wet Air Oxidation technique is important compared to Catalytic Wet Air Oxidation?

Operational cost	Extremely important		Very strong important		Strong important		Moderate important		Equal important		Moderate important		Strong important		Very strong important		Extremely important	
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Catalytic Wet Air Oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Microbial Fuel Cell	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy

Considering Environmental impact and safety concerns only, the following comparison is for the five different alternatives.

Example for row 1: when comparing Environmental impact and safety concerns, to what extent Wet Air Oxidation technique is important compared to Catalytic Wet Air Oxidation?

Environmental impact and safety concerns	Extremely important		Very strong important		Strong important		Moderate important		Equal important		Moderate important		Strong important		Very strong important		Extremely important	
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Catalytic Wet Air Oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Microbial Fuel Cell	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy

Considering Materials availability only, the following comparison is for the five different alternatives.

Example for row 1: when comparing Materials availability, to what extent Wet Air Oxidation technique is important compared to Catalytic Wet Air Oxidation?

Materials availability	Extremely important	Very strong important	Strong important	Moderate important	Equal important	Moderate important	Strong important	Very strong important	Extremely important	
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Catalytic Wet Air Oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Advance chemical oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Biological treatment
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Microbial Fuel Cell
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Pre-treatment technology/ philosophy
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Advance chemical oxidation
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Biological treatment
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Microbial Fuel Cell
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	Pre-treatment technology/ philosophy
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	Biological treatment
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	Microbial Fuel Cell
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	Pre-treatment technology/ philosophy
Biological treatment	9	8	7	6	5	4	3	2	1	Microbial Fuel Cell
Biological treatment	9	8	7	6	5	4	3	2	1	Pre-treatment technology/ philosophy
Microbial Fuel Cell	9	8	7	6	5	4	3	2	1	Pre-treatment technology/ philosophy

Considering Treatment benefit only, the following comparison is for the five different alternatives.

Example for row 1: when comparing treatment benefits, to what extent Wet Air Oxidation technique is important compared to Catalytic Wet Air Oxidation?

Treatment benefit	Extremely important		Very strong important		Strong important		Moderate important		Equal important		Moderate important		Strong important		Very strong important		Extremely important	
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Catalytic Wet Air Oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Advance chemical oxidation
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Catalytic Wet Air Oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Biological treatment
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Advance chemical oxidation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Microbial Fuel Cell
Biological treatment	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy
Microbial Fuel Cell	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Pre-treatment technology/ philosophy

Thank you for your participation

Your participation is a value

End of questionnaire

A2-3 Summary of questionnaire results

Table (26) summarize the result obtained from valid response 1.

Table (26): Valid response 1 results

Criteria		Priority vector X weight				
Initial investment cost		0.36				
Operational cost		0.33				
Environmental impact and safety concerns		0.06				
Materials availability		0.16				
Treatment benefit		0.10				
CI		0.060				
		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
		Priority vector X Weight				
Alternatives	Wet Air Oxidation (WAO)	0.29	0.39	0.14	0.49	0.08
	Catalytic Wet Air Oxidation (CWAO)	0.16	0.18	0.15	0.14	0.08
	Advance chemical oxidation (AOP)	0.11	0.15	0.33	0.10	0.08
	Biological treatment	0.33	0.06	0.07	0.07	0.08
	Microbial Fuel Cell (MFC)	0.08	0.06	0.07	0.07	0.52
	Pre-treatment technology/ philosophy	0.03	0.17	0.23	0.13	0.14
	CI	0.02	0.05	0.08	0.08	0.10

Table (27) summarize the result obtained from valid response 2.

Table (27): Valid response 2 results

Criteria		Priority vector X Weight				
Initial investment cost		0.41				
Operational cost		0.23				
Environmental impact and safety concerns		0.14				
Materials availability		0.17				
Treatment benefit		0.05				
CI		0.091				
		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
		Priority vector X Weight				
Alternatives	Wet Air Oxidation (WAO)	0.10	0.18	0.22	0.21	0.05
	Catalytic Wet Air Oxidation (CWAO)	0.10	0.06	0.07	0.09	0.06
	Advance chemical oxidation (AOP)	0.15	0.06	0.12	0.11	0.18
	Biological treatment	0.27	0.38	0.35	0.26	0.18
	Microbial Fuel Cell (MFC)	0.34	0.24	0.21	0.26	0.21
	Pre-treatment technology/ philosophy	0.04	0.07	0.04	0.06	0.33
	CI	0.08	0.10	0.08	0.07	0.10

Table (28) summarize the result obtained from valid response 3.

Table (28): Valid response 3 results

Criteria		Priority vector X/ weight				
Initial investment cost		0.11				
Operational cost		0.25				
Environmental impact and safety concerns		0.33				
Materials availability		0.09				
Treatment benefit		0.22				
CI		0.10				
		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
		Priority vector X weight				
Alternatives	Wet Air Oxidation (WAO)	0.13	0.05	0.05	0.04	0.19
	Catalytic Wet Air Oxidation (CWAO)	0.05	0.10	0.06	0.08	0.19
	Advance chemical oxidation (AOP)	0.08	0.09	0.09	0.09	0.06
	Biological treatment	0.39	0.42	0.36	0.34	0.12
	Microbial Fuel Cell (MFC)	0.27	0.27	0.34	0.31	0.09
	Pre-treatment technology/ philosophy	0.08	0.07	0.10	0.13	0.34
	CI	0.02	0.05	0.08	0.08	0.10

Table (29) summarize the aggregated result from all valid responses.

Table (29): Aggregated result from all valid responses

Criteria		Priority vector X				
Initial investment cost		0.29				
Operational cost		0.27				
Environmental impact and safety concerns		0.18				
Materials availability		0.14				
Treatment benefit		0.12				
		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
		Priority vector X Local weights				
Alternatives	Wet Air Oxidation (WAO)	0.17	0.21	0.14	0.25	0.11
	Catalytic Wet Air Oxidation (CWAO)	0.11	0.12	0.09	0.11	0.11
	Advance chemical oxidation (AOP)	0.11	0.10	0.18	0.10	0.11
	Biological treatment	0.33	0.28	0.26	0.22	0.13
	Microbial Fuel Cell (MFC)	0.23	0.19	0.21	0.21	0.28
	Pre-treatment technology/ philosophy	0.05	0.10	0.12	0.11	0.27
		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
		Priority vector X Global weights				
Wet Air Oxidation (WAO)		0.049	0.057	0.024	0.034	0.013
Catalytic Wet Air Oxidation (CWAO)		0.031	0.031	0.017	0.014	0.014
Advance chemical oxidation (AOP)		0.033	0.027	0.032	0.014	0.013
Biological treatment		0.096	0.077	0.046	0.031	0.016
Microbial Fuel Cell (MFC)		0.067	0.052	0.037	0.029	0.034
Pre-treatment technology/ philosophy		0.015	0.029	0.022	0.015	0.033

A2-4 Detailed questionnaire results

Table (30): Participant no.1 AHP result

A						
Criteria		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost		1	3	4	2	5
Operational cost		1/3	1	2	2	6
Environmental impact and safety concerns		1/4	1/2	1	1/2	7
Materials availability		1/2	1/2	2	1	3
Treatment benefit		1/5	1/6	1/7	1/3	1
sum		2.3	5.2	9.1	5.8	22.0
Normalized A						
Criteria		Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost		0.438	0.581	0.438	0.343	0.227
Operational cost		0.146	0.194	0.219	0.343	0.273
Environmental impact and safety concerns		0.109	0.097	0.109	0.086	0.318
Materials availability		0.219	0.097	0.219	0.171	0.136
Treatment benefit		0.088	0.032	0.016	0.057	0.045
sum		1	1	1	1	1
Priority vector X		AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)	CR= CI/RI
0.405		2.260	5.577		0.1021	0.09
0.235		1.280	5.453			
0.144		0.780	5.421			
0.168		0.919	5.456			
0.048		0.245	5.135			
				5.409		
Initial investment cost						
A						
	Wet Air	Catalytic Wet Air Oxidation	Advanced chemi	Biological treatment	Microbial Fuel Cell	Pre-treatment

