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BTEX Concentration and Risk Assessment from Biological Activated Sludge in Municipal Wastewater Treatment Plants: Systematic Review

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BTEX CONCENTRATION AND RISK ASSESSMENT FROM BIOLOGICAL ACTIVE SLUDGE IN MUNICIPAL WASTEWATER TREATMENT PLANTS: SYSTEMATIC REVIEW

RESEARCH REPORT

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28 July 2025

DECLARATION

I, Thabiso Jerry Maimela, declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science in Medicine (Exposure Science) of Public Health at the University of the Witwatersrand, Johannesburg, South Africa. It has not been submitted before for any degree or examination at any other University.



_____

Signature

28th day of July 2025 in Johannesburg, South Africa

DEDICATION

I would like to dedicate this piece of my academic work to our late Grandmother, Atiitsa Sarah Maimela, a true leader who raised motivated young men through her fruit business. Her strength and guidance have been a source of inspiration. To my late mother, Masileisi, and my aunt, Meitana Maimela, both of whom had a deep passion for education and ensured that I had the opportunity to attend university, even though they never had such a chance after their matriculation. May their souls rest in eternal peace.

To my wife, Emily Hlokoa-Maimela, you have been a pillar of my strength. Thank you for all your support throughout this journey. You have sacrificed your time and endured loneliness, yet you never deserted me. I love you dearly. To my dearest daughter, Tshegofatso Joy Maimela, thank you, my baby girl, for your unwavering support and love.

To my siblings, Boitumelo, Bradley, and Brett Maimela, thank you so much for your unwavering support. Your encouragement has been invaluable, and I am deeply grateful for each of you.

God has been my constant companion throughout the trials and tribulations of these studies. Without His Love and Wisdom, I would not be where I am today. I am deeply grateful for His guidance and support. Thank you, Dear Lord, for your unwavering presence in my life. Your name deserves to be praised at all times. As James 1:12 says, "Blessed is the one who perseveres under trial because, having stood the test, that person will receive the crown of life that the Lord has promised to those who love him." This verse has been a source of strength and inspiration, reminding me that perseverance through challenges leads to divine rewards.

ACKNOWLEDGEMENT

It is with great sense of humour and pleasure to begin by saluting my Clan “Ditlou tsaga Maimela, bo-Maramanyane, bo-Vuyeye, bo-Vumisa, bo-Atiitsa, bo-Masileisi, bo Meitana le ba-bina Kwena baga Sekonya” for protecting me throughout this journey. (Anon., n.d.)

A man we struggled together, a true patriot, an intellect, fearless academia, unselfish individual, my supervisor Prof Masilu Daniel Masekameni and my co-supervisor Dr Daniel Mmereki, a brilliant, intellect, and specialised in systematic reviews, your support has been immensely valuable.

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Abstract

Background: The municipal wastewater treatment plants are crucial for protecting the environment and the scarce water resource, but they also release volatile organic compounds like BTEX, Benzene (B), Toluene (T), Ethylbenzene (E) and Xylenes (X) during the treatment processes. BTEX emissions poses significant challenges due to their potential to endanger public health and environment, this is because the efficiency of the wastewater treatment plants (WWTP) and quality of influent determines the effluent quality and emissions. In this research report an attention was given to primary studies which evaluated the emissions of BTEX concentration from Municipal WWTP and subsequently undertake a health risk assessment.

Aim: The study aimed to identify and synthesize existing literature on average BTEX emission concentrations from biological activated sludge in municipal wastewater treatment plants (WWTPs). Additionally, the study will evaluate the associated health risks from exposure to these emissions.

Methodology: A systematic review was conducted to gather information from literature, focusing on the South African context while also exploring global studies in the absence of related research in South Africa. A total of 579 articles were reviewed using the PRISMA framework with some exclusion based on the criterion. Publications were sourced from several databases, including ScienceDirect, ProQuest, SCOPUS, and PubMed. For the health risk assessment, exposure assessment, and risk characterization, including carcinogenic risk (CR) and hazard quotient (HQ), the United States Environmental Protection Agency (U.S. EPA) method was used, summarizing data from relevant studies for the review paper.

Results: Numerous studies have been conducted globally to investigate BTEX emissions from municipal wastewater treatment plants (WWTPs). However, South Africa remains underrepresented in this research area, with a notable lack of studies. Globally, biological activated sludge technology is widely used due to its effectiveness and efficiency in treating municipal wastewater.

The BTEX concentrations emitted from WWTPs often exceed the South African Occupational Health and Safety (SAOHS) and National Institute for Occupational Safety and Health (NIOSH) occupational exposure limits (OEL). The carcinogenic risks (CRs) for benzene from macro-scale and average-scale WWTPs surpass the U.S. EPA threshold risk limit in ambient air of 1×10^{-4}, indicating an average risk of two additional cancer cases per 10,000 individuals exposed in biological activated sludge (BAS) WWTPs.

Conclusion: Overall, this report indicates that during the wastewater treatment process in biological activated sludge (BAS) wastewater treatment plants (WWTPs), BTEX compounds are released into the ambient air. The health risk assessment results suggest a potential carcinogenic risk from macro-scale and average-scale WWTPs, although the likelihood of developing non-carcinogenic health effects for both male and female workers is lower. However, due to limited available data, there remains some uncertainty regarding the risk. In summary, BTEX compounds are released into the ambient air, exposing employees in this microenvironment to potential inhalation. Consequently, employees might develop adverse health effects over time. More studies in this field are needed to reduce uncertainty and safeguard workers' health**.**

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GLOSSARY OF TERMS

BAS	Biological Activated Sludge
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CDI	Chronic Daily Intake
CNS	Central Nervous System
CR	Carcinogenic/Cancer Risk
EBNR	Enhanced Biological Nutrients Removal systems
HQ	Hazard Quotient
IARC	International Agency for Research on Cancer
LADD	Lifetime Average Daily Dose
PICO	Patient/Population, Intervention. Comparison and Outcomes
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta Analysis
RfC	Reference Concentration
RfD	Reference dose
SF	Slope factor
SR	Systematic Review
VOCs	Volatile Organic Compound
WWTP	Wastewater Treatment Plant
WWTT	Wastewater Treatment Technology
US EPA	United States Environmental Protection Agency
IARC	International Agency for Research on Cancer
SA	South Africa

CHAPTER ONE

This chapter begins with sources of municipal wastewater, its treatment processes and technologies and emissions of BTEX from WWTP. The BTEX emissions in relation to the WWTP process activities. The employees exposures during work at WWTP, possible health effects of BTEX, qualification and quantification of the risk using US.EPA risk assessment method. This chapter also discusses public health risks from BTEX emissions at WWTPs, outlines the problem statement and study justification, and concludes with the study's aim and objectives.

1. INTRODUCTION

Different wastewater treatment technologies are used to treat municipal wastewater from domestic, industrial, and stormwater sources (Edward Jones, 2021). The untreated wastewater is hazardous and it must be treated to protect and prevent impacts to the environment, public health and safety (Hansen and Hansen, 2015). With the global increase in urbanization, population growth and climate change; the need for the availability of the scarce freshwater resource rises and as such adequate wastewater treatment plants (WWTP) must be established (Choy *et al.*, 2014). The municipal wastewater treatment plants are crucial for protecting the environment and the scarce resource of water, but they also release volatile organic compounds like BTEX, Benzene (B), Toluene (T), Ethylbenzene (E) and Xylenes (X) during the treatment processes. BTEX emissions poses significant challenges due to their potential to endanger public health and environment, this is because the efficiency of the WWTP and quality of influent determines the effluent quality and emissions (Dehghani, Mohammadpour, *et al.*, 2022a; Ravina *et al.*, 2019). A study by Popitanu et al. (2021), found that the highest levels of BTEX emissions from WWTP were in winter (February) at an average of 89.29µg/m3, while the lowest levels were in autumn (October) at 24.01µg/m3. It is crucial to note that BTEX emissions decrease under Biological activated sludge (BAS) during different months. However, information on the emission profiles and the associated health risks of exposure to BTEX from Wastewater treatment plants (WWTPs) is not well documented and characterized in South Africa (Padhi and Gokhale, 2017).

The BTEX emissions from the biological activated sludge wastewater treatment technology (WWTT) occurs during the aeration process, drying the sludge, and mechanical filtering

processes in the WWTP. BAS utilizes over 200 species of bacteria, yeasts, and fungi to degrade hydrocarbons according to (Forouzanfar et al., 2015; Zhu et al., 2016). However, Hassanshahian and Cappello (2012), reported that 79 bacterial genera, including 9 cyanobacterial genera, 103 fungal genera, and 14 algal genera can degrade or convert to hydrocarbons. Therefore, to increase the removal of BTEX concentration except for benzene only, the level of hydrocarbon concentrations should be lower in WWTPs to ensure effective reduction and safe discharge of treated wastewater.

Since workers spend a significant portion of their day in this microenvironment, they are at risk of substantial exposure to chemical hazards, potentially leading to various adverse health effects(Qadir *et al.*, 2010). Exposure to BTEX compounds, which have high vapor pressure and low water solubility (Zhang *et al.*, 2019; Zhang *et al.*, 2020), is associated with approximately 2.3 million premature deaths due to occupational health and safety issues resulting from hazardous substances and poor working conditions. High absenteeism in working areas and approximately a million workers die due to exposure to hazardous substances and chronic illness as a result of exposure to BTEX (Takala, 2019).

From epidemiological studies and toxicological point of view the exposure to benzene compound has been linked to serious health issues such as leukemia and other blood disorders (Padhi and Gokhale, 2017). Toluene exposure can cause neurological effects like headaches and dizziness. Ethylbenzene exposure may result in respiratory problems while xylene exposure can affect the central nervous system (Lebrero *et al.*, 2011; Widiana *et al.*, 2019). In the field of exposure science, risk estimation methods are employed to determine the likelihood of health effects resulting from exposure, utilizing risk assessment processes. Which is the method used to characterise the probability of potential human health effects from exposure to chemical, physical and biological stressors following a four step process which include hazard identification, dose-response assessment, exposure assessment and risk characterisation (Durmusoglu, Taspinar and Karademir, 2010; Senatore *et al.*, 2021; Phillips and Moya, 2014).

There are number of risk assessment processes which are used globally to estimate the risk which include quantitative health risk assessment, qualitative health risk assessments, exposure -specific assessments, population specific assessment and regulatory frameworks. The study adopted the quantitative health risk assessment with U.S.EPA method in undertaking risk estimation for occupational setting of the BAS WWTPs in South Africa. This method utilise the exposure assessment and risk characterization to quantify the impacts

of chemical contaminants to human health through distinguishing between carcinogens and non-carcinogens. A mathematical expression is used to determine the risk through a threshold whereby it is considered non-carcinogenic if it is below and carcinogen if it is above the threshold carcinogenic risk and hazard quotient (Durmusoglu, Taspinar and Karademir, 2010).

Routine concentration measurements are undertaken in many countries usually in response to suspected potential occupational health effects from the setting. However, risk assessment exercise has not yet been a routine in WWTP to quantify BTEX exposures and evaluations of health risk using a mathematical expression which considers all determinants of exposure pathway model (Durmusoglu, Taspinar and Karademir, 2010). Hence, limited studies in South Africa and the fact that these compounds even at individual capacity may present a significant health hazard (Byliński, Gębicki and Namieśnik, 2019); especially to site operators working in the field, this concentration profiles should be characterized and risk assessed in South Africa to inform and influence policy makers.

1.1 PROBLEM STATEMENT

Exposure to benzene has been associated with severe health problems, including leukemia and various blood disorders (Padhi and Gokhale, 2017). Toluene exposure can cause neurological effects like headaches and dizziness. Ethylbenzene exposure may result in respiratory problems while xylene exposure can affect the central nervous system (Weng, et al., 2012). BTEX is often ignored in municipal wastewater treatment plants, leading to significant health risks for the public. In terms of environmental impact, BTEX emissions contribute to air pollution which can harm ecosystems through acid rain formation and ground-level ozone production. Several methods are available for monitoring and measuring BTEX emissions from biologically active sludge systems. These include gas chromatography-mass spectrometry (GC-MS) analysis and the use of flux chambers placed over treatment units to directly capture emitted gases (Fernández-Espinosa, et al., 2022; Akmirza, et al., 2017).

Exposure limits typically address external doses, making it challenging to assess internal risks without toxicological research. Many epidemiological studies lack adequate exposure data, preventing a full understanding of BTEX-related health outcomes. Comprehensive exposure assessments, using predictive models such as the U.S. EPA risk assessment framework (assuming 25 years of occupational exposure), are necessary. Accurate

measurement is vital for evaluating potential risks and ensuring regulatory compliance to protect public health and the environment (Gallastegui *et al.*, 2017).

However, information on the emission profiles and the associated health risks of exposure to BTEX from WWTPs is not well documented and characterized globally (Padhi and Gokhale, 2017). Fewer studies have concentrated on BTEX emissions from wastewater treatment plants (WWTPs), considering factors such as plant size, wastewater composition, the type of wastewater treated, and the technologies used (Byliński, Gębicki and Namieśnik, 2019; Widiana *et al.*, 2019). Therefore, this study aim to identify and synthesize existing literature on average BTEX emission concentrations from biological activated sludge in municipal WWTPs. Risk Assessment was undertaken adopting the U.S.EPA framework to characterise the potential exposure of WWTP employees to BTEX in the workplace. A systematic review method adopted focused on three search engines within a period of 10 years due to nature of the master's degree and resource constraints. The mean concentration of BTEX emitted from BAS was determined and used as input parameters into a U.S.EPA Risk assessment framework to estimate the carcinogenic and non-carcinogenic risk.

1.2 RESEARCH QUESTION

What was the average BTEX emission concentration from the Biological activated sludge in a Municipal wastewater treatment plant and its associated health risk?

1.3 AIM

The study aims was to identify and synthesize existing literature on average BTEX (Benzene, Toluene, Ethylbenzene, and Xylene) emission concentrations from biological activated sludge in municipal wastewater treatment plants (WWTPs). Additionally, the study evaluated the health risks associated with exposure to BTEX emissions.

1.4 OBJECTIVES

- To conduct a comprehensive review of existing studies to gather data on average BTEX emission concentrations from biologically activated sludge in municipal wastewater treatment plants (WWTPs); investigate the average BTEX emissions concentration from the biologically activated sludge in municipal WWTPs;
- To evaluate the potential health risks associated with exposure to BTEX emissions from activated sludge, focusing on both acute and chronic effects.

1.5 JUSTIFICATION

Factors contributing to the release of BTEX compounds in wastewater treatment processes include inadequate containment measures, equipment leaks, and poor ventilation systems (Padhi and Gokhale, 2017). These emissions risk workers' and nearby communities' health by polluting air and contaminating groundwater. They are unfortunately often ignored in municipal wastewater treatment plants, leading to significant health risks for the public (Akmirza *et al.*, 2017).

Therefore, determination of the average BTEX concentration from the BAS WWTP is of paramount importance to provide clear emission profiles of BTEX from the WWTP and to assist in determining the exposures and to risk assess the potential health effects to workers in the WWTP. Scattered data on BTEX concentrations from WWTP necessitates this study, which provides collation and analysis of emission profiles; and assist in evaluating the associated risks.

It is estimated that human occupation life expectancy is 25 years which equate to the years of exposure to occupational stressors such as BTEX in WWTP setting. U.S.EPA risk assessment framework suggests a prediction of exposure related risk assuming 25 years of exposure in occupational setting, therefore this study will adopt the U.S.EPA framework to ascertain the health effects from exposure. The study intended to inform policymakers on mitigating these hazards and developing a baseline emission profile database for future risk assessments. The insights gained can also aid in educational programs about environmental pollution sources and promoting sustainable practices. Evidence-based recommendations from the study data can support policy development for stricter regulations on pollutant containment and emission reduction efforts.

CHAPTER TWO

In the previous chapter, we provide an overview of the academic literature on the emissions of BTEX from WWTP and its wastewater origin. In this chapter we expand whereby studies have shown health effects associated with exposure to BTEX compounds. Exposure through inhalation or dermal contact with these chemicals has been linked to an increased risk of cancer development, including leukaemia. Additionally, neurological impacts such as headaches and dizziness have been reported among individuals exposed to high levels of BTEX compounds over extended periods (Weng, et al., 2012). When considering BTEX emissions from biological active sludge in wastewater treatment plants specifically, there is a need for further exploration into how these particular sources may uniquely affect human health compared to other sources of exposure (Fernández-Espinosa, et al., 2022). Risk Assessment becomes the major application in determining the effects of exposure to human health.

2. LITERATURE REVIEW

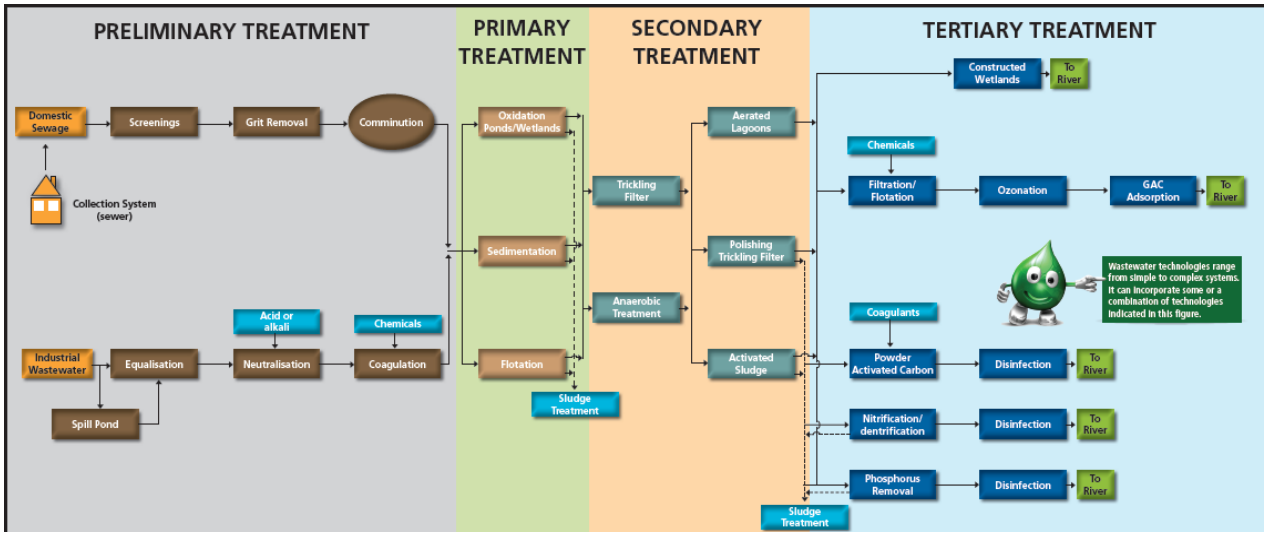
2.1 WASTEWATER TREATMENT PLANT

Wastewater treatment plant (WWTP) refers to a facility used to clean and remove the contaminants from the water which contains contaminants from the residential, industrial and agricultural settings. The treated water can be reused or returned to the water cycle with a process called water reclamation. There are several types of wastewater treatment plants which include domestic or municipal, industrial and agricultural wastewater treatment plant which adopted a centralised or a decentralised system depending on the setting and designs. The general treatment process involves pretreatment whereby coarse solids are removed, biological separation via anaerobic and aerobic processes in the aerators and chemical disinfections (Qadir *et al.*, 2010; Banchón *et al.*, 2021).

Wastewater treatment is an essential process that removes contaminants and pollutants while recovering valuable resources like water, nutrients, organic matter, and energy from municipal wastewater and sludge before it is discharged into the environment or reused (Muga and Mihelcic, 2008). Recently, water contamination and scarcity are major problems facing the world especially with the observed rate of over 0.84% increase in human population (Qadir *et al.*, 2010; Kumar, 2013). According to World Population Growth rate (1950-2023), by 2050, the world population should be around 9.7 billion people and with urban population increasing leading to more production of wastewater from the cities (Rafiei

et al., 2015; White and Sabarwal, 2012 ; Takeuchi, Kojima and Luetzow, 2014). This simply implies that there will be a great threat to availability of freshwater for human consumption (Kumar *et al.*, 2014).

Therefore, wastewater treatment plants are important for water sustainability. The wastewater undergoes the following series of steps to ensure the water is well treated, this includes the preliminary, primary, secondary and tertiary treatments as in



. Primary treatment removes suspended solids, while secondary treatment focuses on organic waste and ammonia removal through bacterial processes. Various technologies like biologically activated sludge (BAS), trickling filters, aerated lagoons, oxidation ditches and constructed wetlands which are extensive process are used in secondary treatment (Raschid-sally, no date). Tertiary treatment includes disinfection with chlorine, ozone, or UV to eliminate hazardous substances. The goal of wastewater treatment is to ensure that the water released back into the environment is safe and clean, thereby protecting aquatic life and human health from the dangers of water contamination and scarcity (Kumar, 2013).

4.2.1. *Preliminary Treatment*

The collected wastewater from different sources is collected in a tank to stabilize the flow. Wastewater is injected into the facility and passes through a bar screen to remove larger particles such as solids, grease, trash, sanitary napkins, broken glass, stones, bricks, metal, logs, grits and other floatable (Boyd and Mbelu, 2009), after which the pump transfers the waste from the preliminary treatment to primary treatment.

4.2.2. *Primary Treatment*

This involves basically clearing the wastewater of suspended organic and inorganic solids such as fats, oils, and grease. In a wastewater for industrial treatment plants, such wastewaters are sent to primary clarifiers where heavy solids settle to the bottom and fats and oils and grease float. These greases are removed by skimmers in order to prevent damage of the plugging pumps (Forest et al., 2019).

4.2.3. *Secondary Treatment*

The primary goal of secondary treatment is to remove organic waste and ammonia, which are crucial for protecting fish habitats and drinking water. This includes soluble biodegradable materials such as phenols, biological oxygen demand, and chemical oxygen demand from wastewater through either aerobic or anaerobic bacterial activities. The available secondary treatment technologies for wastewater treatment plants include biologically activated sludge (BAS), bio-filters, and variations of pond and artificial wetland systems (Dhote, Pradeep Ingole and Chavhan, 2012).

4.2.4. *Tertiary Treatment*

This treatment includes disinfection through chlorine, ozone, UV and others and afterwards a water reclamation stage (Raschid-sally, no date; Qadir et al., 2010). This procedure removes hazardous substance such as heavy metals, dyes, surfactant, and aromatic compounds with great specificity for contaminants removal (Kumar, 2013).

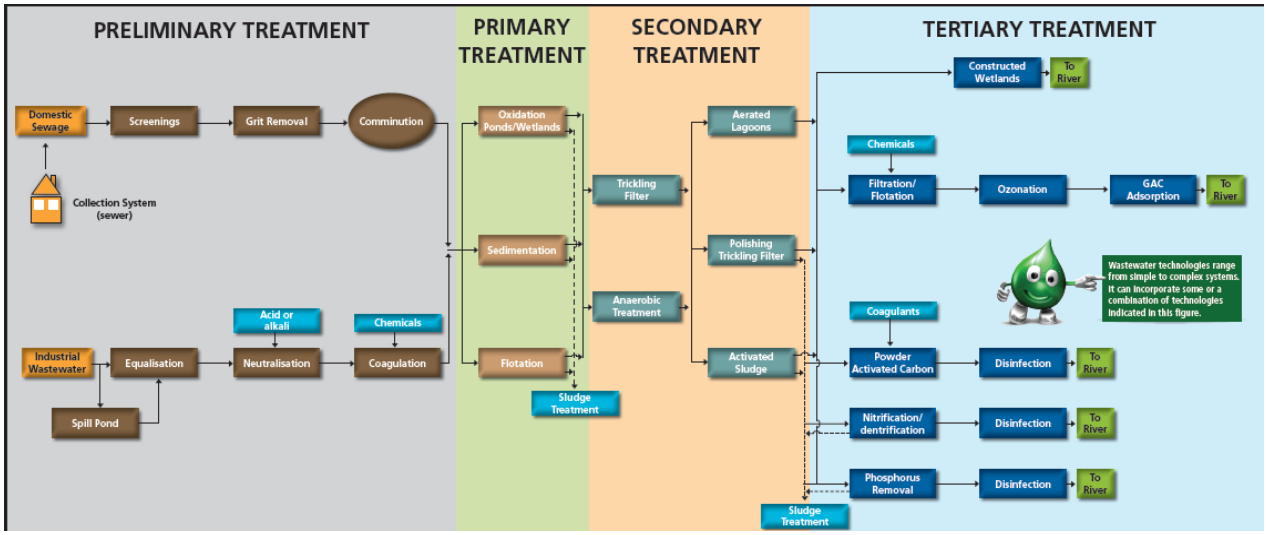


Figure 1: Adopted wastewater treatment process flow diagram.

2.2 WASTEWATER TREATMENT TECHNOLOGIES

Globally, various technologies are employed for wastewater treatment. Collected wastewater from different sources typically undergoes several stages: pre-treatment, which involves the removal of solids, grease, and grit; primary treatment, which eliminates suspended organic and inorganic solids; secondary treatment, where soluble biodegradable materials are removed through either aerobic or anaerobic bacterial activities using technologies such as aerated lagoons, anaerobic ponds, trickling filters, biological activated sludge, fixed film reactors, oxidation ditches, rotating biological contactors, or bio-disks; and finally, tertiary treatment, which includes disinfection using chlorine, ozone, UV, and other methods, followed by a water reclamation stage. (Raschid-sally, no date; Qadir *et al.*, 2010).

4.2.5. *Aerated Lagoon anaerobic ponds (AL)*

Effluent from primary treatment is collected in lagoons and aerated with mechanical floating or fixed aerators. This treatment plant technology uses the aerators to mix and add oxygen into the wastewater, usually used to treat low to medium strength municipal and industrial wastewater. The aeration can either be partial or fully operated and the aerated lagoons are more common than anaerobic lagoons which are deeper and free from dissolved oxygen which makes the system more anaerobic and is usually used to treat animal waste from the farms.

4.2.6. *Trickling Filter (TF)*

This is a wastewater treatment technology which uses a biological process and medium with high surface area such as rocks, gravels or plastic media to grow microbes which remove organic matter from wastewater. In the trickling or percolating filter process, microorganisms are attached to a highly permeable medium. Wastewater is sprayed onto this medium and trickles down, coming into contact with the microorganisms. These microorganisms consume the organic matter, producing carbon dioxide and water (Jiang *et al.*, 2007; Pal *et al.*, 2024).

The TF are effectively used in the micro, small and medium enterprises for the treatment of industrial or municipal waste water with highly loaded with COD. This systems are highly automated with about 85% efficiency and water recovery rate. In contrast, high clogging and huge sludge releases are some of the system drawbacks (Samie *et al.*, 2009).

4.2.7. *Biological Activated Sludge (BAS)*

This is a commonly used aerobic method of wastewater treatment that uses bacteria and air to treat sewage and wastewater. The effluent from both industrial and municipal decentralized systems enters the primary treatment stage and get collected in the aeration tanks whereby it is mechanically aerated to create a mixture of microorganisms and suspended solids. This method applies to all biodegradable industrial and municipal wastewater streams.

The aeration process supplies oxygen for biochemical reactions that stabilize wastewater and also mixes the returned sludge with effluent and keeps the activated sludge in suspension. The bacterial culture degrades biodegradable organics into water, carbon dioxide and other inorganic compounds. This method is regarded highly effective and efficient treatment process which is more flexible as an advantage but due to more mechanical dependents it has high construction and operational cost as drawbacks (Muga and Mihelcic, 2008).

4.2.8. *Fixed Film Reactors (FFRs)*

This is a treatment process that uses attached microorganisms to treat wastewater from both municipal and industrial sources. FFRs utilize less energy for the treatment process which makes the system to be regarded as more sustainable option than other wastewater treatment methods, such as activated sludge. It can be operated under aerobic, anoxic, and/or fully anaerobic conditions which makes the system versatile.

FFRs are primarily designed as secondary treatment to treat medium strength effluent processes although the degree of treatment can vary, as can their suitability for different wastewater types.

4.2.9. *Rotating Biological Contact (RBC)*

This is a wastewater treatment system that uses rotating discs to remove contaminants from wastewater. The partially submerged rotating discs promote the microbial growth and biological slime formation which when rotating it allows assimilation of nutrients and degradation of pollutants.

This is a quiet reliable, simple and low energy system which is versatile for different applications but it is sensitive to wastewater composition changes and requires regular, reliable maintenance.

All these wastewater treatment technologies as mentioned above have advantages and disadvantages which requires the background understanding of the type of effluent to be treated, capacity and geographical setting; for the effective choice of the technology which will yield the required objectives.

2.3 REGIONAL WASTEWATER STATUS

Africa is one of the driest continents in the world, and this water scarcity is exacerbated by inadequate treatment of water and wastewater, which hinders reuse. Although efforts are made to improve the situation, the growing population and urbanization lead to increased economic activities that consume more water and generate more wastewater, negatively impacting the environment and human health (Qadir et al., 2013).

Poor urban planning has increased informal settlements with inadequate sanitation, as 60% of Africa's urban population lives in slum conditions without proper sewage or wastewater treatment. Many industries in Africa use stabilisation ponds, which often result in high effluent concentrations due to limited capability. This situation impacts water resources and public health (Qadir et al.). 2013).

The following wastewater treatment processes are used in Africa such as on-site treatment, off-site treatment and conventional treatment processes. The onsite treatment process includes the pit-latrines and septic tanks mostly used in rural and semi-rural areas which unfortunately lacks maintenance which results in pollution of the groundwater and lead to waterborne diseases. In urban areas the offsite treatment is widely used whereby wastewater is collected through pipeline infrastructures and transported to the municipal or industrial WWTP which utilizes different secondary treatment technologies such as BAS, TF, FFRs, RBC, etc. for treatment depending on the setting and capacity required (Jones *et al.*, 2021; Qadir *et al.*, 2010).

2.4 WASTEWATER TREATMENT STATE IN SOUTH AFRICA

South Africa, being a semi-arid country, faces significant water scarcity, with many communities lacking reliable and sufficient water supplies for various activities. The need for wastewater reuse is particularly high to address these scarcity challenges. Therefore, establishing more wastewater treatment facilities is essential to ensure adequate reuse for landscape irrigation and industrial processes, especially in the arid regions of the country (Hansen and Hansen, 2015). However, it is acknowledged that the wastewater contains

contaminants which can pose danger to the ecosystem, human and the environment and it is of utmost importance to treat the wastewater before disposed into the river, lake or wetlands. This treatment processes involve the use of engineered systems such as WWTP to clean the contaminants from the wastewater. Even after enormous investment into the wastewater treatment infrastructure in South Africa, most of the WWTP are still non-compliant and in return this poor compliance affects the country water quality (Edokpayi *et al.*, 2020; Ramin *et al.*, 2022).

South Africa has approximately 950 wastewater treatment plants (WWTPs), which are distributed across all nine provinces as shown in Figure 2. Although the number of WWTPs varies by province, the treatment processes used are generally consistent throughout the country. These processes range from biological activated sludge, anaerobic ponds, trickling filters, and aeration basins to more advanced enhanced biological nutrient removal (EBNR) systems. Most WWTPs in South Africa are relatively small, handling between 500 and 2000 m^3/day, with over 70% classified as micro-, small-, or semi-sized systems. (Edokpolo, Yu and Connell, 2014; Edokpayi *et al.*, 2020). However, the National Green Drop 2022 annual report (Department of Water and Sanitation, 2022) indicated that, South Africa has a combined total of 6,971 Mega-litres per day (Ml/day) capacity of the installed treatment plants, mostly in the medium to macro-sized treatment plants as in Table 1 below.

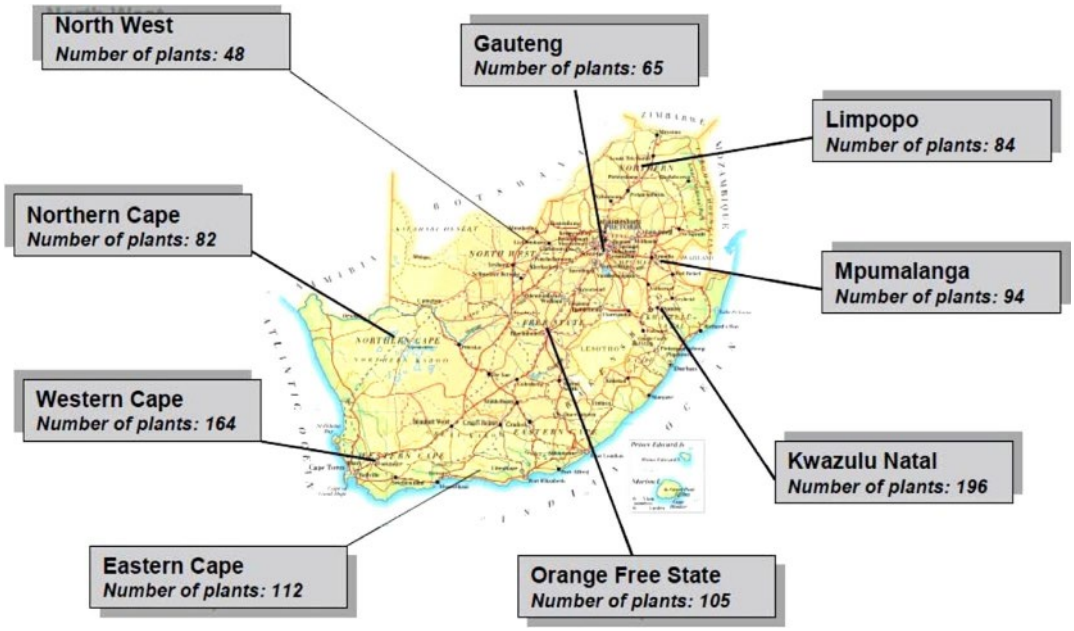


Figure 2: Adopted distribution of WWTP in South African (Edokpayi et al., 2020).

Table 1: Summary of WWTP capacity and flow distribution according to plant sizes in SA (Edokpayi et al., 2020).