	Oxidation		cal oxidation			technology/philosophy
Wet Air Oxidation	1	1/3	1	1/3	1/3	3
Catalytic Wet Air Oxidation	3	1	1/3	1/4	1/5	2
Advance chemical oxidation	1	3	1	1/2	1/2	3
Biological treatment	3	4	2	1	1/2	9
Microbial Fuel Cell	3	5	2	2	1	7
Pre-treatment technology/philosophy	1/3	1/2	1/3	1/9	1/7	1
sum	11.3	13.8	6.7	4.2	2.7	25.0
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.088	0.024	0.150	0.079	0.125	0.120
Catalytic Wet Air Oxidation	0.265	0.072	0.050	0.060	0.075	0.080
Advance chemical oxidation	0.088	0.217	0.150	0.119	0.187	0.120
Biological treatment	0.265	0.289	0.300	0.238	0.187	0.360
Microbial Fuel Cell	0.265	0.361	0.300	0.477	0.374	0.280
Pre-treatment technology/philosophy	0.029	0.036	0.050	0.026	0.053	0.040

sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	$\lambda_{\max}$	CI = $(\lambda_{\max} - n)/(n - 1)$	CR = CI/RI	
0.098	0.601	6.150		0.0935	0.08	
0.100	0.658	6.562				
0.147	0.971	6.611				
0.273	1.785	6.536				
0.343	2.252	6.569				
0.039	0.250	6.376				
			6.468			
Operational cost						
A						
	Wet Air Oxidat ion	Catalytic Wet Air Oxidation	Advan ce chemi cal oxidati on	Biological treatment	Microbial Fuel Cell	Pre- treatm ent techno logy/ philos ophy
Wet Air Oxidation	1	4	4	1/4	1/4	4
Catalytic Wet Air Oxidation	1/4	1	1	1/4	1/4	1
Advance chemical oxidation	1/4	1	1	1/4	1/4	1
Biological treatment	4	4	4	1	4	3
Microbial Fuel Cell	4	4	4	1/4	1	3
Pre- treatment technolog y/ philosoph y	1/4	1	1	1/3	1/3	1
sum	9.8	15.0	15.0	2.3	6.1	13.0
Normalized A						
	Wet Air Oxidat ion	Catalytic Wet Air Oxidation	Advan ce chemi cal oxidati on	Biological treatment	Microbial Fuel Cell	Pre- treatm ent techno logy/ philos ophy
Wet Air Oxidation	0.103	0.267	0.267	0.107	0.041	0.308

Catalytic Wet Air Oxidation	0.026	0.067	0.067	0.107	0.041	0.077
Advance chemical oxidation	0.026	0.067	0.067	0.107	0.041	0.077
Biological treatment	0.410	0.267	0.267	0.429	0.658	0.231
Microbial Fuel Cell	0.410	0.267	0.267	0.107	0.164	0.231
Pre-treatment technology/philosophy	0.026	0.067	0.067	0.143	0.055	0.077
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)	CR= CI/RI	
0.182	1.138	6.252		0.1289	0.10	
0.064	0.400	6.251				
0.064	0.400	6.251				
0.377	2.798	7.425				
0.241	1.792	7.436				
0.072	0.452	6.251				
			6.645			
Environmental impact and safety concerns						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	1	4	2	1/3	2	5
Catalytic Wet Air Oxidation	1/4	1	1/4	1/4	1/4	4
Advance chemical oxidation	1/2	4	1	1/3	1/3	3
Biological treatment	3	4	3	1	2	6
Microbial Fuel Cell	1/2	4	3	1/2	1	6
Pre-treatment	1/5	1/4	1/3	1/6	1/6	1

technolog y/ philosoph y						
sum	5.5	17.3	9.6	2.6	5.8	25.0
Normalized						
	Wet Air Oxidat ion	Catalytic Wet Air Oxidation	Advan ce chemi cal oxidati on	Biological treatment	Microbial Fuel Cell	Pre- treatm ent techno logy/ philos ophy
Wet Air Oxidation	0.183	0.232	0.209	0.129	0.348	0.200
Catalytic Wet Air Oxidation	0.046	0.058	0.026	0.097	0.043	0.160
Advance chemical oxidation	0.092	0.232	0.104	0.129	0.058	0.120
Biological treatment	0.550	0.232	0.313	0.387	0.348	0.240
Microbial Fuel Cell	0.092	0.232	0.313	0.194	0.174	0.240
Pre- treatment technolog y/ philosoph y	0.037	0.014	0.035	0.065	0.029	0.040
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λ_{max}	CI = $(\lambda_{max}-n)/(n-1)$	CR= CI/RI	
0.217	1.461	6.739		0.1004	0.08	
0.072	0.441	6.150				
0.122	0.812	6.625				
0.345	2.284	6.619				
0.207	1.362	6.569				
0.037	0.231	6.309				
			6.502			
Materials availability						
A						
	Wet Air Oxidat ion	Catalytic Wet Air Oxidation	Advan ce chemi cal oxidati on	Biological treatment	Microbial Fuel Cell	Pre- treatm ent techno logy/

						philosophy
Wet Air Oxidation	1	4	4	1/2	1/2	3
Catalytic Wet Air Oxidation	1/4	1	1/2	1/3	1/3	3
Advance chemical oxidation	1/4	2	1	1/3	1/3	3
Biological treatment	2	3	3	1	1	3
Microbial Fuel Cell	2	3	3	1	1	3
Pre-treatment technology/philosophy	1/3	1/3	1/3	1/3	1/3	1
sum	5.8	13.3	11.8	3.5	3.5	16.0
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.171	0.300	0.338	0.143	0.143	0.188
Catalytic Wet Air Oxidation	0.043	0.075	0.042	0.095	0.095	0.188
Advance chemical oxidation	0.043	0.150	0.085	0.095	0.095	0.188
Biological treatment	0.343	0.225	0.254	0.286	0.286	0.188
Microbial Fuel Cell	0.343	0.225	0.254	0.286	0.286	0.188
Pre-treatment technology/philosophy	0.057	0.025	0.028	0.095	0.095	0.063
sum	1	1	1	1	1	1

Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax- n)/(n-1)	CR= CI/RI	
0.214	1.454	6.803		0.0908	0.07	
0.090	0.555	6.188				
0.109	0.699	6.402				
0.263	1.733	6.579				
0.263	1.733	6.579				
0.061	0.374	6.172				
			6.454			
Treatment benefit						
A						
	Wet Air Oxidat ion	Catalytic Wet Air Oxidation	Advan ce chemi cal oxidati on	Biological treatment	Microbial Fuel Cell	Pre- treatm ent techno logy/ philos ophy
Wet Air Oxidation	1	1/3	1/4	1/2	1/5	1/5
Catalytic Wet Air Oxidation	3	1	1/5	1/5	1/5	1/6
Advance chemical oxidation	4	5	1	1/2	1/2	1
Biological treatment	2	5	2	1	1	1/4
Microbial Fuel Cell	5	5	2	1	1	1/2
Pre- treatment technolog y/ philosoph y	5	6	1	4	2	1
sum	20.0	22.3	6.5	7.2	4.9	3.1
Normalized A						
	Wet Air Oxidat ion	Catalytic Wet Air Oxidation	Advan ce chemi cal oxidati on	Biological treatment	Microbial Fuel Cell	Pre- treatm ent techno logy/ philos ophy
Wet Air Oxidation	0.050	0.015	0.039	0.069	0.041	0.064

Catalytic Wet Air Oxidation	0.150	0.045	0.031	0.028	0.041	0.053
Advance chemical oxidation	0.200	0.224	0.155	0.069	0.102	0.321
Biological treatment	0.100	0.224	0.310	0.139	0.204	0.080
Microbial Fuel Cell	0.250	0.224	0.310	0.139	0.204	0.160
Pre-treatment technology/philosophy	0.250	0.269	0.155	0.556	0.408	0.321
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λ_{max}	CI = $(\lambda_{max}-n)/(n-1)$		CR= CI/RI
0.046	0.307	6.614		0.1284		0.10
0.058	0.365	6.301				
0.179	1.176	6.584				
0.176	1.212	6.879				
0.215	1.433	6.677				
0.326	2.218	6.797				
			6.642			

Table (31): Participant no.2 AHP result

A					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	1	1/3	1/3	1/3	1/3
Operational cost	3	1	3	3	1/3
Environmental impact and safety concerns	3	1/3	1	3	3
Materials availability	3	1/3	1/3	1	1/3
Treatment benefit	3	3	1/3	3	1
sum	13.0	5.0	5.0	10.3	5.0
Normalized					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	0.077	0.067	0.067	0.032	0.067
Operational cost	0.231	0.200	0.600	0.290	0.067

Environmental impact and safety concerns		0.231	0.067	0.200		0.290	0.600
Materials availability		0.231	0.067	0.067		0.097	0.067
Treatment benefit		0.231	0.600	0.067		0.290	0.200
sum		1	1	1		1	1
Priority vector X	AX	Average {Ax/x}		λ_{max}	CI = (λ_{max} -n)/(n-1)	CR= CI/RI	
0.062	0.375	6.057		5.974	0.2436	0.2175	
0.278	1.705	6.142					
0.278	1.705	6.142					
0.106	0.569	5.389					
0.278	1.705	6.142					
CR>0.1				Invalid entry			

Table (32): Participant no.3 AHP result

A					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	1	1	5	2	7
Operational cost	1	1	4	2	6
Environmental impact and safety concerns	1/5	1/4	1	1/5	1/4
Materials availability	1/2	1/2	1/2	1	4
Treatment benefit	1/7	1/6	4	1/4	1
sum	2.8	2.9	14.5	5.5	18.3
Normalized					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	0.352	0.343	0.345	0.367	0.384
Operational cost	0.352	0.343	0.276	0.367	0.329
Environmental impact	0.070	0.086	0.069	0.037	0.014

and safety concerns						
Materials availability		0.176	0.171	0.034	0.183	0.219
Treatment benefit		0.050	0.057	0.276	0.046	0.055
sum		1	1	1	1	1
Priority vector X	AX	Average {Ax/x}		λmax	CI = (λmax-n)/(n-1)	CR= CI/RI
0.358	1.958	5.469		5.268	0.0670	0.0598
0.333	1.806	5.420				
0.055	0.266	4.821				
0.157	0.917	5.846				
0.097	0.463	4.784				
Initial investment						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	1	2	3	1	3	7
Catalytic Wet Air Oxidation	1/2	1	1	1/2	3	5
Advance chemical oxidation	1/3	1	1	1/4	1	4
Biological treatment	1	2	4	1	4	9
Microbial Fuel Cell	1/3	1/3	1	1/4	1	2
Pre-treatment technology/philosophy	1/7	1/5	1/4	1/9	1/2	1
sum	3.3	6.5	10.3	3.1	12.5	28.0
Normalized						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology /

						philosophy
Wet Air Oxidation	0.302	0.306	0.293	0.321	0.240	0.250
Catalytic Wet Air Oxidation	0.151	0.153	0.098	0.161	0.240	0.179
Advanced chemical oxidation	0.101	0.153	0.098	0.080	0.080	0.143
Biological treatment	0.302	0.306	0.390	0.321	0.320	0.321
Microbial Fuel Cell	0.101	0.051	0.098	0.080	0.080	0.071
Pre-treatment technology/philosophy	0.043	0.031	0.024	0.036	0.040	0.036
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λ_{max}	$CI = (\lambda_{max} - n)/(n-1)$	CR= CI/RI	
0.285	1.752	6.138	6.115	0.0231	0.0186	
0.163	0.994	6.079				
0.109	0.669	6.136				
0.327	2.011	6.151				
0.080	0.490	6.117				
0.035	0.212	6.071				
Operational cost						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical	Biological treatment	Microbial Fuel Cell	Pre-treatment technology

			oxidatio n			logy/ philos ophy
Wet Air Oxidation	1	2	4	5	6	3
Catalytic Wet Air Oxidation	1/2	1	1	2	3	2
Advance chemical oxidation	1/4	1	1	4	2	1
Biological treatment	1/5	1/2	1/4	1	1	1/5
Microbial Fuel Cell	1/6	1/3	1/2	1	1	1/4
Pre-treatment technology/ philosophy	1/3	1/2	1	5	4	1
sum	2.5	5.3	7.8	18.0	17.0	7.5
Normalized						
	Wet Air Oxidati on	Cataly tic Wet Air Oxidat ion	Advanc e chemica l oxidatio n	Biologic al treatmen t	Microbial Fuel Cell	Pre- treatment technolog y/ philosoph y
Wet Air Oxidation	0.408	0.375	0.516	0.278	0.353	0.403
Catalytic Wet Air Oxidation	0.204	0.188	0.129	0.111	0.176	0.268
Advance chemical oxidation	0.102	0.188	0.129	0.222	0.118	0.134
Biological treatment	0.082	0.094	0.032	0.056	0.059	0.027
Microbial Fuel Cell	0.068	0.063	0.065	0.056	0.059	0.034
Pre- treatment technology/ philosophy	0.136	0.094	0.129	0.278	0.235	0.134
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	$\lambda_{\max}$	CI = $(\lambda_{\max}$ - n)/(n-1)	CR= CI/RI	
0.389	2.480	6.378	6.281	0.0562	0.0453	
0.179	1.146	6.385				
0.149	0.940	6.318				
0.058	0.354	6.080				

0.057	0.356	6.232				
0.168	1.055	6.292				
Environmental impact and safety concerns						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	1	1/2	1/5	4	3	1/2
Catalytic Wet Air Oxidation	2	1	1/3	3	2	1/2
Advance chemical oxidation	5	3	1	5	3	1
Biological treatment	1/4	1/3	1/5	1	2	1/3
Microbial Fuel Cell	1/3	1/2	1/3	1/2	1	1/2
Pre-treatment technology/philosophy	2	2	1	3	2	1
sum	10.6	7.3	3.1	16.5	13.0	3.8
Normalized						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.094	0.068	0.065	0.242	0.231	0.130
Catalytic Wet Air Oxidation	0.189	0.136	0.109	0.182	0.154	0.130
Advance chemical oxidation	0.472	0.409	0.326	0.303	0.231	0.261
Biological treatment	0.024	0.045	0.065	0.061	0.154	0.087
Microbial Fuel Cell	0.031	0.068	0.109	0.030	0.077	0.130

Pre-treatment technology/ philosophy	0.189	0.273	0.326	0.182	0.154	0.261
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)	CR= CI/RI	
0.139	0.909	6.560	6.522	0.1043	0.0841	
0.150	1.020	6.801				
0.334	2.294	6.873				
0.073	0.450	6.191				
0.074	0.458	6.167				
0.231	1.508	6.537				
Materials availability						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/ philosophy
Wet Air Oxidation	1	6	5	4	4	9
Catalytic Wet Air Oxidation	1/6	1	3	2	2	1
Advance chemical oxidation	1/5	1/3	1	2	2	1
Biological treatment	1/4	1/2	1/2	1	1	1/3
Microbial Fuel Cell	1/4	1/2	1/2	1	1	1/3
Pre-treatment technology/ philosophy	1/9	1	1	3	3	1
sum	2.0	9.3	11.0	13.0	13.0	12.7
Normalized						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/ philosophy
Wet Air Oxidation	0.506	0.643	0.455	0.308	0.308	0.711

Catalytic Wet Air Oxidation	0.084	0.107	0.273	0.154	0.154	0.079
Advance chemical oxidation	0.101	0.036	0.091	0.154	0.154	0.079
Biological treatment	0.126	0.054	0.045	0.077	0.077	0.026
Microbial Fuel Cell	0.126	0.054	0.045	0.077	0.077	0.026
Pre-treatment technology/philosophy	0.056	0.107	0.091	0.231	0.231	0.079
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)		CR= CI/RI
0.488	3.584	7.341	6.519	0.1039	0.0838	
0.142	0.933	6.581				
0.102	0.650	6.349				
0.068	0.423	6.265				
0.068	0.423	6.265				
0.132	0.836	6.315				
Treatment benefit						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	1	1	1	1	1/9	1
Catalytic Wet Air Oxidation	1	1	1	1	1/9	1
Advance chemical oxidation	1	1	1	1	1/9	1
Biological treatment	1	1	1	1	1/9	1
Microbial Fuel Cell	9	9	9	9	1	1
Pre-treatment technology/philosophy	1	1	1	1	1	1

sum	14.0	14.0	14.0	14.0	2.4	6.0
Normalized						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.071	0.071	0.071	0.071	0.045	0.167
Catalytic Wet Air Oxidation	0.071	0.071	0.071	0.071	0.045	0.167
Advanced chemical oxidation	0.071	0.071	0.071	0.071	0.045	0.167
Biological treatment	0.071	0.071	0.071	0.071	0.045	0.167
Microbial Fuel Cell	0.643	0.643	0.643	0.643	0.409	0.167
Pre-treatment technology/philosophy	0.071	0.071	0.071	0.071	0.409	0.167
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λ_{max}	CI = $(\lambda_{max} - n)/(n-1)$	CR= CI/RI	
0.083	0.534	6.433	6.611	0.1222	0.0985	
0.083	0.534	6.433				
0.083	0.534	6.433				
0.083	0.534	6.433				
0.525	3.655	6.968				
0.144	1.000	6.965				