	Micro Size Plants	Small Size Plants	Medium Size Plants	Large Size Plants	Macro Size Plants		
	<0.5 Ml/day	0.5-2 Ml/day	2-10 Ml/day	10-25 Ml/day	>25 Ml/day	Unknown	Total
No. of WWTP	156 (18%)	281 (33%)	257 (30%)	74 (9%)	58 (7%)	24 (3%)	850
Total Design Capacity Ml/day	31.80	274.10	1115.73	1142.01	4408.10	24	6,971.74
Total Daily Inflow Ml/day	14.98	109.56	503.84	577.75	3623.86	341	4,829.98
Use of Design Capacity (%)	47%	40%	45%	51%	82%	-	69%

Many WWTP have not achieved their ultimate objective of the system due to the lack of skills, finances and other resources for daily operations, as the main reason for their installation is to treat and clean municipal; and industrial wastewater to allow for safe disposal into the aquatic environment without causing an adverse effect to the environment and ultimately safeguarding human health (Zhang *et al.*, 2015; Edokpayi *et al.*, 2020; Department of Water and Sanitation, 2022). The primary types of wastewater treatment plant (WWTP) methods used in the country include the activated sludge process, ponds, and trickling filters. Among these, the activated sludge process is the most widely utilized treatment technology, as shown in Figure 3 (National Department of Health, 1991; Hansen and Hansen, 2015).

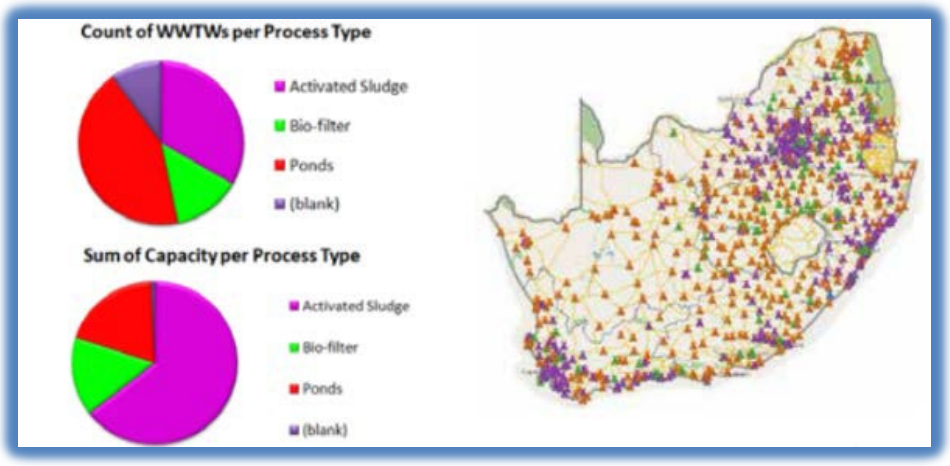


Figure 3: Adopted types of secondary treatment in SA (Dept of Water Affairs, 2012)**.**

It has been noted that many wastewater treatment plants (WWTPs) in the country do not comply with legislative limits. This non-compliance is due to the limited availability of plants in many areas, a shortage of skilled labor, lack of capital investment, and infrastructure overloading, where small facilities handle large volumes. Despite having wastewater management legislation comparable to that of developed countries, the main issue is non-

compliance. This situation necessitates regular monitoring and sampling of water quality, quantity, and emissions from WWTPs to protect the receiving environment and public health (Edokpayi *et al.*, 2020).

2.5 BIOLOGICALLY ACTIVATED SLUDGE

The BAS is a known secondary treatment method mostly adopted by domestic, municipality, and industrial WWTPs. This is a commonly used aerobic method of wastewater treatment that uses bacteria and air to treat sewage and wastewater. The effluent from both industrial and municipal decentralized systems enters the primary clarifiers and get collected into the aeration tanks whereby it is mechanically aerated to create a mixture of microorganisms and suspended solids. This method is applicable to all biodegradable industrial and municipal wastewater streams. The aeration process supplies oxygen for biochemical reactions that stabilize wastewater and also mixes the returned sludge with effluent and keeps the activated sludge in suspension. The bacterial culture degrades biodegradable organics into water, carbon dioxide and other inorganic compounds as in.

The term "activated sludge" refers to sludge particles in aeration tanks rich in living organisms containing toxic chemicals: paints, and fumes, which in turn produce hazardous sewage gas and dissolved oxygen when wastewater is either raw or settled. Afterwards, a disinfectant is used to eradicate any remaining bacteria through the sedimentation tank (Roman *et al.*, 2022). The microorganisms needed to remove organic matter from wastewater include bacteria, yeast, and fungi. It is acknowledged that the coliform bacteria serve as a natural indicator of water pollution. The aquatic ecosystem's inhabitants are dependent on dissolved oxygen for the breakdown of the massive amounts of biodegradable substances in their environment. Microorganisms in aeration tanks convert dissolved organic matter into biomass.

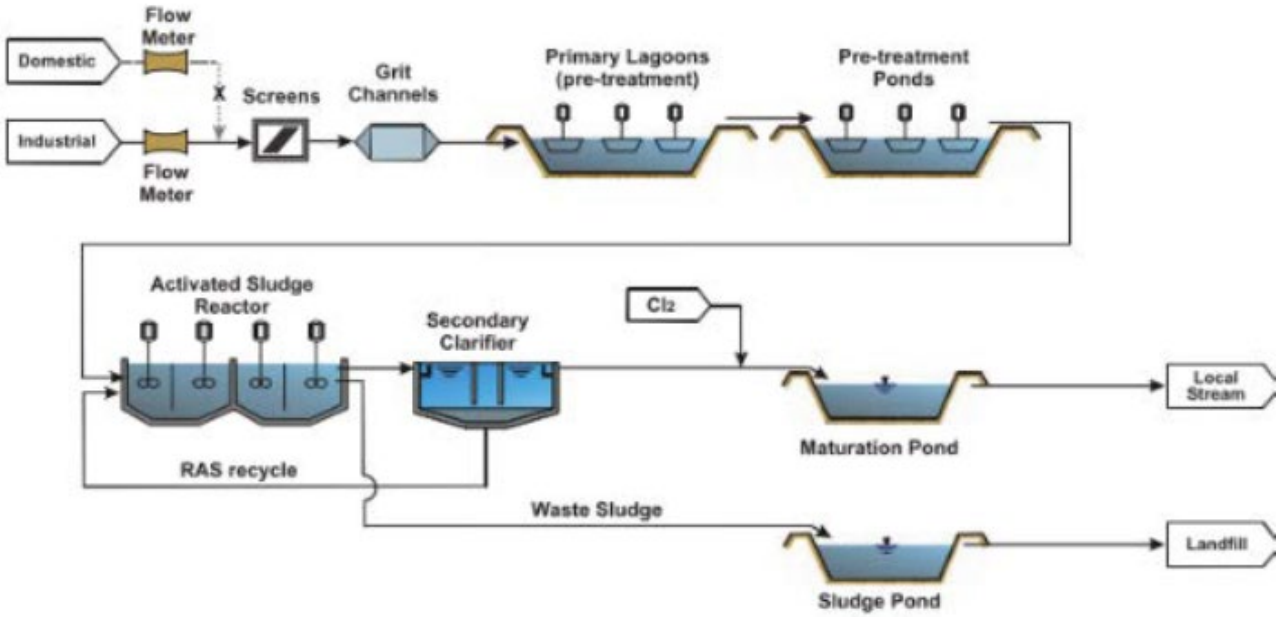


Figure 4: Adopted Schematic of an activated sludge WWTP (Roman *et al.*, 2022).

4.2.10. *Mode of action of BAS*

Effluent from the primary clarifier chamber is pumped into an aeration basin. The first section of the aeration chamber is an anoxic zone, which contains microorganisms that thrive in low-oxygen conditions. The second section is an oxic zone, where diffusers break up the air to supply the microorganisms with ample oxygen, as shown in **Error! Reference source not found.**. The time the wastewater spends in the aeration basin is known as the solids retention time (SRT). For proper functioning, a continuous supply of electricity is necessary for the diffusers (Boyd and Mbelu, 2009). The BAS contains oxygen, microorganisms, and food needed for water cleaning. Specific microorganisms in the sludge system are boosted during wastewater treatment, accelerating microbial activity and eliminating complex contaminants (Roman *et al.*, 2022).

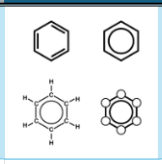
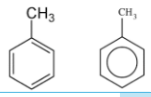
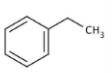
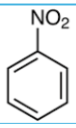
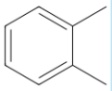
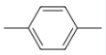
Temperature differences in wastewater impact feeding movement and toxic chemicals, slowing down biodegradation in contaminated BAS. BTEX levels in BAS are affected by temperature and precipitation, with a strong correlation coefficient of 0,8 indicating significance. Higher temperatures and water discharge lead to lower pollutants in WWTPs, with BTEX in seawater experiencing changes during summer. Research by (Moliner-Martínez *et al.*, 2013) shows that seasonal temperature and precipitation impact BTEX levels in natural waters, highlighting the environmental influence on pollutants in wastewater treatment. VOCs have negative health effects like irritation, headache, anxiety, and breathing issues, with potential long-term risks from high levels. Monitoring VOC presence is crucial

due to seasonal variations in BTEX emissions near wastewater treatment plants (Ahaghotu *et al.*, 2005).

2.6 BTEX EMISSION OVERVIEW

WWTPs are crucial for protecting the environment, but they also release volatile organic compounds (VOCs) like BTEXs. The wastewater from domestic or municipal setting contains traces of products used in the household such as solvents used in the kitchen, laundry, bathrooms, personal hygiene products, cleaning compounds, automotives, gardening products, painting activities, photographic chemicals and medicines (Muga and Mihelcic, 2008). All these traces finds its way to the WWTP through waterpipes and in the process of sewer transportation there are some biochemical reactions which occurs and causes the release of VOCs into the ambient air (Muga and Mihelcic, 2008). BTEX are considered the crucial kind of VOCs due to their potential to cause carcinogenic effect and their extensive availability in the ambient air. The International Agency for Research on Cancer (IARC) has classified benzene as carcinogenic to humans (group 1). BTEX are common VOCs that come from rubber, printing, leather, and gasoline industries (Rossi-Manaresi ed, 1981; Dehghani, Mohammadpour, *et al.*, 2022a). Each year, a significant amount of BTEX-contaminated wastewater is discharged into water bodies. BTEXs are commonly found in groundwater near gas stations and are a major source of pollution due to industrial effluents, household waste, oil spills, and pipeline leaks. These aromatic hydrocarbons pose a threat to the environment and human health, making it important to address the sources and impacts of BTEX contamination (Mazzeo *et al.*, 2010; Fayemiwo, Daramola and Moothi, 2017).

Table 2: BTEX Structure and physicochemical properties

Compound	Structure	Molecular weight g/mol	Equivalent Molar diameter (nm)	Dipole moment (D)
Benzene		78.11	0.68	0
Toluene		92.14	0.70	0.37
EthylBenzene		107.17	0.72	0.4
Nitrobenzene		123.11	0.69	3.8
o-Xylene		106.17	0.67	0.64
m-Xylene		106.17	0.66	0.3
p-Xylene		106.17	0.626	0

A study conducted by Gharedaghloo and Price (2017) found that the ratio of BTEX compounds in drinking water varies, with benzene showing limited dispersion compared to TEX compounds. Toluene is occasionally detected in drinking water supplies at concentrations below 3 µg/L. However, in industrial wastewater treatment plants (WWTPs), groundwater can contain up to 3,500 µg/L of toluene. The concentration of ethylbenzene in groundwater typically remains below 0.1 µg/L. It is important to note that lower hydrocarbon concentrations facilitate faster removal of BTEX from WWTPs, excluding benzene (Tawabini, Plakas, and Karabelas, 2020)A further study by Tawabini et al. (2020) observed reductions in the levels of other hydrocarbons: toluene by 93.2% (from 0.364 to 0.025 min^{-1}), ethylbenzene by 85.4% (from 0.171 to 0.025 min^{-1}), m&p-xylene by 20.3% (from 0.281 to 0.224 min^{-1}), and o-xylene by 8.4% (from 0.166 to 0.152 min^{-1}).

BTEX is often ignored in municipal wastewater treatment plants, leading to significant health risks for the public. The WWTPs have several treatment stages, including preliminary, primary, secondary, and advanced techniques (Zhang *et al.*, 2017).

2.7 BTEX EMISSIONS FROM MUNICIPAL WASTEWATER TREATMENT PLANT

Globally, there has been more focus on polyaromatic hydrocarbons (PAH), due to their impact on the degradation of environmental factors and pollution sites (Yu *et al.*, 2022). BTEX are pollutants commonly found in groundwater plumes and various water resources. They originate from the disposal of industrial effluents, oil spills, and oil pipeline leakages (Mazzeo et al. 2010; Costa et al., 2012). Furthermore, BTEX are the major VOCs found in paint manufacturing, chemical, petrochemical industries, and wastewater treatment plants (Akmirza et al., 2017). They are not easily detectable like PAH and are more abundant since they have many sources such as household waste, petrochemical industry waste streams, and municipal landfills (Fayemiwo et al., 2017).

The emission of BTEX compounds into the atmosphere leads to various environmental issues, including ground-level ozone formation, ozone depletion, and global warming. These problems, in turn, have harmful effects on human health. BTEX emissions significantly impact air quality in several ways. They contribute to the formation of ground-level ozone, a major component of smog, when they react with nitrogen oxides (NOx) in the presence of sunlight. Some BTEX compounds can also participate in reactions that deplete the ozone layer, which protects the Earth from harmful ultraviolet (UV) radiation. Additionally, as volatile organic compounds (VOCs), BTEX compounds can contribute to global warming by acting as greenhouse gases. These environmental issues, in turn, have harmful effects on human health, including respiratory problems, cardiovascular diseases, and increased mortality rates (Mohammad et al., 2007).

Surprisingly, BTEX are mostly overlooked in municipal WWTPs, thereby posing a serious health threat to consumers. Volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, and xylenes are emitted during anaerobic digestion processes and the use of various chemical reagents. These emissions occur because the breakdown of organic matter in anaerobic conditions releases these compounds into the atmosphere. Additionally, VOCs are found in significant amounts in both municipal and industrial wastewater due to the presence of various organic pollutants. In municipal wastewater, these compounds can originate from household products, personal care items, and other domestic sources. In industrial wastewater, VOCs often come from manufacturing processes, chemical production, and other industrial activities. The presence of these compounds in wastewater

poses environmental and health risks, necessitating effective treatment and management strategies to mitigate their impact (Lebrero *et al.*, 2011; Zhang *et al.*, 2017).

Wastewater treatment plants are crucial for protecting the environment, but they also release volatile organic compounds like BTEXs. BTEX are common Volatile Organic Compounds (VOCs) that come from rubber, printing, leather, and gasoline industries (Dehghani *et al.*, 2018). Each year, a significant amount of BTEX-contaminated wastewater is discharged into water bodies. BTEXs are commonly found in groundwater near gas stations and are a major source of pollution due to industrial effluents, household waste, oil spills, and pipeline leaks. These aromatic hydrocarbons pose a threat to the environment and human health, making it important to address the sources and impacts of BTEX contamination (Mazzeo *et al.*, 2010; Wang *et al.*, 2010; Fayemiwo, Daramola and Moothi, 2017).

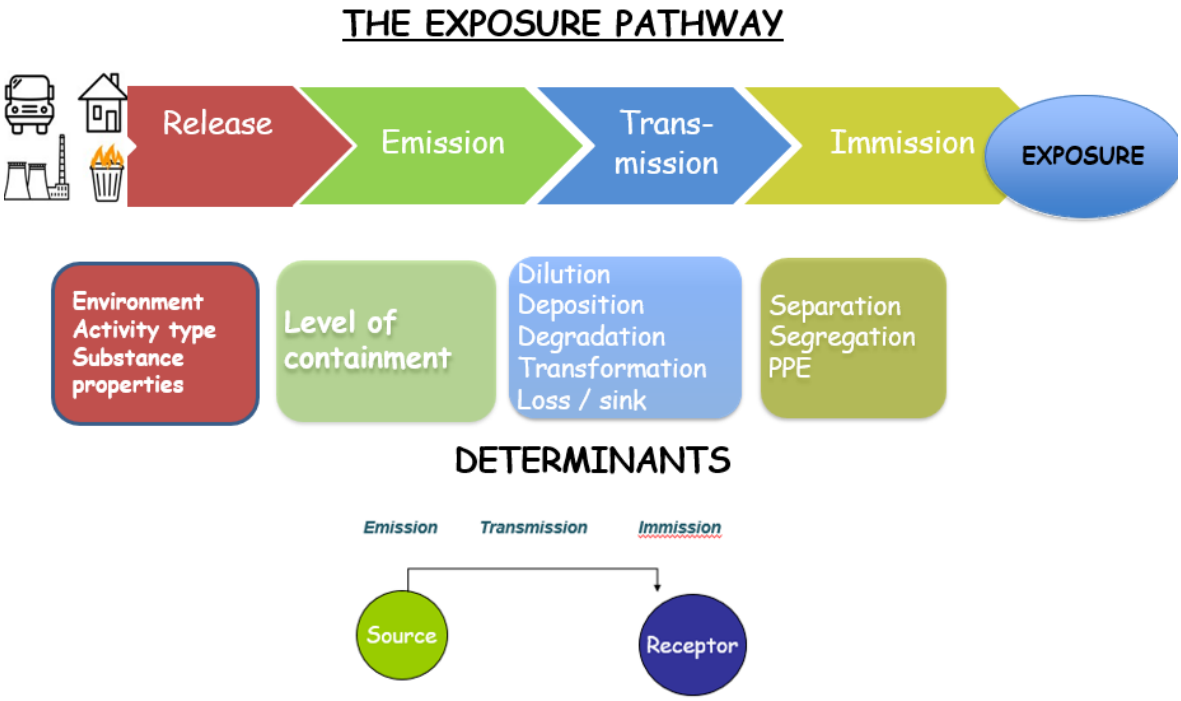


Figure 5: Adopted exposure pathway (Brouwer *et al.*, 2019).