Table (33): Participant no.4 AHP result

A					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit

					ef it	
Initial investment cost	1	1/5	1/3	1	1	
Operational cost	5	1	1/3	3	1	
Environmental impact and safety concerns	3	3	1	3	1	
Materials availability	1	1/3	1/3	1	1/3	
Treatment benefit	1	1	1	3	1	
sum	11.0	5.5	3.0	11.0	4.3	
Normalized A						
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit	
Initial investment cost	0.091	0.036	0.111	0.091	0.231	
Operational cost	0.455	0.181	0.111	0.273	0.231	
Environmental impact and safety concerns	0.273	0.542	0.333	0.273	0.231	
Materials availability	0.091	0.060	0.111	0.091	0.077	
Treatment benefit	0.091	0.181	0.333	0.273	0.231	
sum	1	1	1	1	1	
Priority vector X	AX	Average {Ax/x }	λmax	CI = (λmax-n)/(n-1)	CR= CI/RI	
0.112	0.580	5.178		0.1107	0.0988	
0.250	1.400	5.599				
0.330	1.896	5.739				
0.086	0.465	5.410				
0.222	1.172	5.287				
			5.443			
Initial investment cost						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	1	5	3	1/5	1/5	1

Catalytic Wet Air Oxidation	1/5	1	1/3	1/5	1/5	1
Advanced chemical oxidation	1/3	3	1	1/5	1/5	1
Biological treatment	5	5	5	1	3	3
Microbial Fuel Cell	5	5	5	1/3	1	3
Pre-treatment technology / philosophy	1	1	1	1/3	1/3	1
sum	12.5	20.0	15.3	2.3	4.9	10.0
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.080	0.250	0.196	0.088	0.041	0.100
Catalytic Wet Air Oxidation	0.016	0.050	0.022	0.088	0.041	0.100
Advanced chem	0.027	0.150	0.065	0.088	0.041	0.100

ical oxida tion						
Biolo gical treat ment	0.399	0.250	0.326	0.441	0.608	0.300
Micr obial Fuel Cell	0.399	0.250	0.326	0.147	0.203	0.300
Pre- treat ment techn ology / philo sophy	0.080	0.050	0.065	0.147	0.068	0.100
sum	1	1	1	1	1	1
Priori ty vector X	AX	Average {Ax/x}		$\lambda_{\max}$	CI = ($\lambda_{\max}$ -n)/(n-1)	CR= CI/RI
0.126	0.841	6.693			0.1308	0.1055
0.053	0.321	6.078				
0.078	0.495	6.313				
0.387	2.739	7.070				
0.271	1.939	7.161				
0.085	0.561	6.607				
				6.654		
Operational cost						
A						
		Wet Air Oxidati on	Catalyt ic Wet Air Oxidat ion	Advan ce chemi cal oxidat ion	Biological treatment	Microbial Fuel Cell
						Pre- treat ment techn ology / philos ophy
Wet Air Oxidation		1	1/5	1/3	1/5	1/5
Catalytic Wet Air Oxidation		5	1	1	1/5	1/5
Advance chemical oxidation		3	1	1	1/5	1/5

Biological treatment	5	5	5	1	3	5
Microbial Fuel Cell	5	5	5	1/3	1	3
Pre-treatment technology/philosophy	1	1	1	1/5	1/3	1
sum	20.0	13.2	13.3	2.1	4.9	12.0
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.050	0.015	0.025	0.094	0.041	0.083
Catalytic Wet Air Oxidation	0.250	0.076	0.075	0.094	0.041	0.083
Advanced chemical oxidation	0.150	0.076	0.075	0.094	0.041	0.083
Biological treatment	0.250	0.379	0.375	0.469	0.608	0.417
Microbial Fuel Cell	0.250	0.379	0.375	0.156	0.203	0.250
Pre-treatment technology/philosophy	0.050	0.076	0.075	0.094	0.068	0.083
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)		CR= CI/RI
0.051	0.312	6.081		0.0998		0.0805
0.103	0.657	6.376				
0.086	0.555	6.419				
0.416	2.798	6.721				
0.269	1.834	6.823				
0.074	0.488	6.571				
			6.499			
Environmental impact and safety concerns						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy

Wet Air Oxidation	1	1/3	1/3	1/7	1/5	1
Catalytic Wet Air Oxidation	3	1	1/3	1/7	1/7	1/3
Advance chemical oxidation	3	3	1	1/7	1/7	1
Biological treatment	7	7	7	1	1	3
Microbial Fuel Cell	5	7	7	1	1	3
Pre-treatment technology/philosophy	1	3	1	1/3	1/3	1
sum	20.0	21.3	16.7	2.8	2.8	9.3
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.050	0.016	0.020	0.052	0.071	0.107
Catalytic Wet Air Oxidation	0.150	0.047	0.020	0.052	0.051	0.036
Advance chemical oxidation	0.150	0.141	0.060	0.052	0.051	0.107
Biological treatment	0.350	0.328	0.420	0.362	0.355	0.321
Microbial Fuel Cell	0.250	0.328	0.420	0.362	0.355	0.321
Pre-treatment technology/philosophy	0.050	0.141	0.060	0.121	0.118	0.107
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}		λ_{max}	CI = $(\lambda_{max}-n)/(n-1)$	CR = CI/RI
0.053	0.32	6.117			0.1175	0.0947

0.059	0.3 8	6.431				
0.093	0.6 3	6.720				
0.356	2.4 3	6.823				
0.339	2.3 2	6.849				
0.099	0.6 5	6.583				
			6.58 7			
Materials availability						
A						
	Wet Air Oxidatio n	Catalytic Wet Air Oxidatio n	Advance chemical oxidatio n	Biologica l treatment	Microbia l Fuel Cell	Pre- treatment technology / philosophy
Wet Air Oxidation	1	1/5	1/3	1/5	1/5	1/3
Catalytic Wet Air Oxidation	5	1	1/3	1/7	1/4	1/2
Advance chemical oxidation	3	3	1	1/5	1/5	1/3
Biological treatment	5	7	5	1	1	3
Microbial Fuel Cell	5	4	5	1	1	3
Pre- treatment technology / philosophy	3	2	3	1/3	1/3	1
sum	22.0	17.2	14.7	2.9	3.0	8.2
Normalized A						
	Wet Air Oxidati on	Catalyti c Wet Air Oxidati on	Advanc e chemic al oxidati on	Biologic al treatmen t	Microbial Fuel Cell	Pre- treatment technolog y/ philosoph y
Wet Air Oxidation	0.045	0.012	0.023	0.070	0.067	0.041
Catalytic Wet Air Oxidation	0.227	0.058	0.023	0.050	0.084	0.061

Advance chemical oxidation	0.136	0.174	0.068	0.070	0.067	0.041	
Biological treatment	0.227	0.407	0.341	0.348	0.335	0.367	
Microbial Fuel Cell	0.227	0.233	0.341	0.348	0.335	0.367	
Pre-treatment technology/philosophy	0.136	0.116	0.205	0.116	0.112	0.122	
sum	1	1	1	1	1	1	
Priority vector X		AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)	CR= CI/RI	
0.043	0.264596187		6.173		0.1262	0.10	
0.084	0.52166746		6.225				
0.093	0.646802203		6.975				
0.338	2.314291121		6.856				
0.308	2.06287523		6.687				
0.135	0.92428583		6.870				
				6.631			
Treatment benefit							
A							
		Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation		1	1	3	3	3	1/3
Catalytic Wet Air Oxidation		1	1	3	3	3	1/3
Advance chemical oxidation		1/3	1/3	1	1/3	1/3	1/3
Biological treatment		1/3	1/3	3	1	3	1/3
Microbial Fuel Cell		1/3	1/3	3	1/3	1	1/3
Pre-treatment technology/philosophy		3	3	3	3	3	1
sum		6.0	6.0	16.0	10.7	13.3	2.7
Normalized A							

	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology/philosophy
Wet Air Oxidation	0.167	0.167	0.188	0.281	0.225	0.125
Catalytic Wet Air Oxidation	0.167	0.167	0.188	0.281	0.225	0.125
Advance chemical oxidation	0.056	0.056	0.063	0.031	0.025	0.125
Biological treatment	0.056	0.056	0.188	0.094	0.225	0.125
Microbial Fuel Cell	0.056	0.056	0.188	0.031	0.075	0.125
Pre-treatment technology/philosophy	0.500	0.500	0.188	0.281	0.225	0.375
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λ_{max}	CI = $(\lambda_{max}-n)/(n-1)$	CR= CI/RI	
0.192	1.3 13	6.835		0.1147	0.0925	
0.192	1.3 13	6.835				
0.059	0.3 73	6.303				
0.124	0.8 09	6.539				
0.088	0.5 50	6.227				
0.345	2.3 10	6.701				
			6.57 3			

Table (34): Participant no.5 AHP result

A					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit

Initial investment cost	1	1	9	9	9	
Operational cost	1	1	9	8	8	
Environmental impact and safety concerns	1/9	1/9	1	1/9	9	
Materials availability	1/9	1/8	9	1	9	
Treatment benefit	1/9	1/8	1/9	1/9	1	
sum	2.3	2.4	28.1	18.2	36.0	
Normalized A						
Criteria	Initial invest ment cost	Operatio nal cost	Environ mental impact and safety concern s	Materials availability	Treatment benefit	
Initial investment cost	0.429	0.424	0.320	0.494	0.250	
Operational cost	0.429	0.424	0.320	0.439	0.222	
Environmental impact and safety concerns	0.048	0.047	0.036	0.006	0.250	
Materials availability	0.048	0.053	0.320	0.055	0.250	
Treatment benefit	0.048	0.053	0.004	0.006	0.028	
sum	1	1	1	1	1	
Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)	CR= CI/RI	
0.383	3.001	7.830		0.4628	0.4133	
0.367	2.828	7.711				
0.077	0.426	5.511				
0.145	1.178	8.118				
0.028	0.141	5.087				
			6.851			
CR>0.1			Invalid entry			
Initial investment cost						
A						
	Wet Air Oxidat ion	Catalyti c Wet Air Oxidati on	Advan ce chemic al oxidati on	Biological treatment	Microbial Fuel Cell	Pre-treat ment techn ology / philo soph y
Wet Air Oxidation	1	1/3	1/3	1/5	1/5	1/7
Catalytic Wet Air Oxidation	3	1	1/2	1/5	1/5	1/5

Advance chemical oxidation	3	2	1	1/5	1/5	1/5
Biological treatment	5	5	5	1	1/5	5
Microbial Fuel Cell	5	5	5	5	1	1/5
Pre-treatment technology/ philosophy	7	5	5	1/5	5	1
sum	24.0	18.3	16.8	6.8	6.8	6.7
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology / philosophy
Wet Air Oxidation	0.042	0.018	0.020	0.029	0.029	0.021
Catalytic Wet Air Oxidation	0.125	0.055	0.030	0.029	0.029	0.030
Advance chemical oxidation	0.125	0.109	0.059	0.029	0.029	0.030
Biological treatment	0.208	0.273	0.297	0.147	0.029	0.742
Microbial Fuel Cell	0.208	0.273	0.297	0.735	0.147	0.030
Pre-treatment technology/ philosophy	0.292	0.273	0.297	0.029	0.735	0.148
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	$\lambda_{\max}$	CI = ($\lambda_{\max}$ -n)/(n-1)	CR= CI/RI	
0.027	0.219	8.249	7.932	0.3865	0.3117	
0.050	0.333	6.717				
0.064	0.415	6.515				
0.283	2.517	8.905				
0.282	2.454	8.711				
0.296	2.513	8.499				
CR>0.1				Invalid entry		
Operational cost						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical	Biological treatment	Microbial Fuel Cell	Pre-treatment technology

			oxidati on			/ philo soph y
Wet Air Oxidation	1	1/5	1/5	1/5	1/5	1/7
Catalytic Wet Air Oxidation	5	1	1/2	1/7	1/7	1/5
Advance chemical oxidation	5	2	1	1/7	1/7	1/7
Biological treatment	5	7	7	1	1	5
Microbial Fuel Cell	5	7	7	1	1	1
Pre-treatment technology/ philosophy	7	5	7	1/5	1	1
sum	28.0	22.2	22.7	2.7	3.5	7.5
Normalized A						
	Wet Air Oxidat ion	Catalyti c Wet Air Oxidati on	Advan ce chemic al oxidati on	Biological treatment	Microbial Fuel Cell	Pre-treat ment techn ology / philosoph y
Wet Air Oxidation	0.036	0.009	0.009	0.074	0.057	0.019
Catalytic Wet Air Oxidation	0.179	0.045	0.022	0.053	0.041	0.027
Advance chemical oxidation	0.179	0.090	0.044	0.053	0.041	0.019
Biological treatment	0.179	0.315	0.308	0.372	0.287	0.668
Microbial Fuel Cell	0.179	0.315	0.308	0.372	0.287	0.134
Pre-treatment technology/ philosophy	0.250	0.225	0.308	0.074	0.287	0.134
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λ_{max}	CI = (λ_{max} - n)/(n-1)	CR= CI/RI	
0.034	0.215	6.312	7. 031	0.2062	0.1663	
0.061	0.398	6.519				
0.071	0.483	6.799				
0.355	2.781	7.836				
0.266	1.929	7.255				
0.213	1.591	7.466				
CR>0.1				Invalid entry		

Environmental impact and safety concerns						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology / philosophy
Wet Air Oxidation	1	1/5	1/4	1/5	1/5	1/5
Catalytic Wet Air Oxidation	5	1	1/5	1/5	1/5	1/5
Advanced chemical oxidation	4	5	1	1	1	1/5
Biological treatment	5	5	1	1	1	1/3
Microbial Fuel Cell	5	5	1	1	1	1/3
Pre-treatment technology/philosophy	5	5	5	3	3	1
sum	25.0	21.2	8.5	6.4	6.4	2.3
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology / philosophy
Wet Air Oxidation	0.040	0.009	0.030	0.031	0.031	0.088
Catalytic Wet Air Oxidation	0.200	0.047	0.024	0.031	0.031	0.088
Advanced chemical oxidation	0.160	0.236	0.118	0.156	0.156	0.088
Biological treatment	0.200	0.236	0.118	0.156	0.156	0.147
Microbial Fuel Cell	0.200	0.236	0.118	0.156	0.156	0.147
Pre-treatment technology/philosophy	0.200	0.236	0.592	0.469	0.469	0.441
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	$\lambda_{\max}$	CI = $(\lambda_{\max} - n)/(n-1)$	CR= CI/RI	

0.038	0.24	6.222	6. 688	0.1377	0.1110	
0.070	0.44	6.262				
0.152	1.08	7.050				
0.169	1.17	6.906				
0.169	1.17	6.906				
0.401	2.72	6.782				
CR>0.1				Invalid entry		
Materials availability						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology / philosophy
Wet Air Oxidation	1	1/3	1/3	1/2	1/2	1/4
Catalytic Wet Air Oxidation	3	1	1	1	1/4	1/4
Advance chemical oxidation	3	1	1	1	1	1/4
Biological treatment	2	1	1	1	1	1/4
Microbial Fuel Cell	2	4	1	1	1	1/4
Pre-treatment technology/philosophy	4	4	4	4	4	1
sum	15.0	11.3	8.3	8.5	7.8	2.3
Normalized A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advanced chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology / philosophy
Wet Air Oxidation	0.067	0.029	0.040	0.059	0.065	0.111
Catalytic Wet Air Oxidation	0.200	0.088	0.120	0.118	0.032	0.111
Advance chemical oxidation	0.200	0.088	0.120	0.118	0.129	0.111
Biological treatment	0.133	0.088	0.120	0.118	0.129	0.111