The source-receptor model is vital for the understanding of the exposure pathway which occurs when the workers are working in the WWTP on daily basis and the determinants of exposure as in Figure 5. The BTEX as contaminants from the WWTP follows the exposure pathway model whereby following the activities at the BAS WWTP, the BTEX will be released, emitted, transmitted until it reaches the workers microenvironment whereby an exposure might occur. The assumption will be that the available concentration on the workers microenvironment will be regarded as the exposure. However there is level of

uncertainty towards the health effects which the exposure to such concentration will cause to the worker.

Exposure science suggests that health effects from certain stressors depend on factors like contaminant concentration, inhalation rate, exposure frequency, duration, body weight, and lifetime average exposure. Thus, risk characterization is crucial to assess BTEX exposure from BAS WWTP.

2.8 BTEX SAMPLING, MEASUREMENTS AND ANALYSIS METHODS

There are several methods for sampling and measuring BTEX compounds, including:

4.2.11. *Gas chromatography (GC)*

A standard method that involves trapping analytes onto sealed vessel such as sorbent tubes, then warmed the compound to between liquid and gas and analyzing them by GC port. GC can be used with headspace sampling techniques which is ideal for volatile compounds.

When undertaking a GC analysis, headspace sampling technique allows the BTEX to be analyzed without pre-sample extraction. Whereby a sample is put in a sealed vessel prior being warmed. The heat brings the compounds into a supercritical state. Then the sample is then removed from the atmosphere and introduced into the port of the GC (Krone *et al.*, 2010).

Gas Chromatograph Mass Spectrometer (GC-MS)

A GC-MS is a high-resolution technique that measures compounds and elements at the ion level in as little as 30 minutes. These instruments are costly to buy, operate, calibrate, and maintain.

GC-MS merges gas chromatography and mass spectrometry to identify substances in a sample. It's used in environmental analysis, forensics, drug testing, and food safety. By separating chemical mixtures and identifying components at a molecular level, GC-MS offers both qualitative and quantitative data.

It offers high sensitivity and specificity, the ability to analyze complex mixtures, and has a broad range of applications. Disadvantages: However, it comes with significant costs for equipment and maintenance, and requires skilled operators to function effectively (Krone *et al.*, 2010; Vu, Lap and Van Tan, 2018; Gross, 2017).

4.2.12. *Photo-ionization detector (PID)*

A PID is an easy-to-use and cost-effective tool for measuring BTEX compounds by separating them through trap and purge based on solubility and volatility differences. It is non-destructive and responds differently to aromatic hydrocarbons compared to other gases. PIDs, or Photoionization Detectors, operate by emitting ultraviolet light that ionizes the gas samples. This causes the release of electrons and generates a measurable current proportional to the concentration of the target compounds. Due to their sensitivity and selectivity, PIDs are extensively used in environmental monitoring, industrial hygiene, and hazardous materials detection, offering rapid and reliable measurements. Additionally, these instruments can be calibrated to detect various volatile organic compounds (VOCs), making them versatile tools in many fields (Atabi *et al.*, 2013).

4.2.13. *Solid-phase microextraction (SPME)*

SPME is a passive extraction method using a polymer-coated fiber to extract VOCs, with desorption in a GC injection port. It is preferable over standard methods as it eliminates the need for a thermal desorption unit or canister interface. Desorption from SPME is quick, requires no cryogenic focusing, and can be easily automated.

This method entails exposing the fiber to the sample, allowing volatile organic compounds (VOCs) to adsorb onto the coating. Post adsorption, the fiber is placed into the gas chromatograph (GC) injection port, where the analytes undergo thermal desorption directly into the chromatographic system for subsequent analysis. Solid Phase Microextraction (SPME) not only streamlines the sample preparation process but also improves both sensitivity and selectivity. Additionally, it reduces potential contamination and solvent usage since no liquid phase is involved. These advantages make SPME particularly suitable for environmental monitoring, food safety analysis, and clinical applications where high-throughput and precise detection of trace compounds are essential (Nicolle, Desauziers and Mocho, 2008; Baimatova, Koziel and Kenessov, 2015).

4.2.14. *Passive sampling*

Passive sampling is a simple, inexpensive method using sorbent tubes but has limited data resolution. This technique involves placing a sorbent material in an environment where it can absorb contaminants over a period of time. The primary advantage of passive sampling is its cost-effectiveness and ease of use, as it does not require power sources or complex

equipment. However, one major limitation is that it provides a cumulative measurement of contaminant levels over the sampling period rather than real-time or high-resolution data. Consequently, passive sampling may not be suitable for capturing rapid changes in pollutant concentrations or providing detailed temporal variations (Schneider *et al.*, 2001; Baimatova, Koziel and Kenessov, 2015).

4.2.15. *Canister sampling*

Canister sampling is labor-intensive and typically lacks the continuous data required for epidemiological studies. This method often involves manual collection, transportation, and processing of samples, which can be time-consuming and resource-draining. Additionally, because canister sampling captures only specific moments in time rather than providing ongoing data, it may fail to identify temporal variations and trends in exposure levels. This limitation can hinder the ability to draw accurate correlations between environmental factors and health outcomes, thereby impacting the reliability and comprehensiveness of epidemiological research (EPA, 1995; Liu *et al.*, 2008).

4.2.16. *Charcoal tube*

The charcoal tube technique involves adsorbing BTEX compounds from ambient air onto the charcoal section as it passes through the tube. This method is commonly employed in environmental monitoring to identify and quantify the concentration of benzene, toluene, ethylbenzene, and xylene pollutants. The charcoal tube generally consists of a glass container filled with activated charcoal, which possesses a high surface area and a strong affinity for organic compounds. As the air flows through the tube, the BTEX compounds are trapped on the surface of the charcoal. Once the sampling period concludes, the tube is sealed and transported to a laboratory. There, the adsorbed compounds are extracted with a solvent and analyzed through gas chromatography. This analysis helps in assessing air quality and ensuring compliance with environmental regulations (Chen *et al.*, 2011; Johnson *et al.*, 2011).

2.9 HEALTH EFFECTS OF BTEX EXPOSURE

Exposure to BTEX compounds can pose significant health risks and is considered among the most toxic to human life (Moolla, Curtis and Knight, 2015; Chauhan, Saini and Yadav, 2014). Monoaromatic hydrocar-bons like benzene, ethylbenzene, toluene, and xylenes have

been linked to various diseases such as liver lesions, organ irritations, drowsiness, and even cancer (Costa et al., 2012).

Prolonged exposure to BTEX compounds can lead to irritations in the central nervous system, skin, and sensory system (Mitra and Roy 2011). Symptoms of such exposure include nausea, throat irritation, drowsiness, and headaches. Benzene, in particular, is linked to central nervous system depression, eye irritation, respiratory issues, reproductive problems, and an increased risk of cancer, as it is classified as a Group 1 human carcinogen. Ethylbenzene can cause respiratory and neurological issues and is considered a potential carcinogen under Group 2B. Meanwhile, xylene and toluene are classified as non-carcinogenic to humans and are assigned to Group 3 by the International Agency for Research on Cancer (IARC) (Duan et al., 2023).

Toluene exposure can result in central nervous system (CNS) depression, liver and kidney issues, and reproductive effects. Xylenes may cause irritation to the nose, eyes, skin, and throat, along with neurological symptoms and gastrointestinal problems. According to the International Agency for Research on Cancer (IARC), these compounds are classified as either human carcinogens or potential carcinogens, underscoring the serious health risks associated with BTEX exposure (Duan et al., 2023). Acute exposure to BTEX compounds above permissible limits can lead to both immediate and long-term health effects, including weakened respiration, leukemia, pulmonary edema, coma, birth defects, and even death (Abbasi et al., 2020), as shown in Table 33.

Table 3: BTEX acute and chronic health effects (Abbasi et al., 2020; Duan et al., 2023).

Compound	Health effects from inhalation exposure
Benzene	Central nervous system (CNS) depression: drowsiness, tremors, most Neurological related
	Eye irritant Haematological and Respiratory
	Reproductive (animals: low birth weight, bone marrow damage)
	Cancer (leukaemia)
Ethyl-	Respiratory (throat irritation, chest constriction)
benzene	Liver, eye effects, Kidney
	Neurological (CNS toxicity)
Toluene	Central Nervous System depression: drowsiness, tremors
	Liver, Kidney impairment, Reproductive effects

Xylenes	Nose, eye, skin, throat irritation
	Neurological (dizziness, memory loss, headache)
	Nausea, vomiting, gastrointestinal effects

4.2.1. *Health risks associated with benzene*

Benzene (C6H6) is naturally a colourless, combustible volatile liquid, with a relatively sweet scent. The chemical is classified by WHO as a human Group 1 carcinogen (WHO, 2012). Human exposure to this chemical should be minimized due to its potential effects. Acute exposure can cause central nervous system (CNS) depression, including drowsiness, tremors, neurological symptoms, eye irritation, and reproductive issues. Chronic exposure to benzene may lead to endocrine, blood, and nerve disorders if absorbed by tissues, and it can decrease lymphocyte count.

4.2.2. *Health risks associated with toluene*

Toluene (C7H8) is a naturally occurring, colourless liquid that is highly flammable. It emits a sweet odour similar to that of benzene. Toluene has both acute and chronic exposure effects. It can be absorbed through the gastrointestinal tract and penetrate the liver, kidneys, adipose tissues, and brain. This poses a threat to the respiratory tract, visual tissues, and central nervous system, leading to symptoms such as confusion, fatigue, impaired color vision, and memory loss (Masekameni et al., 2018)('Agency for Toxic Substances & Disease Registry Xylene', 2011).

4.2.3. *Health risks associated with ethyl-benzene*

Ethyl-benzene (C8H10) is a colourless, flammable compound with a gasoline-like odour. Acute exposure can cause eye irritation, dizziness, CNS depression, and respiratory issues. Chronic exposure may lead to cancer, hearing loss, and kidney problems based on animal studies. Ethylbenzene is quickly sucked up by the kidneys and mainly causes tumors to develop (Hazrati *et al.*, 2016).

4.2.4. *Health risks associated with xylenes*

Xylene (C_8H_{10}), this is an aromatic hydrocarbons which is also known as dimethyl-benzene, derived from substitution of two hydrogen atoms with methyl group in benzene ring, and like the other PAHs, has a sweet smelling odour. It is a colorless, flammable and slightly greasy liquid. Acute exposure to xylenes can cause similar effects to those of benzene, excluding the carcinogenic risk. Xylenes can enter the human body through inhalation,

ingestion, and dermal contact, leading to damage in both the liver and kidneys (Tunsaringkarn, Tanasorn; Tassanee Prueksasit , Mingkwan Kitwattanavong , Wattasit Siriwong , Saowanee Sematong; Kalaya Zapuang, 2012).

2.10 HEALTH RISK ASSESSMENT METHODS

Health Risk Assessment (HRA) is an exercise to evaluate the nature and probability of adverse health effects occurring on human being after being exposed to chemical hazards in a contaminated microenvironment taking into consideration both acute and chronic effects (Xu, Liu and Tao, 2006; of the Science Advisor, 2019). This is a vital tool to identify and control the health risks associated with occupational health stressors from physical, chemical, biological and psychosocial state. Through qualitative and quantitative evaluation, potential occupational stressors, concentrations, or conditions that could impact employee health are predicted using the available matrix. The probability and severity of harm to workers under normal conditions are assessed and estimated, enabling the identification of acceptable risk levels to health. This process provides clear scientific criteria for recommending appropriate control measures (Yu *et al.*, 2022).

Noting that the primary goal of HRA is to identify, quantify, and manage risks to human health. It employs both qualitative and quantitative methods to assess the likelihood and severity of harm under normal and accidental exposure conditions. This enables the establishment of acceptable risk thresholds and informs the implementation of control measures (Yu et al., 2022). In occupational settings such as WWTPs, where workers may be exposed to volatile organic compounds (VOCs) like benzene, toluene, ethylbenzene, and xylene (BTEX), HRA becomes essential for safeguarding health.

Globally, there are number of risk assessment methods, which range from quantitative health risk assessment, qualitative health risk assessments, exposure -specific assessments, population specific assessment and regulatory frameworks. However, this study will focus on the quantitative health risk assessment to evaluate the carcinogenic risk and non-carcinogenic risk from chemical (BTEX) exposure in WWTP, adopting the U.S.EPA's Risk Assessment Framework which is one of the health risk assessment methods which are considered matured and adopted by number of countries including South Africa.

The United States EPA model principle focuses on managing chemical pollutants by establishing various risk assessment guidelines, including those for carcinogens, mutagens,

reproductive toxins, and hazards to human health. The U.S.EPA Health Risk assessment follows the four step process: Step 1: hazard identification, which involves the examination of the presence and potential of stressors to cause harm human; Step 2: Dose-response assessment, which involves quantification by getting a numeric value to determine the relationship between exposure and effects; Step 3: Exposure assessment, which involves the duration and frequency of exposure and activities been undertaken at the time of exposure; and Step 4: Risk characterisation which includes the risk estimation and description to determine the effects as in Figure 6.

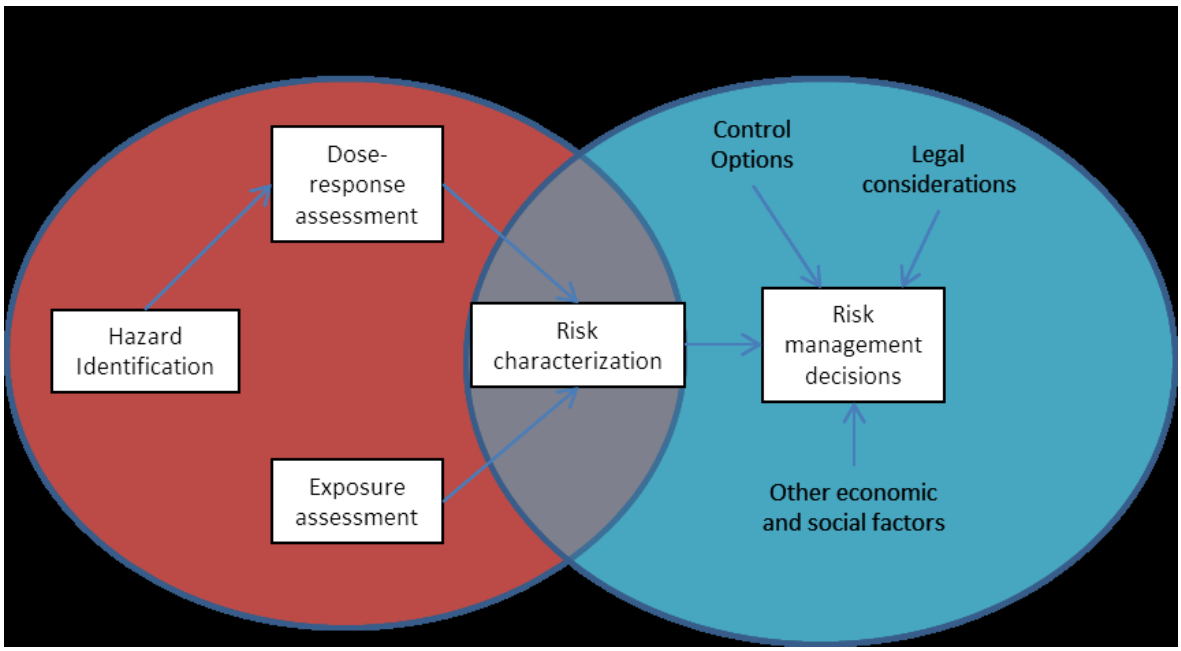


Figure 6:Adopted The US National Research Council's Risk Assessment Model, as developed by the United States Environmental Protection Agency (US EPA) (Source: after (USEPA, 2010).

In most cases people confusedly uses the word "Hazard" and "Risk" interchangeably without realizing the distinction between the words. Hazard refers to any chemical, physical, biological, or a combination of stressors that have the potential to cause harm to humans or the environment. While risk is the likelihood of the occurrence of adverse effects from the hazard (Moolla, Curtis and Knight, 2015a). Therefore, determining risk involves combining several factors, such as the hazard state, potential for exposure, frequency and magnitude of exposure, and the characteristics of the exposed population. This gives the Risk Assessment method an advantage over other methodologies, such as observational studies and epidemiological studies, as it can link environmental exposures with potential human health effects. By employing either qualitative or quantitative approaches, Risk Assessment effectively determines the available risk.

The HRA method uses exposure data to evaluate the health impacts of stressors on humans. The other advantage of Risk assessment method is that, it is economically viable as it can be undertaken in a short duration and still provide quite valuable scientific predictions (Moolla *et al.*, 2013); (Kalaya Zapuang *et al*., 2012).