Microbial Fuel Cell	0.133	0.353	0.120	0.118	0.129	0.111
Pre-treatment technology/ philosophy	0.267	0.353	0.480	0.471	0.516	0.444
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	λmax	CI = (λmax-n)/(n-1)		CR= CI/RI
0.062	0.3855 59889	6.243	6.387	0.0774	0.06	
0.112	0.6866 55422	6.156				
0.128	0.8071 63539	6.322				
0.117	0.7454 08672	6.395				
0.161	1.0800 34437	6.722				
0.422	2.7346 15222	6.483				
CR>0.1				Invalid entry		
Treatment benefit						
A						
	Wet Air Oxidation	Catalytic Wet Air Oxidation	Advance chemical oxidation	Biological treatment	Microbial Fuel Cell	Pre-treatment technology / philosophy
Wet Air Oxidation	1	1	7	5	5	5
Catalytic Wet Air Oxidation	1	1	5	5	5	5
Advance chemical oxidation	1/7	1/5	1	5	1/4	1/4
Biological treatment	1/5	1/5	1/5	1	1/4	1
Microbial Fuel Cell	1/5	1/5	4	4	1	5
Pre-treatment technology/ philosophy	1/5	1/5	4	1	1/5	1
sum	2.7	2.8	21.2	21.0	11.7	17.3
Normalized A						
	Wet Air	Catalytic Wet Air	Advance chemical	Biological treatment	Microbial Fuel Cell	Pre-treatment

	Oxidat ion	Oxidati on	al oxidati on			techn ology / philo soph y
Wet Air Oxidation	0.365	0.357	0.330	0.238	0.427	0.290
Catalytic Wet Air Oxidation	0.365	0.357	0.236	0.238	0.427	0.290
Advance chemical oxidation	0.052	0.071	0.047	0.238	0.021	0.014
Biological treatment	0.073	0.071	0.009	0.048	0.021	0.058
Microbial Fuel Cell	0.073	0.071	0.189	0.190	0.085	0.290
Pre-treatment technology/ philosophy	0.073	0.071	0.189	0.048	0.017	0.058
sum	1	1	1	1	1	1
Priority vector X	AX	Average {Ax/x}	$\lambda_{\max}$	CI = ($\lambda_{\max}$ - n)/(n-1)	CR= CI/RI	
0.335	2.535	7.577	7. 215	0.2430	0.1959	
0.319	2.387	7.486				
0.074	0.476	6.424				
0.047	0.306	6.533				
0.150	1.144	7.635				
0.076	0.580	7.634				
CR>0.1				Invalid entry		

Table (35): Participant no.6 AHP result

A					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	1	5	6	5	1/3
Operational cost	1/5	1	9	9	9
Environmental impact and safety concerns	1/6	1/9	1	1	1/6
Materials availability	1/5	1/9	1	1	1
Treatment benefit	3	1/9	6	1	1
sum	4.6	6.3	23.0	17.0	11.5
Normalized					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit

Initial investment cost			0.219	0.789	0.261	0.294	0.029
Operational cost			0.044	0.158	0.391	0.529	0.783
Environmental impact and safety concerns			0.036	0.018	0.043	0.059	0.014
Materials availability			0.044	0.018	0.043	0.059	0.087
Treatment benefit			0.657	0.018	0.261	0.059	0.087
sum			1	1	1	1	1
Priority vector X	AX	Average {A _x /x}	$\lambda_{\max}$		CI = $(\lambda_{\max}$ -n)/(n-1)		CR= CI/RI
0.318	2.751	8.638			0.6562	0.5859	
0.381	3.149	8.266	7.625				
0.034	0.216	6.314					
0.050	0.407	8.111					
0.216	1.469	6.794					
CR>0.1			Invalid entry				

Table (36): Participant no.7 AHP result

A					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	1	1/7	7	1	1/5
Operational cost	7	1	3	8	8
Environmental impact and safety concerns	1/7	1/3	1	3	5
Materials availability	1	1/8	0.3333333333	1	1/3
Treatment benefit	5	1/8	1/5	3	1
sum	14.1	1.7	11.5	16.0	14.5
Normalized					
Criteria	Initial investment cost	Operational cost	Environmental impact and safety concerns	Materials availability	Treatment benefit
Initial investment cost	0.071	0.083	0.607	0.063	0.014
Operational cost	0.495	0.579	0.260	0.500	0.550
Environmental impact and safety concerns	0.010	0.193	0.087	0.188	0.344
Materials availability	0.071	0.072	0.029	0.063	0.023

Treatment benefit			0.354	0.072	0.017	0.188	0.069
sum			1	1	1	1	1
Priority vector X	AX	Average {A _x /x}	$\lambda_{\max}$		CI = ($\lambda_{\max}$ -n)/(n-1)	CR= CI/RI	
0.167	1.465	8.755	7.978		0.7444	0.6646	
0.477	3.672	7.700					
0.164	1.201	7.312					
0.051	0.380	7.377					
0.140	1.224	8.745					
CR>0.1			Invalid entry				

Appendix 3

A3-1 Lab analysis results

1- CGP-I weathering pit -2014



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Geotechnical Engineering Services - Material Testing - Chemical Analysis - NDT Services - Calibration

Test Report - Chemical Analysis of Water				Page No. 1 of 2
Test Method: APHA				
Customer / Contractor	Banagas	Report No. / Ref. No.	ILS/12/2014/5617	
Address	Al-Shakeer - Bahrain	Report Date	12-01-2015	
Project Name	-	Date of sample receipt	22-12-2014	
Sample description	Waste water	Sample Id. No.	-	
Source / Location	CGP- Pit-1	Date of test	23-12-2014	
Condition of sample on receipt	Satisfactory	P.O.Number	LPO14/1225	
Parameter	Units	Test Method	Test Results	
PHYSICAL				
Floating Particles	mg/l	APHA 2530	Nil	
pH @ 25°C	-	APHA 4500-H ⁺	10.62	
Temperature°C (as received)	°C	APHA 2550	28.2	
Total Suspended Solids (TSS)	mg/l	APHA 2540 D	38.00	
Turbidity	NTU	APHA 2130	29.00	
INORGANIC				
Ammonical Nitrogen as N	mg/l	APHA 4500 NH ₃	12.750	
Nitrate as NO ₃ - N	mg/l	APHA 4500 NO ₃ ⁻	24.200	
Nitrite as NO ₂ - N	mg/l	APHA 4500 NO ₂ ⁻	18.400	
Sulfide as H ₂ S	mg/l	APHA 4500 S ²⁻	5.600	
Chlorine Residual	mg/l	APHA 4500 Cl ₂	1.400	
Cyanide ,CN ⁻	mg/l	APHA 4500 CN ⁻	<0.01	
Total Phosphate	mg/l	APHA 4500 P	19.600	
ORGANIC POLLUTANTS				
Biochemical Oxygen Demand,BOD,5days	mg/l	APHA 5210 B	5220.000	
Chemical Oxygen Demand,COD	mg/l	APHA 5220 C	4960.000	
Total Nitrogen	mg/l	APHA 4500 N _{Org}	110.000	
Total Organic Carbon,TOC	mg/l	APHA 5310	1210.000	
Fluorescent Petroleum Matter	mg/l	APHA 5520 F	<0.001	
Oil & Grease	mg/l	APHA 5520	<1.0	
Phenol	mg/l	APHA 5530	<0.01	