Scholars are increasingly focusing on Health Risk Assessments (HRA) in wastewater treatment plants to predict health effects from exposures. It is evident that the HRA has an ability to indicate the likelihood of carcinogenic and non-carcinogenic effects using mathematical arithmetic to predict the impacts of exposure considering all the factors which determines the exposure following the four step process. Th US.EPA and Integrated Risk Information System (IRIS) developed a method which through threshold level a distinction can be made between carcinogenity and non carcinogenity effects of exposure to chemicals, hence the Average daily dose through respiratory pathway of the BTEX concentration, cancer risk and hazard quotient will be determined using mathematic expression. (Dehghani, Abbasi, *et al.*, 2022). Recent studies have increasingly applied HRA in WWTPs to assess the health risks associated with BTEX exposure. These compounds are known for their toxicity and are commonly found in industrial effluents. A study by Dehghani et al. (2022) demonstrated the use of mathematical models to estimate average daily doses (ADD), cancer risks, and hazard quotients (HQ) for BTEX compounds via inhalation pathways. The findings underscore the importance of continuous monitoring and risk mitigation in such environments.

A 2025 study by Cruz et al. assessed BTEX exposure in groundwater near gas stations using probabilistic risk assessment and Monte Carlo simulations. The study found that while non-carcinogenic risks (HQ) were within acceptable limits, carcinogenic risks from ethylbenzene exceeded USEPA thresholds for certain age groups, particularly via ingestion routes. This highlights the need for targeted interventions and stricter regulatory oversight in similar occupational settings (Cruz et al., 2025).

Health Risk Assessment is an indispensable tool in occupational health, particularly in high-risk environments like WWTPs. By leveraging robust frameworks such as the USEPA model, occupational health and hygiene professionals can proactively manage chemical hazards and protect worker health. The integration of empirical data and predictive modeling enhances the reliability of HRA, making it a vital component of modern environmental health practices.

2.10. LEGISLATIVE REQUIREMENTS IN SOUTH AFRICA

There are number of legislations in South Africa which regulate the operation of WWTP and the use of hazardous chemical, pollutants, environmental pollution and the public health exposure. The available legislation includes the followings:

- The Constitution of the Republic of South Africa Act, 1996, forms the foundation of democracy in South Africa. It guarantees everyone the right to an environment that is not harmful to their health or well-being and ensures the protection of the environment for the benefit of present and future generations. This is achieved through reasonable legislative and other measures aimed at maintaining equality among individuals www.info.gov.za.
- The National Environmental Management Act (NEMA), No. 107 of 1998, reinforces the provisions of Section 24 of the Constitution, which guarantees everyone the right to an environment that is not harmful to their health or well-being. NEMA incorporates internationally accepted principles of sustainability, making it a legal requirement to consider these principles in all decisions that may impact the environment. This includes ensuring that development is socially, environmentally, and economically sustainable, promoting the conservation of biodiversity, and preventing pollution and ecological degradation. By mandating the integration of these principles, NEMA aims to protect the environment for the benefit of present and future generations, ensuring that all actions and policies contribute to sustainable development and environmental justice.
- The National Water Act (NWA), No. 36 of 1998, regulates all water-related aspects in South Africa, aligning with the Constitutional rights mentioned earlier. The principles of sustainability and equity are central to the NWA, guiding the protection, use, development, conservation, management, and control of the country's water resources. These principles ensure that water resources are managed in a way that supports both current and future generations, promoting fair and sustainable use. A Water Act license from the DWA and a Waste Act license from the DEA are necessary for the erection of any new wastewater treatment works in South Africa. The full statute can be accessed from www.info.gov.za.
- The Water Services Act (WSA), No. 108 of 1997, establishes the framework for the provision of water services in South Africa. This Act ensures that all developments related to water services are regulated and managed effectively. Typically, any development aimed at providing water services will necessitate a water use

authorization, regardless of the source of funding for such projects. The WSA aims to ensure that water services are delivered in a sustainable and equitable manner, promoting access to clean water for all communities. It also emphasizes the importance of proper planning and management to protect water resources and ensure their availability for future generations. By setting clear guidelines and requirements, the WSA plays a crucial role in maintaining the integrity and sustainability of South Africa's water services infrastructure.

- The Hazardous Substances Act (Act 5 of 1973) regulates substances that are inherently toxic and/or flammable. This Act is designed to protect public health and safety by controlling the manufacture, sale, use, and disposal of hazardous substances. It categorizes these substances into different groups based on their potential risks and outlines specific requirements for handling, storage, and transportation to minimize exposure and prevent accidents. The Act also mandates proper labeling and provides guidelines for emergency response in case of spills or other incidents. By enforcing these regulations, the Hazardous Substances Act aims to reduce the risks associated with hazardous materials and ensure a safer environment for all.
- The Environment Conservation Act (Act 73 of 1989) regulates environmental pollution and contaminants to ensure the protection and controlled use of the environment. This Act provides a comprehensive framework for managing and mitigating the impact of human activities on the environment. It addresses various forms of pollution, including air, water, and soil contamination, and sets standards for waste management and disposal. The Act also promotes the sustainable use of natural resources, encouraging practices that minimize environmental degradation. By enforcing these regulations, the Environment Conservation Act aims to preserve ecological integrity, protect public health, and ensure that environmental resources are available for future generations. It empowers authorities to take necessary actions against violators and supports initiatives that enhance environmental conservation and sustainability.
- The Occupational Health and Safety Act (Act 85 of 1993) is designed to safeguard the health and safety of individuals at work, as well as the well-being of related communities, from work-related stressors and hazards. This Act establishes comprehensive guidelines and standards to ensure safe working conditions across

various industries. It mandates employers to identify potential hazards, implement preventive measures, and provide necessary training and protective equipment to employees. Additionally, the Act requires regular workplace inspections and risk assessments to monitor compliance and address any safety concerns promptly. By promoting a culture of safety and health, the Occupational Health and Safety Act aims to reduce workplace accidents, injuries, and illnesses, thereby enhancing the overall quality of life for workers and their communities. It also empowers employees to participate in safety programs and report unsafe conditions without fear of retaliation, fostering a collaborative approach to workplace safety.

- The National Environmental Management: Air Quality Act (Act 39 of 2004) is dedicated to protecting the environment, with a specific focus on maintaining and improving air quality. This Act aims to prevent air pollution and ecological degradation by implementing reasonable measures and regulations. It sets standards for air quality and emissions, requiring industries and other sources of pollution to comply with these standards to minimize their impact on the environment. The Act also promotes the use of cleaner technologies and practices to reduce emissions and encourages continuous monitoring and reporting of air quality data. By enforcing these regulations, the NEM: Air Quality Act seeks to ensure a healthier environment for all, protecting both human health and the natural ecosystem from the harmful effects of air pollution. Additionally, it supports public awareness and participation in air quality management, fostering a collaborative approach to environmental protection.

There are also number of policies in South Africa which affects and regulate the uses and operation of wastewater treatment in the country. These include:

- The Department of Water Affairs (DWA) Water Supply and Sanitation Policy of 2001 emphasizes the necessity of providing basic sanitation, particularly in rural areas where households often rely on on-site dry toilets. This policy highlights the importance of ensuring that all communities have access to safe and hygienic sanitation facilities to improve public health and quality of life. However, the policy is less explicit about what sanitation improvements entail in urban settings, where reticulated services and grey water management are more prevalent. In urban areas, enhancing sanitation involves upgrading sewer systems, ensuring efficient wastewater treatment, and managing grey water to prevent contamination and

promote water reuse. Addressing these aspects is crucial for maintaining environmental sustainability and supporting the growing urban population's needs. By expanding its focus to include urban sanitation challenges, the policy can better address the diverse requirements of both rural and urban communities, ensuring comprehensive and equitable access to sanitation services across the country.

- The White Paper on National Sanitation Policy emphasizes the objectives of the National Water Act (Act 54 of 1956), which aims to ensure the equitable distribution of water for industrial and other uses. This policy seeks to regulate the abstraction, use, supply, distribution, and pollution of water resources, as well as the treatment of discharges. By focusing on these objectives, the policy aims to promote sustainable water management practices that balance the needs of various users while protecting water quality and availability. Additionally, the White Paper highlights the importance of improving sanitation infrastructure and services to enhance public health and environmental protection. This includes addressing the challenges of both rural and urban sanitation, ensuring that all communities have access to safe and reliable sanitation facilities. By integrating these principles, the policy supports the broader goals of sustainable development and equitable resource management, contributing to the well-being of present and future generations.

The above legislations provide the framework into protecting and preventing the environmental pollution with an aim to protect the environment and safeguarding people's lives and protection of the environment from the emissions of pollutants such as BTEX during the wastewater treatment process across the country.

CHAPTER THREE

This chapter commences with an overview of the study design, followed by an elucidation of the search strategy employed. As this is a secondary study, the PRISMA framework for systematic review has been adopted, with consideration given to the PICO strategy for data collection. The chapter then details the information recorded during the systematic literature review and describes the methods by which the data has been analysed and stored on the desktop shared drive. Then explains management of the information before it gets summarised to give sense of what has been systematically reviewed. Further highlights the relevancy and not relevant articles, criteria for inclusion and exclusion to the study and use of Risk assessment to process the available data and conclude on the residual risk.

3. METHODOLOGY

3.1 STUDY DESIGN

The study adhered to a systematic review approach in compliance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA). PRISMA method included the three categories such as literature search, articles selection, and data extraction; which follows the four-flow phase diagram which includes identification, screening, eligibility and inclusions based on the available scope of work (Selcuk, 2019).

A systematic review is a rigorous method of synthesizing scientific literature to address a specific research question in a transparent and reproducible manner. This approach aims to include all relevant peer-reviewed publications on a given topic, thoroughly assessing the quality of the evidence presented. By following a structured protocol, systematic reviews minimize bias and provide a comprehensive overview of the existing research. This methodology has gained widespread acceptance in health sciences and public policy research due to its ability to produce high-quality, reliable findings. Unlike traditional literature reviews, systematic reviews employ a more refined and scientific approach, ensuring that the conclusions drawn are based on robust and well-evaluated evidence(Lame, 2019; Selcuk, 2019). As a result, systematic reviews are increasingly recognized as a valuable tool for informing evidence-based practice and policy-making.

3.2 SEARCH STRATEGY

Due to limited duration and magnitude of the study, timeframe selected for the search of articles was between 2013 and 2023 to identify relevant articles for the past 10 years. In consultation with the Librarian a search strategy was used adopting programmes EBSCO to identify the relevant keywords for the study. The search was conducted from published articles following a Population, Intervention, Comparison and Outcomes (PICO) search strategy on articles related to concentration of BTEX from BAS in municipal WWTPs as in Table 5.

Table 4: PICO Search Strategy

PICO ELEMENTS	KEYWORDS	SEARCH TERMS	SEARCH STRATEGIES
P- Population	BTEX exposure to workers in the BAS WWTP	BAS WWTP Workers, BTEX Exposure	WWTP/STP Workers or BTEX or Exposure
I - Intervention	BTEX Concentration, Carcinogenic risk, Hazard Quotient	BTEX, BTEX Concentration, BAS WWTP	BTEX or BTEX Concentration or Benzene or Toluene or Ethyl-benzene or Xylene
C - Comparison	No BTEX Concentration, Non carcinogenic risk		
O- Outcomes	Cancer risk or Carcinogenic risk, Non cancer risk Non carcinogenic risk	Cancer risk or Carcinogenic risk, non cancer risk or Non carcinogenic risk	Cancer risk or Carcinogenic or non cancer risk or Non carcinogenic

Search terms and keywords included “BTEX Concentrations”, “BTEX Exposure” ‘Biological activated sludge”, “Municipal wastewater treatment Plants”, well defined synonyms “Sewage treatment plant (STP)”, “Carcinogenic risk”, “Non-carcinogenic risk”. Boolean strings “And”, “OR” were used. The following search engines were utilized: ScienceDirect, Scopus, PubMed and ProQuest journals as in Table 5 for South African WWTP.

Table 5: Database and Search Strategy for South African WWTP only

Database	Search Strategy For South Africa
Pub Med	" BTEX concentration from municipal wastewater treatment plants in south africa"; "BAS WWTP" and "South Africa"[All Fields]
Science Direct	TITLE-ABST-KEY ("BTEX concentration from municipal wastewater treatment plants in south africa*") and TITLE-ABST-KEY("South Africa")
SCOPUS	TITLE-ABST-KEY ("benzene, AND toluene, AND ethylbenzene, AND xylene OR BTEX AND concentration AND from AND municipal AND wastewater AND treatment AND plants AND south AND africa*" AND "South Africa")
ProQuest	(BTEX concentration from municipal wastewater treatment plants in south africa*) AND (South Africa)[TITLE-ABST-KEY]

The search strategy presented in Table 6 outlines how the researcher's systematically retrieved literature related to BTEX (benzene, toluene, ethylbenzene, and xylene) concentrations in municipal wastewater treatment plants (WWTPs) from various global databases. The focus is on identifying relevant peer-reviewed publications that report on BTEX levels in wastewater treatment systems worldwide. Here's a breakdown and explanation of each component

Table 6: Database and Search Strategy for global WWTP

Database	Search Strategy (Global)
Pub Med	" BTEX concentration from municipal wastewater treatment plants"; "BAS WWTP" and "Global"[All Fields]
Science Direct	TITLE-ABST-KEY ("BTEX concentration from municipal wastewater treatment plants*") and TITLE-ABST-KEY("Global")
SCOPUS	TITLE-ABST-KEY ("benzene, AND toluene, AND ethylbenzene, AND xylene OR BTEX AND concentration AND from AND municipal AND wastewater AND treatment AND plants *" AND "Global")
ProQuest	(BTEX concentration from municipal wastewater treatment plants*) AND (Global)[TITLE-ABST-KEY]

All the articles and reports that are associated with BTEX concentration from municipal wastewater treatment plants in South Africa in the last 10 years were included in the study to broaden the limited data as in Figure 7. A total of 66 articles from ScienceDirect were retrieved without considering relevant or not relevant but making use of key words BTEX concentration from activated sludge in wastewater treatment plants in South Africa.. A total of 25 articles through ProQuest search were retrieved irrespective of relevant or not relevant that contains key words of BTEX concentration from activated sludge in wastewater treatment plants in South Africa. From PubMed and Scopus search, 0 article were retrieved

using key words BTEX concentration from activated sludge in wastewater treatment plants in South Africa.

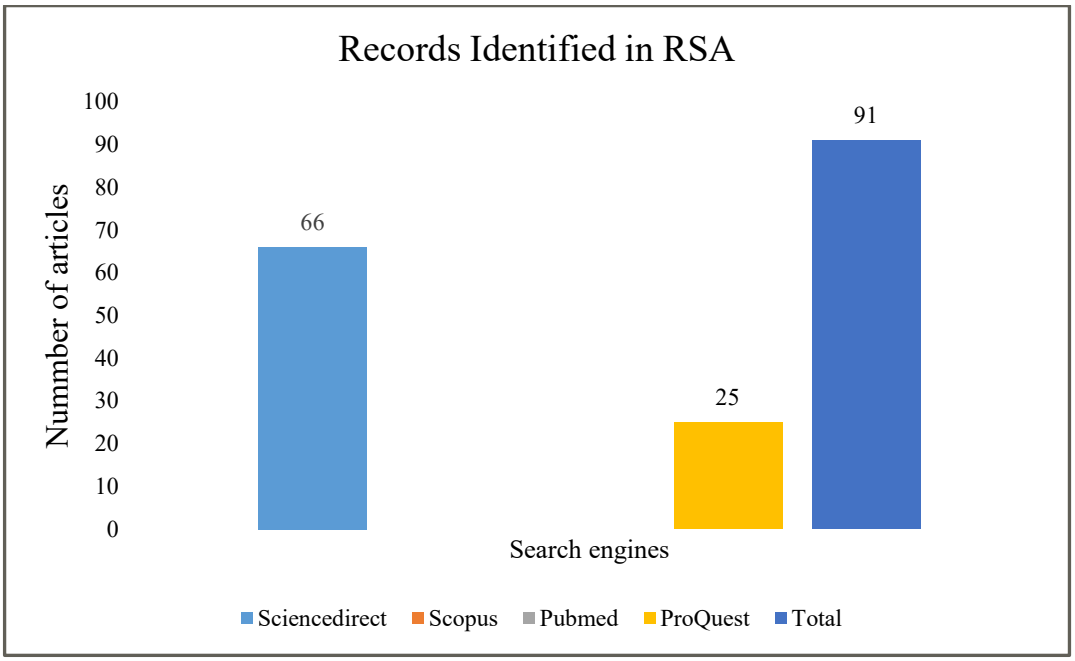


Figure 7: Records identified locally on BTEX Concentration from Municipal WWTP.

Due to limited articles which relates to BTEX emissions from South Africa WWTP; the search was expanded to look into global scale and the following articles were retrieved from different search engines. A total of 521 articles from ScienceDirect were retrieved without considering relevance or not but by making use of the key words BTEX concentration from the municipal wastewater treatment plants.

A total of 27 articles from ProQuest were retrieved by making use of the key words BTEX concentration from the municipal wastewater treatment plants all fields. From Scopus and PubMed search databases a total of 23 and 8 articles respectively, were retrieved without considering relevance or not but by making use of the key words BTEX concentration from the municipal wastewater treatment plants all fields. Several scholarly articles were manually added after the screening based on the selection criteria as stipulated by Figure 9. The searched papers were then collated and rigorously reviewed for duplicates using Mendeley referencing manager. After excluding articles that had little relevance to the objectives of the study and including the main articles, the data from these articles were extracted for later analysis as in Table 8.

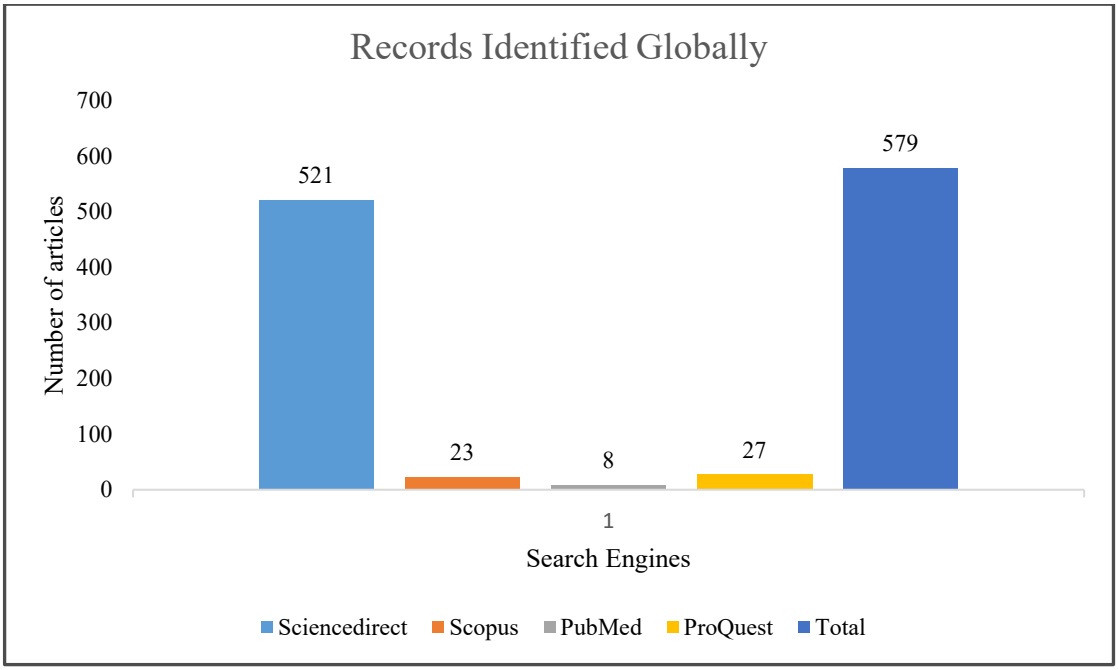


Figure 8: Records identified globally on BTEX Concentration from Municipal WWTP

Full articles were retrieved when the abstract included the investigated topic, and only full papers published in English were considered. Therefore, the objectives of the study were assessed as follows; Objective 1: In consultation with a Librarian, a sensitive search strategy was developed to identify all published research or articles on BTEX emissions concentrations from BAS in municipal WWTPs; first in South Africa only and then expanded the search to global scale due to limited data or no-data related to BTEX concentration specifically to WWTP in South Africa. Then the search strategy was expanded to "BTEX concentration from the municipal wastewater treatment plants"

Objective 2: This is related to the risk assessment framework whereby the first data were from the average BTEX concentrations obtained from objective 1; and the data related to other parameters such the inhalation rate, exposure frequency (days/year); the exposure duration (years); body weight; will be collected from the U.S.EPA guideline for superfund compound for human factor assessment handbook while averaging time (exposure averaged over lifetime/average life expectancy for male and female) (days) from South African labour law as in Table 7.

Table 7: Risk Assessment Parameter and Sources

Risk Assessment Parameters and Sources				
Parameter	**Description**	**Value**	**Unit**	**Source**
C	Average BTEX concentration		mg/m3	Literature
IR	Inhalation Rate	20	m3/day	U.S. EPA

BW	Body Weight	70 males/ 60 females	kg	U.S. EPA
ED	Exposure Duration	79.9 (8 hours/ day)	days/year	Objective 1 of this study
YE	Years of Exposure	25	Years	U.S EPA
AT	Years in Lifetime	60 Male/67 female	Years	StatsSA

3.3 SELECTION CRITERIA

PRISMA flow diagram summarizing the selection process, including the number of records identified, screened and quality assessment of literature, peer-reviewed and assessed for eligibility was considered for this study as in **Error! Reference source not found.**. Exclusion of studies was considered under the following reasons: (1) they are not primary field measurements of BTEX between 2013 and 2023 published in English; (2) Studies which generalize the VOCs not specific to BTEX; (3) all qualitative studies that focus on the exposure to VOCs was excluded as they don't provide concentrations of BTEX; (4) articles that were not peer-reviewed; (5) Studies that use unvalidated methods; (6) the field measurements not conducted in a typical Municipal wastewater treatment plant; (7) there are other duplicating studies from different databases.

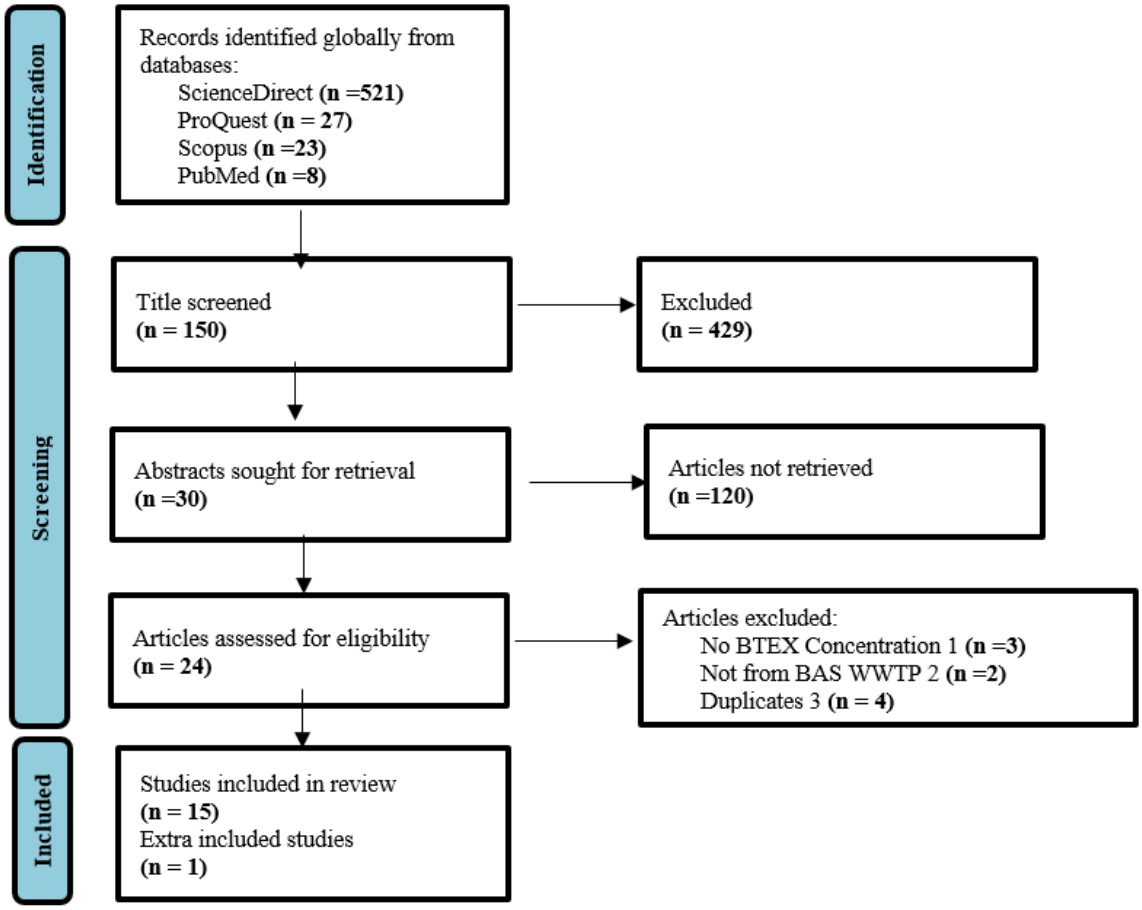


Figure 9: A schematic diagram following a PRISMA framework for data collection.

3.4 DATA EXTRACTION

The data were collected in a database using a manually designed extraction table through Word Microsoft 2010, with the following columns for the subsequent data analysis: first author, year, title, inclusion/exclusion issues, and BTEX concentration and risk assessment from BAS. Inconsistent data between the two data abstracters were resolved through discussion and involvement of the supervisors. Data were abstracted, with the title, first author year of publication, study setting, study design, and additional relevant findings paraphrased.

Before starting data extraction, the selection process for relevant studies were explained under search inclusion criteria and study description using textual and graphical presentation. Following data extraction, the findings were organized into three theme areas: "BTEX Concentrations", "Country of study" and "Potential health risks from Risk Assessment". Finally, data were presented via text.

3.5 DATA PROCESSING AND ANALYSIS

Objective 1: To conduct a comprehensive review of existing studies to gather data on average BTEX emission concentrations from BAS in municipal WWTPs;

The outcome of primary data that was collected by the main researchers, review articles and reports were used for this secondary data and analyses to attain information for this objective were the mean concentration of BTEX from the peer-reviewed articles and journals related to BTEX from BAS in Municipal WWTPs. This information was input into Microsoft Excel covering Title, Author, year of publication, country, BTEX concentration, and conclusions either as mean (SD) or median (IQR) as depicted on Table 8 below. The articles with similarities and commonalities will be identified and clustered together for duplicates.

Table 8: Data processing for objective 1

Example of data processing for Objective 1												
Author	Year of Publication	Title of the article	Type of WWTP	WWTP Capacity	Local/Global	Country of study	Sampling Method	Pollutant	Concentration Summer µg/m3	Concentration Winter µg/m3	Mean Conc µg/m3	Comments
								Benzene		0		
								Toluene		0		
								Ethylbenzene		0		
								m,p-xylene		0		
								O-xylene		0		

First step of this systematic review study showed that; a total of 579 articles and reports were retrieved from various web databases such as ScienceDirect, ProQuest, Scopus and PubMed. Whereby a total of 150 articles were accepted from ScienceDirect database with a total of 371 rejected due to not having relevant key words on the titles. A total of 27 were

retrieved from ProQuest, with 11 being accepted and 16 articles rejected due to not having relevant key words on the titles. A total of 23 articles were retrieved from Scopus search engine, with 9 accepted and 14 articles rejected due to not having relevant key words on the titles. A total of 8 articles were accepted from PubMed, with a total of 1 rejected because of lack of key words on their titles.

Second step of systematic review; A total of 150 articles were accepted with relevant key words on their titles. A total of 30 articles and reports were accepted because key words were on the abstracts. A total of 120 article and reports were rejected because key words were no on abstracts.

Third step of systematic review; a total of 8 articles were rejected because abstracts were not relevant to study, while a total of 22 articles and reports were accepted because abstracts were relevant to study.

Fourth step of systematic review; at total of 22 articles and reports were accepted and reviewed for eligibility, whereby any duplicates, articles with no BTEX concentration and not from BAS WWTP were excluded before final acceptance to the study.

Out of 22 articles and reports there were 4 duplicate articles, 3 articles with no air BTEX concentration and 2 articles not from BAS WWTP were excluded. A total of 15 articles were included and considered for BTEX concentration from municipal WWTP globally.

Objective 2: To evaluate the potential health risks associated with exposure to BTEX emissions from activated sludge, focusing on both acute and chronic effects

Toxicity assessment and Risk characterization using formulas provided in the literature were utilized for answering objective 2. The various formulas used are mentioned in the review below. The exposure assessment and risk characterization along with carcinogenic risk (CR) and hazard quotient (HQ) using the United States Environmental Protection Agency (U.S.EPA) method were summarized from the literature and the data from relevant papers were used for the review paper. Carcinogenic risk (CR) was calculated using Equation 3, the non-carcinogenic hazard quotient (HQ) was calculated using Equation 4.

Chronic Daily Intake (CDI) was calculated using the Equation 1; Inhalation slope factor (SF) for carcinogenic risk and reference dose (RfD) standard values for benzene, toluene, ethylbenzene, and xylenes were acquired from the literature and used for calculations.

To calculate the CDI of employees, $\text{CDI (average daily intake)} = \frac{\text{C x CF x IR x ED}}{\text{BW x AT}}$ Equation 1 was used:

$$CDI\ (average\ daily\ intake) = \frac{C\ x\ CF\ x\ IR\ x\ ED}{BW\ x\ AT}$$ **Equation 1**

CDI is the chronic (averaged) daily intake over a year (mg/kg/day);

Where:

C is the breathing zone concentration of BTEX in (μg/m^3), derived from identified literature globally on emission of BTEX concentration from Municipal WWTP;

CF is the conversion factor (1 mg/1000 μg);

IR is the adults inhalation rate (US.EPA standard) (20 m^3/day);

EF is the exposure frequency (days/year);

ED is the exposure duration as in$ED = \frac{\text{Actual exposure duration}}{24H} x240\ \text{days}$ Equation 2;

BW is body weight (US EPA standard) (70 kg, 60 kg for male and female adults, respectively); and

AT is the averaging time (exposure averaged over lifetime/average life expectancy for male and female) (days)

$$ED = \frac{Actual\ exposure\ duration}{24H} x240\ days$$ **Equation 2**

Where:

ED is the exposure duration (days/year);

Actual exposure duration is the 8-h working hours; 24 h is the total hours in a day; and

240 days is the number of exposure days in a year, excluding weekends (104 days) and annual leave of 21 days.

Table 9: Benzene slope factor, and toluene, ethylbenzene, and xylenes (TEX) inhalation reference values.

Chemical	Inhalation Slope Factor (SF)	Inhalation Reference Concentration (R*f* C)
	(mg/kg/day)$^{-1}$	(mg/m^3)
Benzene	0.0273	0.03
Toluene	N/A	5
Ethylbenzene	N/A	1
O-xylene	N/A	0.1
P-xylene	N/A	0.1

CR) = CDI × SF **Equation 3**

Hazard Quotient (HQ) = CDI/reference dose **Equation 4**

An average annual chronic daily intake was determined in $\boldsymbol{CDI}$ (average daily intake) = $\frac{C \times CF \times IR \times ED}{BW \times AT}$ Equation 1. However, on average an occupational exposure is assumed to be 25 years and therefore for the risk assessment, a cumulative exposure concentration needs to be determined. In Equation (5), the average 25 years chronic dose ($CDI_{25\ year}$) is calculated by using the 25 year occupational exposure duration, as obtained from USEPA default value

Where:

CDI is the cumulative average 25-year dose (mg/kg/day);

CDI is the chronic daily intake (mg/kg);

YE is estimated occupational exposure duration, which is equivalent to 25 years;

240 days is the number of exposure days in a year, excluding weekends (104 days) and annual leave of 21 days.is the total number of days in a year;

60 is the male life expectancy, and 67 is the female life expectancy in South Africa.

Therefore, for a risk assessment calculation, we need the adjusted lifetime chronic daily intake (CDIadj.), taking in to account the occupational life expectancy for a female and a male South African adult in occupational setting.

In Equation (4), we calculated the average CDIadj. Assuming an occupational daily dose intake.

$$CDI\ (adj) = \frac{CDI\ (25\ years\ average\ dose)}{Occupational\ life\ expectancy\ in\ days} \qquad \textbf{Equation 5}$$

We assume that the average chronic daily adjusted dose over an occupational lifetime amongst female and male adults will better simplify the risk assessment calculation, as in Equation (5).

Therefore, for a risk assessment calculation, we need the adjusted occupational lifetime chronic daily intake (CDIadj.), taking in to account the life expectancy for a female and a male South African adult in occupational setting. In Equation (5), we calculated the average CDIadj; assuming a lifetime daily dose intake.

Firth Step: Toxicity Assessment and Risk Characterization

Risk characterization is the final step in the comprehensive process of risk assessment, providing crucial insights into the potential hazards posed by contaminants or pollutants

(Masekameni *et al.*, 2019; Dehghani, Mohammadpour, *et al.*, 2022b). This pivotal stage synthesizes information from hazard identification, dose-response assessment, and exposure assessment to offer a clear depiction of the risk to human health or the environment. For many pollutants, inhalation represents the primary route of exposure. In this context, the inhalation reference concentration (RfC) emerges as a crucial parameter. The RfC is an estimate of the daily human inhalation exposure that is unlikely to result in adverse health effects over a lifetime. It is derived from toxicological and epidemiological studies, focusing on non-carcinogenic health outcomes such as respiratory issues and cellular necrosis (EPA, 2012).

Risk characterization distinguishes between carcinogenic and non-carcinogenic effects. For carcinogens like Benzene, the relative risk is estimated using the slope factor, a metric that quantifies the risk of cancer per unit of exposure. Non-carcinogenic effects, on the other hand, are evaluated through the RfC, which is based on studies of various health outcomes (Masekameni *et al.*, 2019).