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Test Report - Chemical Analysis of Water			Page No. 2 of 2
Test Method: APHA			
Customer / Contractor	Banagas	Report No. / Ref. No.	ILS/12/2014/5617
Address	Al-Shakeer- Bahrain	Report Date	12-01-2015
Project Name	-	Date of sample receipt	22-12-2014
Sample description	Waste water	Sample Id. No.	-
Source / Location	CGP- Pit-1	Date of test	23-12-2014
Condition of sample on receipt	Satisfactory	P.O.Number	LPO14/1225
Parameter	Units	Test Method	Test Results
TRACE METALS			
Aluminum (Al)	mg/l	APHA 3125	<0.001
Cadmium (Cd)	mg/l	APHA 3125	<0.001
Total Chromium (Cr)	mg/l	APHA 3125	<0.001
Copper (Cu)	mg/l	APHA 3125	<0.001
Iron (Fe)	mg/l	APHA 3125	0.085
Lead (Pb)	mg/l	APHA 3125	<0.001
Mercury (Hg)	mg/l	APHA 3125	<0.001
Nickel (Ni)	mg/l	APHA 3125	0.195
Zinc (Zn)	mg/l	APHA 3125	0.400
Arsenic (As)	mg/l	APHA 3125	<0.001
OTHER PARAMETERS			
Total Coliforms	CFU/100 ml	APHA 9222	70.000
Remarks			
1. Test results relates to the sample tested only.			
2. Test Report shall not be reproduced except in full, without written approval of the Laboratory.			
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		 Christy Nicholas Laboratory Incharge Verified by	

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2- CGP-II weathering pit -2014



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Test Report - Chemical Analysis of Water			Page No. 1 of 2
Test Method: APHA			
Customer / Contractor	Banagas	Report No. / Ref. No.	ILS/12/2014/5616
Address	Al-Shakeer - Bahrain	Report Date	12-01-2015
Project Name	-	Date of sample receipt	22-12-2014
Sample description	Waste water	Sample Id. No.	-
Source / Location	CGP- Pit-2	Date of test	23-12-2014
Condition of sample on receipt	Satisfactory	P.O.Number	LPO14/1225
Parameter	Units	Test Method	Test Results
PHYSICAL			
Floating Particles	mg/l	APHA 2530	Nil
pH @ 25°C	-	APHA 4500-H ⁺	12.96
Temperature°C (as received)	°C	APHA 2550	28.0
Total Suspended Solids (TSS)	mg/l	APHA 2540 D	49.00
Turbidity	NTU	APHA 2130	21.00
INORGANIC			
Ammonical Nitrogen as N	mg/l	APHA 4500 NH ₃	8.900
Nitrate as NO ₃ - N	mg/l	APHA 4500 NO ₃ ⁻	45.000
Nitrite as NO ₂ - N	mg/l	APHA 4500 NO ₂ ⁻	20.000
Sulfide as H ₂ S	mg/l	APHA 4500 S ²⁻	6.800
Chlorine Residual	mg/l	APHA 4500 Cl ₂	1.800
Cyanide ,CN ⁻	mg/l	APHA 4500 CN ⁻	<0.01
Total Phosphate	mg/l	APHA 4500 P	43.200
ORGANIC POLLUTANTS			
Biochemical Oxygen Demand,BOD,5days	mg/l	APHA 5210 B	7280.000
Chemical Oxygen Demand,COD	mg/l	APHA 5220 C	7588.800
Total Nitrogen	mg/l	APHA 4500 N _{Org}	380.000
Total Organic Carbon,TOC	mg/l	APHA 5310	860.000
Fluorescent Petroleum Matter	mg/l	APHA 5520 F	<0.001
Oil & Grease (Hexane extract)	mg/l	APHA 5520	<1.0
Phenol (Chloroform extract)	mg/l	APHA 5530	<0.01

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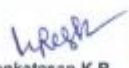
Test Report - Chemical Analysis of Water			Page No. 2 of 2
Test Method: APHA			
Customer / Contractor	Banagas	Report No. / Ref. No.	ILS/12/2014/5616
Address	Al-Shakeer - Bahrain	Report Date	12-01-2015
Project Name	-	Date of sample receipt	22-12-2014
Sample description	Waste water	Sample Id. No.	-
Source / Location	CGP- Pit-2	Date of test	23-12-2014
Condition of sample on receipt	Satisfactory	P.O.Number	LPO14/1225
Parameter	Units	Test Method	Test Results
TRACE METALS			
Aluminum (Al)	mg/l	APHA 3125	1.416
Cadmium (Cd)	mg/l	APHA 3125	0.360
Total Chromium (Cr)	mg/l	APHA 3125	<0.001
Copper (Cu)	mg/l	APHA 3125	<0.001
Iron (Fe)	mg/l	APHA 3125	0.132
Lead (Pb)	mg/l	APHA 3125	<0.001
Mercury (Hg)	mg/l	APHA 3125	<0.001
Nickel (Ni)	mg/l	APHA 3125	2.622
Zinc (Zn)	mg/l	APHA 3125	0.876
Arsenic (As)	mg/l	APHA 3125	<0.001
OTHER PARAMETERS			
Total Coliforms	CFU/100 ml	APHA 9222	Nil
Remarks			
1. Test results relates to the sample tested only.			
2. Test Report shall not be reproduced except in full, without written approval of the Laboratory.			
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3- CGP-I weathering pit -2020