A critical aspect of determining an inhalation dose involves the establishment of a benchmark concentration. In this context, the absolute lymphocyte count (ALC) at an adjusted benchmark concentration (BMCL) of 8.2 mg/m^3 was utilized. This value serves as a pivotal reference for calculating lifetime exposure levels and evaluating potential health impacts. Using benchmark dose modeling, the inhalation benzene lifetime exposure was calculated. The resulting value was found to be 0.03 mg/m^3. This figure, derived from rigorous modeling and analysis, has subsequently been described as the reference concentration (RfC) for benzene. The RfC is a critical metric that informs regulatory standards and public health guidelines, ensuring that exposure levels remain within safe limits. Beyond the determination of RfCs, assessing the non-carcinogenic effects of BTEX pollutants is essential for comprehensive risk evaluation. The inhalation reference concentration (RfC) for each BTEX component was utilized to calculate the hazard quotient for non-carcinogenic effects. The hazard quotient is a ratio that compares the potential exposure to a substance with the level at which no adverse effects are expected (Zhang *et al.*, 2012).

The current study, adopted a robust methodology for calculating the cancer risk, leveraging the slope factor from previous similar studies (Africa, Raeesa Moolla Supervisors and Curtis Jasper Knight, 2015; Masekameni *et al.*, 2019; Dehghani, Mohammadpour, *et al.*, 2022a). The slope factor is a crucial parameter in risk assessment, representing the risk per unit of exposure to a particular carcinogen. The primary reasoning behind using the slope factor is its ability to quantify the probability of cancer occurrence over a lifetime of exposure to a

specific concentration of a carcinogen. One significant aspect of carcinogenic compounds is the absence of a threshold level below which no adverse health effects are anticipated. This characteristic necessitates the use of reference levels as guidelines to support decision-making processes (EPA, 2012). It should be emphasized that these reference levels are in our risk assessment, we employed two designated cancer severity indicators for one case: 1×10^{-4} and 1×10^{-6}. These indicators represent the acceptable risk levels, where 1×10^{-4} indicates a risk of one additional cancer case per 10,000 individuals exposed, and 1×10^{-6} indicates a risk of one additional cancer case per 1,000,000 individuals exposed. These indicators are instrumental in evaluating the potential public health impact and guiding regulatory actions.

For carcinogenic pollutants, it must be noted that there is no safe threshold. The risk characterization of carcinogenic pollutants is a vital process in occupational health. By following systematic methods such as the USEPA's Risk Assessment Guidance for Superfund, we can accurately assess and mitigate the risks posed by these dangerous substances. The use of Equation (6) in calculating cancer risk provides a robust framework for understanding the potential health impacts and prioritizing interventions to safeguard public health.

$$CR = CDIadj\ x\ \text{SF} \qquad \textbf{Equation 6}$$

Where:

SF is the slope factor for carcinogenic pollutant (0.0273); CR is the carcinogenic risk; and

CDIadj. is the cumulative lifetime adjusted dose (Equation (5)) over an estimated exposure in a lifetime of 60 or 67 years for male and female adult, respectively.

Therefore, a cancer risk $>1 \times 10^{-6}$ and 1×10^{-4} means that there are carcinogenic effects of concern, while a cancer risk $<1 \times 10^{-6}$ and $<1 \times 10^{-4}$ means that there is a designated cancer severity indicator.

The hazard quotient (HQ) is a vital tool in assessing and managing the potential health risks associated with non-carcinogenic pollutants. By comparing the estimated exposure to a reference dose, the HQ provides a clear and quantifiable measure of risk. Understanding the implications of HQ values is essential for assessing potential health risks:

> HQ > 1: Indicates that the exposure level exceeds the reference dose, suggesting a significant risk of non-carcinogenic health effects. Such situations require immediate attention and mitigation measures to reduce exposure.

HQ < 1: Suggests that the exposure level is below the reference dose, implying a low probability of adverse health effects. This indicates that the current exposure is within acceptable safety limits.

In Equation (7), the procedure for calculating HQ is shown.

$$HQ = CDIadj.((mg/kg)/day)/(RfC(mg/m^3) \times 20m^3/(70\ kg)) \quad (7)$$

Where:

HQ is the hazard quotient;

CDIadj. is the cumulative intake dose; Rf C is the reference;

20 m^3 is the default value for the average adult daily air volume; and

70 kg is the average body weight for a male adult, while 60 kg will be used for female adult

3.6 SCOPE OF THE STUDY

Since this study was conducted through the systematic review of other studies related to average BTEX concentrations from BAS in Municipal WWTPs, the anticipated limitations such as limited literature which focuses on municipalities and/or BAS. The other limitation was the study focused mainly on benzene, toluene, ethylbenzene, and xylenes from BAS in the Municipal wastewater treatment plant WWTP. Pertinent information might have been missed from other studies in different languages as the focus was only for English written articles between 2013 and 2023.

3.7 VALIDITY AND RELIABILITY

The study focused on the South Africa context, unfortunately due to limited data related to South Africa on BTEX concentration from Municipal WWTP; the study was expanded to global scale and only included the literature ranging from 2013 to 2023. All the articles included were focusing on BTEX Concentration from Municipal WWTP and health effects Risk Assessment. The study can be repeated using the similar method and most probably will reproduce the similar result; however, the conclusion might differ according to the sample size, inclusion, and exclusion criteria methods. The end results of the study do not make a single conclusion due to limited data which relates specifically to South African context and on the investigations related to other treatment technologies which gives a room for other future studies to explore this subject further as it has limited data globally.

3.8 ETHICAL CONSIDERATIONS

This study is nested in a larger primary project titled “Characterisation of bioaerosol, volatile organic compounds, odour emissions in wastewater treatment plants and assessment of the associated emerging epidemiological, occupational, and public health risks”, which warranted to seek ethical clearance. This study was a review of the available literature and did not involve any interaction with human subjects. Therefore, a waiver of ethical clearance was requested through submission of the research report to University of the Witwatersrand Human Research Ethics Committee for ethical clearance certificate. As such the Ethics Waver Certificate **REF: R14/49** was granted.

CHAPTER FOUR

This chapter covers the findings that were obtained from the systematic review process approach undertaken. The systematic review necessitate synthesis of article and reports and using the template process that covers the author, year of publication, title of the article or report, type of WWTP, Capacity of the WWTP, Country of origin, sampling method and pollutant mean Concentration. Furthermore, this chapter will highlight the Risk Assessment results using the U.S.EPA Risk Assessment method.

4. RESULTS

4.1 ARTICLES, ABSTRACTS AND REPORTS REVIEWED

Results shown below on Table 10 depicts the name of search database used during this systematic review, total number of articles reviewed, articles reviewed with titles relevant to the study, articles reviewed with articles not relevant to the study, articles reviewed with abstracts relevant to the study, articles reviewed with abstracts not relevant to the study, articles rejected from the study after eligibility assessment and articles accepted after eligibility assessment.

Table 10: Illustration of number of articles received per search website:

Item	Search website	Total Number of Articles reviewed	Articles reviewed with titles relevant to the study	Articles reviewed with titles not relevant to the study	Articles reviewed with abstracts relevant to the study	Articles reviewed with abstracts not relevant to the study	Articles rejected from the study after eligibility assessment	Articles accepted after eligibility assessment
1.	ScienceDirect	521	123	398	13	110	4	8
2.	ProQuest	27	11	16	5	6	3	3
3.	SCOPUS	23	9	14	6	3	2	2
4.	PubMed	8	7	1	6	1	0	1
	Total	579	150 (25.9%)	429 (74.1%)	30 (5.2%)	120 (20.7%)	9 (1.6%)	14 (2.4%)

In overall, approximately 579 articles were subjected to a systematic review using the PRISMA framework approach. The publications were obtained from several search databases, including ScienceDirect, ProQuest, SCOPUS and PubMed. As a result, Table 10 shows that a total of 150 (25.9%) articles were found with titles relevant to the study from all the search engines, with ScienceDirect dominating the search with about 123 articles and 398 articles reject due to not having the relevant key words “BTEX Concentration”, “Municipal Wastewater” AND/OR “BAS” "[All Fields]" from their titles, a total of 123 publications out of the 521 were pertinent to the study. However, due to the absence of important words in their titles, 30 out of the 123 articles were irrelevant. The ProQuest search did yield 27(15.1%) papers whose titles contained the keywords (BTEX concentration) (municipal wastewater treatment plants*) AND (Global) [TITLE-ABST-KEY] making it the second best search engine which yielded more articles pertinent to the study. There were 11 articles accepted which were relevant to key words in their titles, and the remaining 16 were rejected due to not having the keywords in their titles.

There were 23 (41.7%) articles about BTEX Concentration from municipal WWTP in the SCOPUS search database. Out of 23, 9 papers had the pertinent keywords "all (BTEX Concentration*) AND (Municipal WWTP*) all in their names. The other remaining 14 articles did not have any key terms in their titles and were therefore rejected from the study. During the search of BTEX Concentration from Municipal WWTP using the keywords "BTEX Concentration" and “Municipal WWTP" [All Fields]," the PubMed search engine shown a total of 8 results, or 1.4% of the total articles. Whereby 7 out of 8 articles were relevant to the keywords in the titles of the articles. It has shown in overall that the number of articles rejected due to their titles not having the key words were 74.1% of the total retrieved from all search engines with only 25% of the articles having the related keywords of the study on their titles.

From the 4 search engines on which the articles were found, ScienceDirect were the dominant, followed by both ProQuest and SCOPUS respectively and the least were from PubMed. The number of accepted papers on each search website for the study is shown in ***Error! Reference source not found.*** . The term "BTEX Concentration from Municipal WWTP" appeared in the titles and abstracts of the articles.

The selected key terms were utilised to search for articles across various search engines. This comprehensive search strategy was designed to ensure that no relevant studies were overlooked, and thus the databases included a broad array of sources. Following a review of their titles, the accepted articles for the study are illustrated in Figure 10. To be thorough, the search covered multiple well-regarded academic databases. The primary sources of these articles included ScienceDirect, SCOPUS, ProQuest, and PubMed, each providing an extensive collection of peer-reviewed journals and publications.

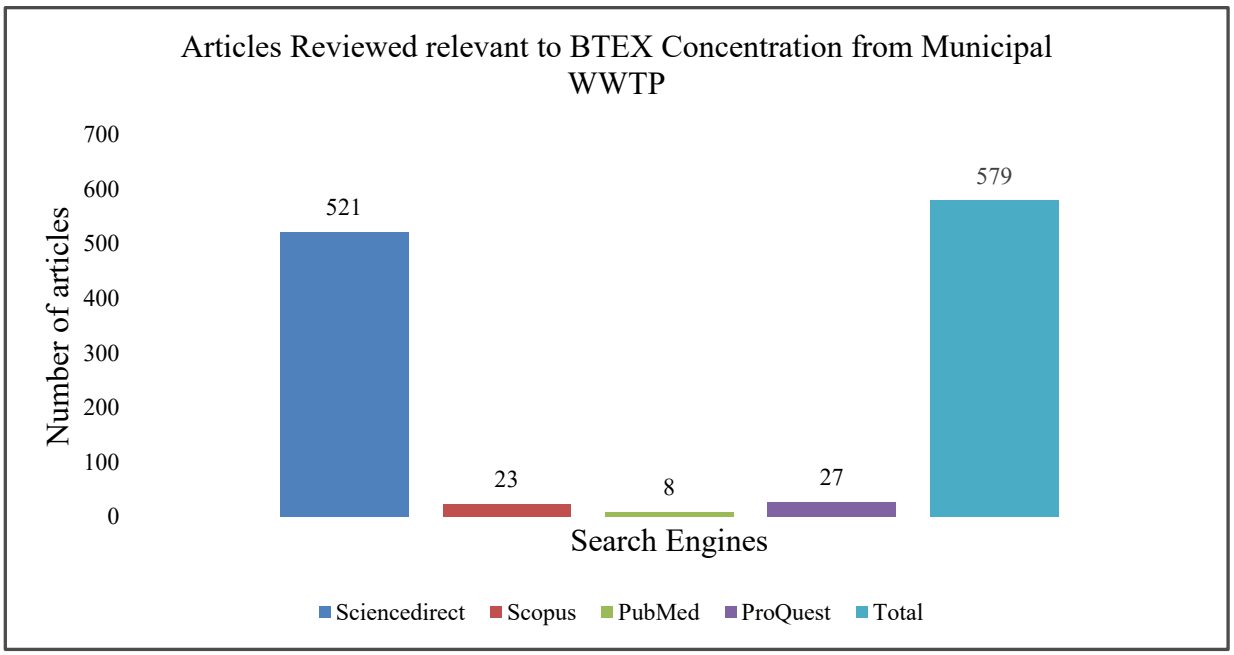


Figure 10: Total Number of Articles reviewed relevant to the BTEX Concentration from Municipal WWTP.

Articles containing relevant keywords in their titles were incorporated into the study, with an aim to capture a wide range of perspectives and findings related to the research topic. After a meticulous selection process, where abstracts were also reviewed to confirm relevance and quality, a final total of 150 articles was achieved, as shown in Figure 11. This curated set of articles forms a solid foundation for the subsequent analysis and discussion sections of the study, ensuring a robust and comprehensive understanding of the subject matter.

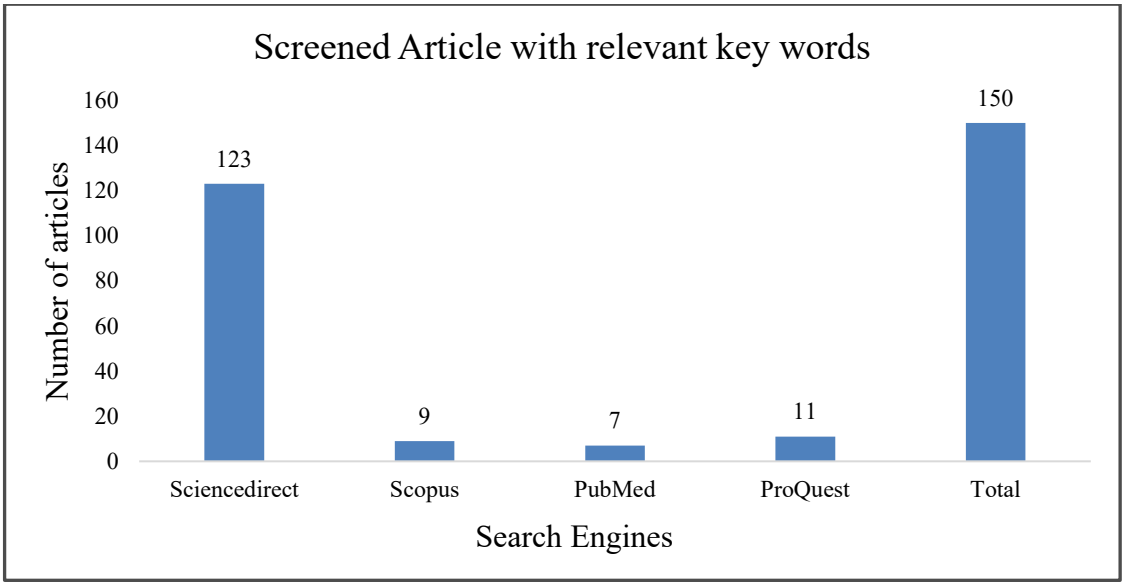


Figure 11 Articles reviewed with titles relevant to the study

The articles that did not have the keywords available in the abstract were determined to be irrelevant to the study. These keywords are crucial for identifying the main themes and relevance of the research. Without them, it is challenging to ascertain whether the articles contribute to the study's objectives. To ensure a focused and pertinent analysis, these articles were excluded from further consideration. Figure 12 illustrates these articles, which total 30. This figure provides a visual representation of the discarded articles, helping to understand the scope of the exclusion process and the criteria applied.

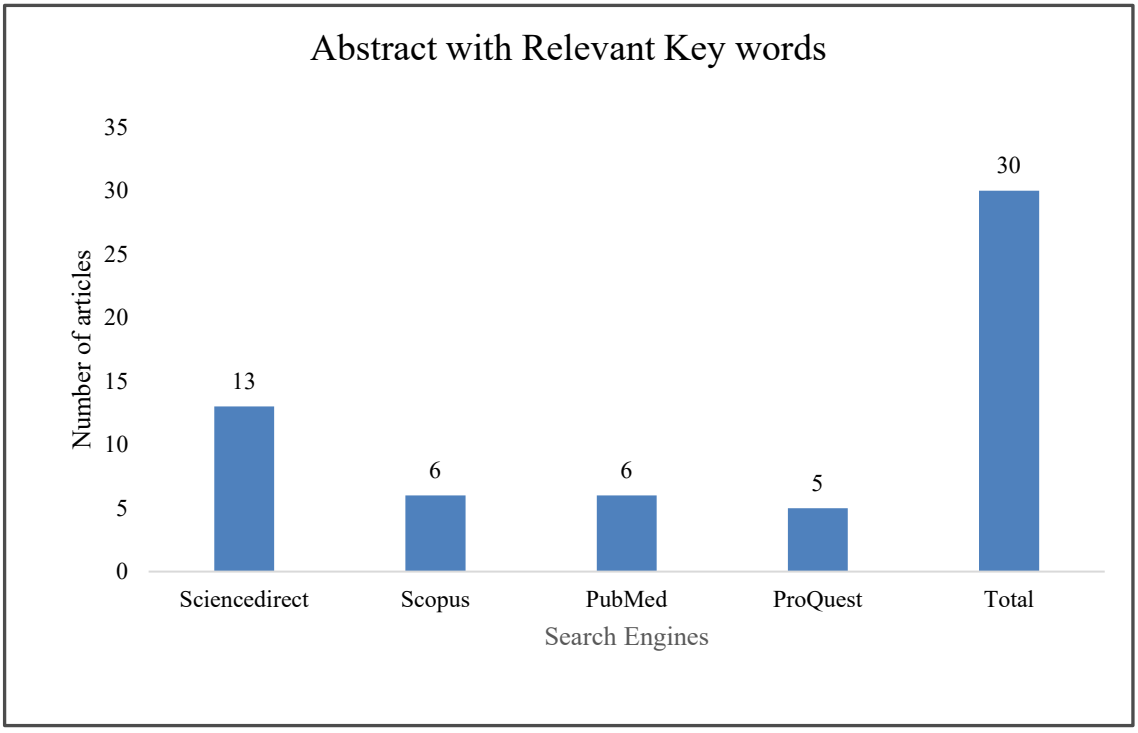


Figure 12: Articles reviewed with abstracts relevant to the study.