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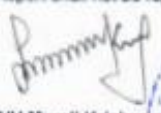
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Test Report: Chemical Analysis of Water			Page 1 of 2
Customer	Banagas	Report No.	ILS/10/2020/4761
Address	-	Report Date	13-10-2020
Project	CGP-1 & 2 Pit Water Testing	Date of Test	06-10-2020
Sample	Waste Water	Date of Receipt	05-10-2020
Source	Banagas - Weathering Pits	Date Sampled	05-10-2020
Location	CGP Pit - 1	Sample Id. No.	-
Sampling method	APHA	Sampled by	ILS
Condition of sample on receipt	Satisfactory	Consultant	Not Mentioned
Test Parameter	Units	Test Method	Result
PHYSICAL			
Floating Particles	mg/l	APHA 2530	NIL
pH @ 25°C	-	APHA 4500-H ⁺	12.01
Temperature (as received)	°C	APHA 2550	34.1
Total Suspended Solids (TSS)	mg/l	APHA 2540 D	89
Turbidity (NTU)	NTU	APHA 2130	40.3
INORGANIC			
Ammonical Nitrogen as N	mg/l	APHA 4500 NH ₃	4.8
Nitrate as NO ₃ - N	mg/l	APHA 4500 NO ₃ ⁻	36.3
Nitrite as NO ₂ - N	mg/l	APHA 4500 NO ₂ ⁻	32.1
Sulfide as H ₂ S	mg/l	APHA 4500 S ²⁻	6.3
Chlorine Residual	mg/l	APHA 4500 Cl	NIL
Cyanide, CN ⁻	mg/l	APHA CN ⁻	<0.01
Total Phosphate (TP)	mg/l	APHA 4500 P	27.6
INORGANIC POLLUTANTS			
Biochemical Oxygen Demand, (BOD) 5days	mg/l	APHA 5210 B	8855
Chemical Oxygen Demand (COD)	mg/l	APHA 5220 C	9100
Total Kjeldhal Nitrogen (TKN)	mg/l	APHA 4500 N _{org}	49.4
Total Organic Carbon (TOC)	mg/l	APHA 5310	2690
Fluorescent Petroleum Matter	mg/l	APHA 5520 F	<0.02
Oil & Grease (Hexane extract)	mg/l	APHA 5520	<1
Phenol (Chloroform extract)	mg/l	APHA 5530	<0.01
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Test Report: Chemical Analysis of Water			Page 2 of 2
Customer	Banagas	Report No.	ILS/10/2020/4761
Address	-	Report Date	13-10-2020
Project	CGP-1 & 2 Pit Water Testing	Date of Test	06-10-2020
Sample	Waste Water	Date of Receipt	05-10-2020
Source	Banagas - Weathering Pits	Date Sampled	05-10-2020
Location	CGP Pit - 1	Sample Id. No.	-
Sampling method	APHA	Sampled by	ILS
Condition of sample on receipt	Satisfactory	Consultant	Not Mentioned
Test Parameter	Units	Test Method	Result
TRACE METALS			
Aluminium (Al)	mg/l	APHA 3125	0.082
Cadmium (Cd)	mg/l	APHA 3125	0.301
Total Chromium (Cr)	mg/l	APHA 3125	0.63
Copper (Cu)	mg/l	APHA 3125	0.32
Iron (Fe)	mg/l	APHA 3125	0.90
Lead (Pb)	mg/l	APHA 3125	0.144
Mercury (Hg)	mg/l	APHA 3125	<0.002
Nickel (Ni)	mg/l	APHA 3125	0.124
Zinc (Zn)	mg/l	APHA 3125	0.80
Arsenic (As)	mg/l	APHA 3125	<0.01
OTHER PARAMETERS			
Total Coliform Count (MPN)	MPN	APHA 9222	81
Remarks:			
1. Test results relate to the sample tested only.			
2. Test Report shall not be reproduced, except in full, without the written approval of the Laboratory.			
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Test Report: Chemical Analysis of Water				Page 1 of 2
Customer	Banagas	Report No.	ILS/10/2020/4762	
Address	-	Report Date	13-10-2020	
Project	CGP-1 & 2 Pit Water Testing	Date of Test	06-10-2020	
Sample	Waste Water	Date of Receipt	05-10-2020	
Source	Banagas - Weathering Pits	Date Sampled	05-10-2020	
Location	CGP Pit - 2	Sample Id. No.	-	
Sampling method	APHA	Sampled by	ILS	
Condition of sample on receipt	Satisfactory	Consultant	Not Mentioned	
Test Parameter	Units	Test Method	Result	
PHYSICAL				
Floating Particles	mg/l	APHA 2530	NIL	
pH @ 25°C	-	APHA 4500-H ⁺	12.14	
Temperature (as received)	°C	APHA 2550	34.2	
Total Suspended Solids (TSS)	mg/l	APHA 2540 D	67.4	
Turbidity (NTU)	NTU	APHA 2310	18.6	
INORGANIC				
Ammonical Nitrogen as N	mg/l	APHA 4500 NH ₃	3.4	
Nitrate as NO ₃ - -N	mg/l	APHA 4500 NO ₃	21.8	
Nitrite as NO ₂ - -N	mg/l	APHA 4500 NO ₂	17.2	
Sulfide as H ₂ S	mg/l	APHA 4500 S ²⁻	4.1	
Chlorine Residual	mg/l	APHA 4500 Cl	NIL	
Cyanide (CN)	mg/l	APHA CN	<0.01	
Total Phosphate (TP)	mg/l	APHA 4500 P	14.1	
INORGANIC POLLUTANTS				
Biochemical Oxygen Demand, (BOD) 5days	mg/l	APHA 5210 B	5030	
Chemical Oxygen Demand (COD)	mg/l	APHA 5220 C	5200	
Total Kjeldhal Nitrogen (TKN)	mg/l	APHA 4500 N _{org}	12.9	
Total Organic Carbon (TOC)	mg/l	APHA 5310	785	
Fluorescent Petroleum Matter	mg/l	APHA 5520 F	<0.02	
Oil & Grease (Hexane extract)	mg/l	APHA 5520	<1	
Phenol (Chloroform extract)	mg/l	APHA 5530	<0.01	
1. Test results relate to the sample tested only. 2. Test Report shall not be reproduced, except in full, without the written approval of the Laboratory.				
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Test Report: Chemical Analysis of Water				Page 2 of 2
Customer	Banagas	Report No.	ILS/10/2020/4762	
Address	-	Report Date	13-10-2020	
Project	CGP-1 & 2 Pit Water Testing	Date of Test	06-10-2020	
Sample	Waste Water	Date of Receipt	05-10-2020	
Source	Banagas - Weathering Pits	Date Sampled	05-10-2020	
Location	CGP Pit - 2	Sample Id. No.	-	
Sampling method	APHA	Sampled by	ILS	
Condition of sample on receipt	Satisfactory	Consultant	Not Mentioned	
Test Parameter	Units	Test Method	Result	
TRACE METALS				
Aluminium (Al)	mg/l	APHA 3125	0.044	
Cadmium (Cd)	mg/l	APHA 3125	0.23	
Total Chromium (Cr)	mg/l	APHA 3125	0.29	
Copper (Cu)	mg/l	APHA 3125	0.07	
Iron (Fe)	mg/l	APHA 3125	0.50	
Lead (Pb)	mg/l	APHA 3125	0.118	
Mercury (Hg)	mg/l	APHA 3125	<0.002	
Nickel (Ni)	mg/l	APHA 3125	0.004	
Zinc (Zn)	mg/l	APHA 3125	0.05	
Arsenic (As)	mg/l	APHA 3125	<0.01	
OTHER PARAMETERS				
Total Coliform Count (MPN)	MPN	APHA 9222	72	
Remarks:				
1. Test results relate to the sample tested only.				
2. Test Report shall not be reproduced, except in full, without the written approval of the Laboratory.				
 PVH Murali Krishna Technical Manager Reviewed & Approved By		 Venkatesan K.R. Laboratory Incharge Verified By		

ملخص البحث

تعد عملية معالجة الغاز الطبيعي أمراً في بالغ الأهمية للتخلص من الملوثات التي تؤثر على جودة المنتج النهائي، إذ أنها قد تتسبب بمشاكل خطيرة متعلقة بالسلامة أو البيئة أو الصحة أو العمليات. تختلف أنواع عمليات المعالجة من خطوة واحدة بسيطة إلى خطوات متعددة و معقدة، وذلك بحسب نوع وكمية الملوثات. تستخدم مادة الصودا الكاوية لعملية المعالجة في مصنع البحرين للغاز القديم والذي ينتج منه رائحة كريهة بسبب وجود غاز كبريتيد الهيدروجين ومركبات الكبريت العضوية الأخرى.

يهدف هذا البحث إلى إيجاد أفضل الطرق لمعالجة المحلول الكاوي المستهلك الناتج من عملية تنقية غاز البترول المسال من الكبريت.

لقد طُلب من مختبر تابع لجهة خارجية إجراء تحليل على طريقة الـ APHA لقياس تركيز مكونات المياه الملوثة . كما تم إجراء استبيان وتم تحليل النتائج باستخدام عملية التسلسل الهرمي التحليلي (AHP) لإيجاد أفضل طرق المعالجة. ومن بين معايير النموذج الخمسة (تكلفة الاستثمار الأولية ، والتكاليف التشغيلية ، وتوافر المواد ، والأثر البيئي والمخاوف المتعلقة بالسلامة وفوائد المعالجة). كانت التكاليف (تكاليف الاستثمار الأولي والتكاليف التشغيلية) المعايير السائدة، يليها معيار التأثيرات البيئية والمخاوف المتعلقة بالسلامة. كما تصدرت المعالجة البيولوجية قائمة البدائل للمعايير الثلاثة الأولية وقد تم إثبات كفاءتها اقتصادياً في إزالة مركبات الكبريت.

أستخدم برنامج GRMM / GRAL لنمذجة انبعاث غاز كبريتيد الهيدروجين حيث كانت تركيزات كبريتيد الهيدروجين 30.86 ميكروغرام / م³ و 16.09 ميكروغرام / م³ عند ارتفاع 1.8 متر فوق سطح الأرض وعلى مسافة 21 إلى 27 متراً من منطقة تجمع المياه الملوثة و 6.4 إلى 7 أمتار من منطقة معالجة الكبريت على التوالي حيث أن هذه النتائج تتجاوز الحد القانوني للبحرين 15 ميكروغرام / م³. بحسب مقاييس الصحة المهنية، فقد كانت جميع التركيزات النمذجة أقل من الحدود الخطرة لتأثيرات الصحة المهنية، أي أن التأثير مقتصر على الرائحة الكريهة.

أهم التوصيات المستخلصة من هذه الدراسة هي: اعتماد طريقة المعالجة البيولوجية للمياه الملوثة والتركيز على تقييم تأثير مركبات الكبريت العضوية الأخرى ذوات الروائح.

جامعة البحرين

برنامج البيئة والتنمية المستدامة



كلية العلوم

تقييم طرق معالجة المخلفات السائلة الكاوية المستهلكة الناجمة من عملية تنقية غاز البترول المسال من الكبريت

الاطروحة المقدمة لاستكمال متطلبات الحصول على درجة الماجستير في البيئة والتنمية

المستدامة - مسار علوم البيئة و التطوير

إعداد:

هيفاء عبدالعزيز مرجان

20123692

بإشراف:

د.سعاد أحمد رشدان

أستاذ مساعد (مشرف رئيسي)

و

أ.د.الأمين محمد الكنزي

أستاذ (مشرف مساعد)

جامعة البحرين

مملكة البحرين

يونيو 2022