During the screening process, certain articles were excluded from the study because their abstracts were not relevant to the search keywords related to BTEX concentration in municipal wastewater treatment plants (WWTP). Consequently, it was necessary to reject 128 articles with non-relevant abstracts. These articles did not meet the criteria for inclusion as they either focused on different pollutants, unrelated wastewater treatment processes, or were reviews without specific data on BTEX concentrations. Additionally, some abstracts lacked sufficient detail to determine their relevance accurately. The total number of abstracts eliminated from the study is depicted in Figure 13, providing a clear visual representation of the screening outcomes and ensuring the focus remains on pertinent research.

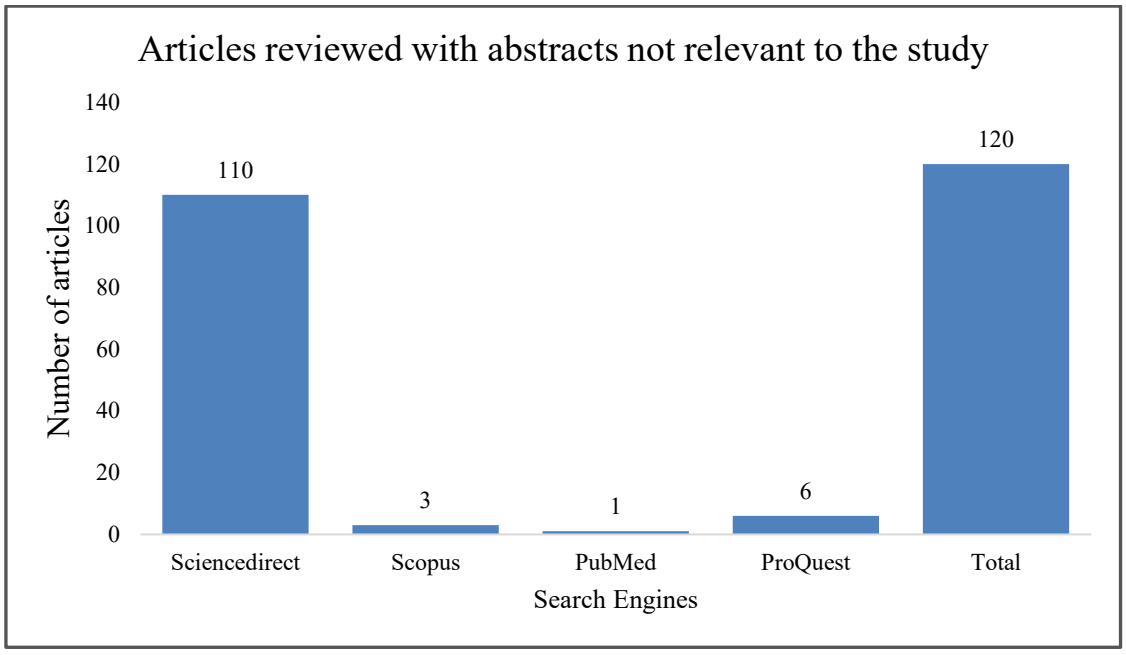


Figure 13: Articles reviewed with abstracts not relevant to the study

After the eligibility assessment, 14 publications from ScienceDirect, SCOPUS, PubMed, and ProQuest remained. Some articles were removed due to duplication, not focusing on BTEX air concentration, or not being from municipal/BAS WWTP, as shown in Figure 14. The eligibility assessment involved a thorough review of each publication's abstract and methodology to ensure relevance and accuracy. Publications were systematically screened based on predefined criteria to identify those specifically addressing BTEX (Benzene, Toluene, Ethylbenzene, and Xylenes) concentrations in the air within the context of wastewater treatment plants. Studies that did not meet these criteria, such as those dealing with other pollutants or conducted in different settings, were excluded to maintain the focus and quality of the review.

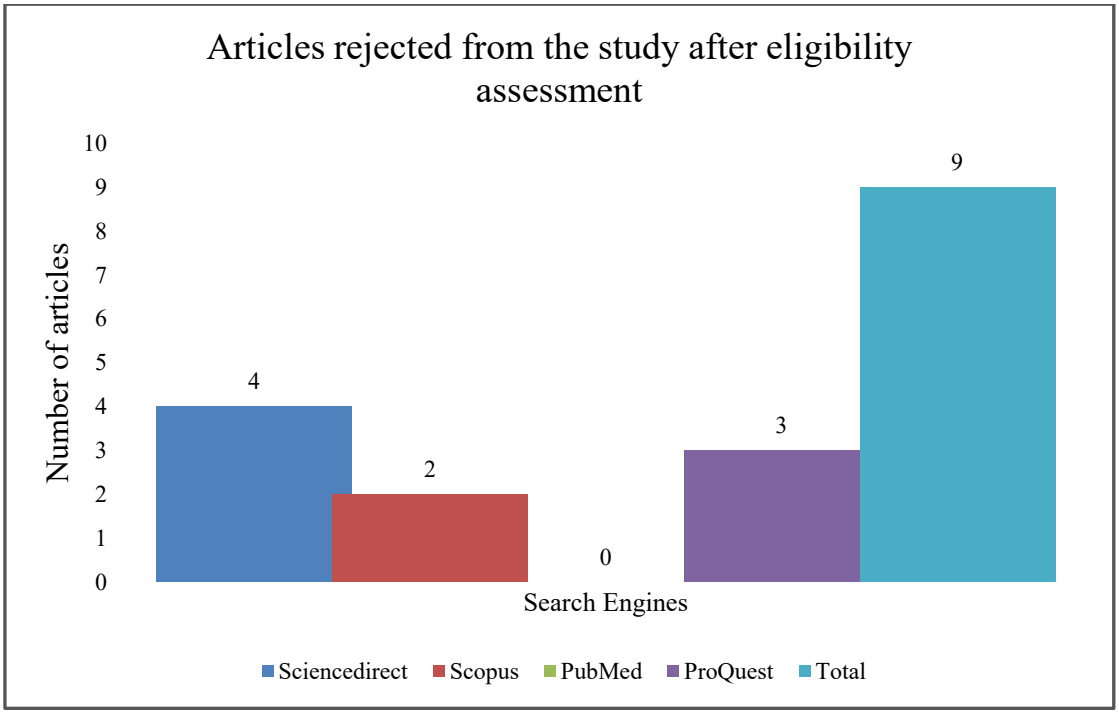


Figure 14 Articles rejected from the study after eligibility assessment

After removing duplicates or articles without BTEX air concentration data and those not related to Municipal/BAS WWTP, the following articles were deemed relevant and eligible for the study. These articles were sourced from ScienceDirect, ProQuest, SCOPUS, and PubMed, as illustrated in Figure 15 of the study results.

The selection process involved an initial screening based on the title and abstract, followed by a full-text review to ensure relevance and the presence of necessary data. Criteria included the specificity of BTEX concentrations, focus on municipal and BAS wastewater treatment plants, and publication within the last ten years. Figure 15 provides a visual summary of the selection methodology, highlighting the numbers of articles reviewed at each stage of the process.

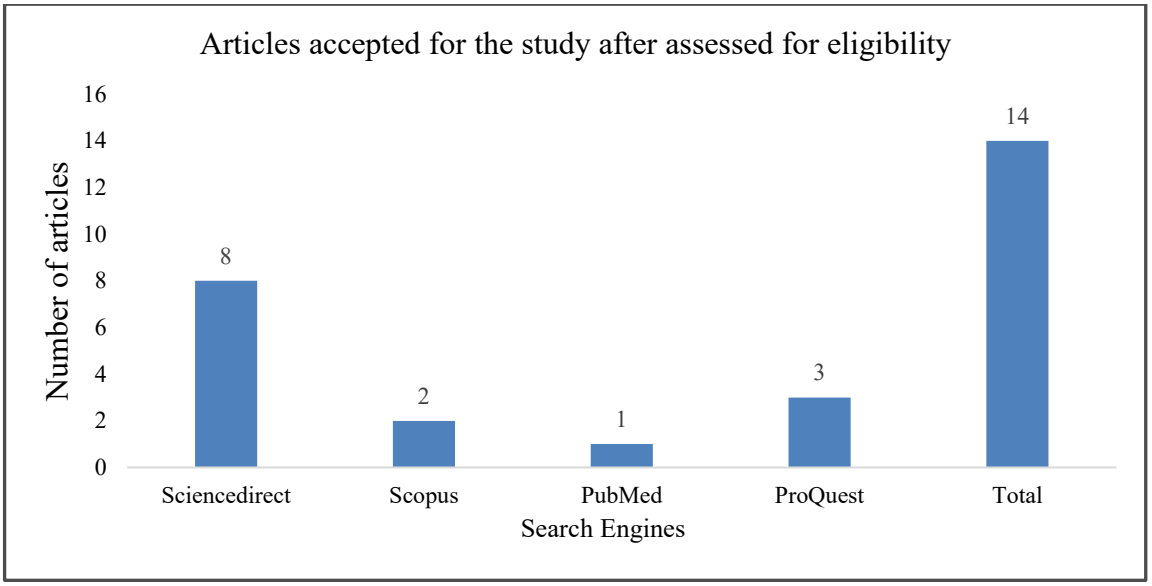


Figure 15: Articles accepted for the study after assessed for eligibility

Total list of articles reviewed is shown in Figure 16, which is a bar chart titled "Number of Relevant Articles with Title and Abstract with key words" compares the number of relevant articles across four databases: ProQuest, PubMed, Scopus, and Sciencedirect. The bars are color-coded to represent three categories: Included Articles with key words (green), Abstracts with Relevant key words (red), and Screened Relevant Title with keywords (blue). The data shows that ProQuest has approximately 2 included articles with key words, 1 abstract with relevant key words, and 3 screened relevant titles with keywords. PubMed has approximately 4 included articles with key words, 2 abstracts with relevant key words, and 6 screened relevant titles with keywords. Scopus has approximately 8 included articles with key words, 4 abstracts with relevant key words, and 12 screened relevant titles with keywords. Sciencedirect has approximately 40 included articles with key words, 20 abstracts with relevant key words, and 120 screened relevant titles with keywords. The chart indicates that Sciencedirect has the highest number of relevant articles in all three categories, followed by Scopus, PubMed, and ProQuest.

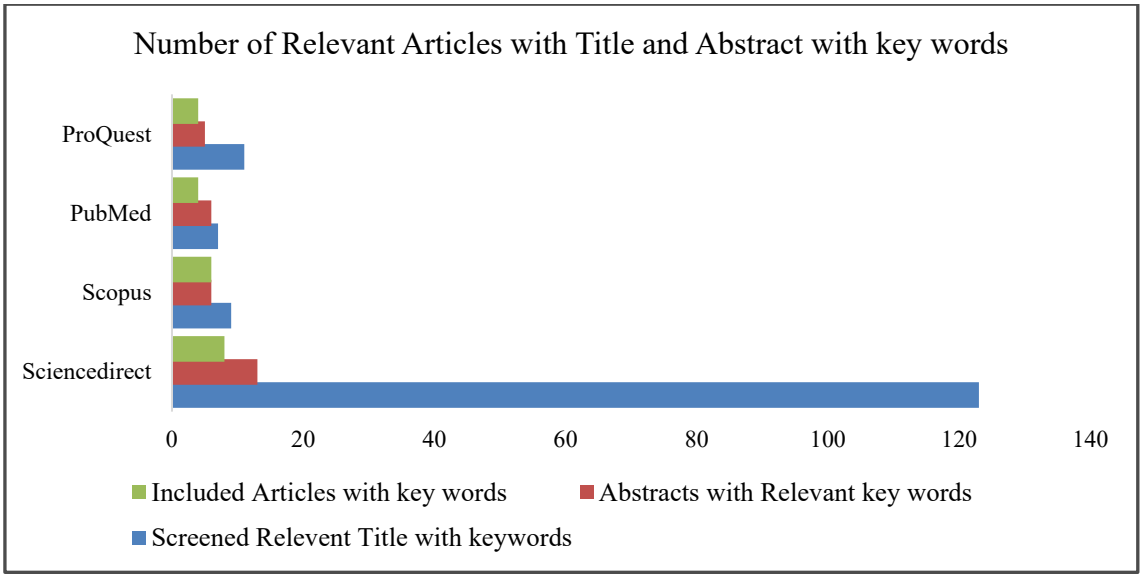


Figure 16: There were four main websites, total of articles, those with keywords and those without key words and finally accepted articles.

Results in Table 11 presents the Mean BTEX Concentration from various studies conducted on municipal BAS WWTPs. The studies analyze pollutant concentrations in µg/m³ for all sized plants from small to macro-sized WWTPs, with a grand total mean concentration calculated across all available data points. This information is critical in understanding the levels of BTEX compounds present in the air around these treatment plants, which can pose health and environmental risks.

The mean benzene concentration varies significantly across studies, with values ranging from 2.78 µg/m³ to 500.0 µg/m³. The highest concentration (500.0 µg/m³) was reported in Study 3 (macro-sized WWTP), while the lowest (2.78 µg/m³) was observed in Study 4. The grand total mean concentration for benzene is 204.9 µg/m³, indicating moderate exposure levels across the studies. These variations may be influenced by factors such as plant size, operational conditions, the wastewater and external environmental factors.

Toluene exhibits the highest mean concentration among the BTEX compounds, with a grand total mean of 596.81 µg/m³. The concentration levels fluctuate significantly across studies, with Study 5 (macro-sized WWTP) reporting an extremely high value of 1,940.0 µg/m³, while Study 4 records one of the lowest at 11.6 µg/m³. This stark difference suggests that certain treatment plants may have operational inefficiencies or process variations that lead to higher emissions of toluene.

Ethylbenzene data is limited, with several studies reporting "No Info." However, where data is available, concentrations range from 3.72 µg/m³ (Study 4) to 550.0 µg/m³ (Study 3). The grand total mean concentration of ethylbenzene is 272.3 µg/m³, which is lower than toluene but still significant. The absence of data from some studies makes it difficult to draw a complete picture of ethylbenzene exposure across all WWTPs.

The presence of m, p-xylene is notable, with concentrations peaking at 953.0 µg/m³ in Study 5, while other studies show widely varying values. Some studies (Study 1, Study 2) report no data, highlighting gaps in research coverage. The grand total mean concentration for m-xylene, p-xylene is 521.6 µg/m³, suggesting that it is a significant pollutant in certain WWTP environments.

Data for o-xylene is also inconsistent across studies, with many studies reporting "No Info." However, where data is available, concentrations vary from 101.5 µg/m³ (Study 1) to 460.0

µg/m³ (Study 5). The grand total mean concentration for o-xylene is 280.7 µg/m³, indicating its presence but with less consistency in monitoring across different studies.

The data highlights significant variability in BTEX concentrations across different WWTPs, with some plants reporting very high levels while others have minimal emissions. Toluene shows the highest overall concentration, while benzene and ethylbenzene have moderate levels. The lack of data ("No Info") in several studies suggests that more research is needed to comprehensively assess BTEX emissions in wastewater treatment environments. These findings are crucial for occupational safety and environmental management, as high BTEX exposure can pose health risks to workers and surrounding communities (Moolla, Curtis and Knight, 2015b).

Table 11: Mean BTEX Concentration from Municipal BAS WWTP

Pollutant	Study 1 Mean Conc. µg/m3	Study 2 Mean Conc. µg/m3	Study 3 Mean Conc. µg/m3	Study 4 Mean Conc. µg/m3	Study 5 Mean Conc. µg/m3	Study 6 Mean Conc. µg/m3	Grand total Mean Concentration µg/m3
WWTP Size	Small	Macro	Macro	Macro	Macro	Macro	
Benzene	91.0	117.6	500.0	2.78	58.0	460	**204.9**
Toluene	459.75	47.7	525.0	11.6	1940.0	No Info	**596.81**
Ethylbenzene	240.5	No info	550.0	3.72	295.0	No Info	**272.3**
m,p-xylene	0	No info	600.0	11.9	953.0	No Info	**521.6**
O-xylene	101.5	No info	No info	No info	460.0	No Info	**280.7**

Table 12 presents the Time-Weighted Average Occupational Exposure Limits (TWA-OELs) established by both the National Institute for Occupational Safety and Health (NIOSH) and South African Occupational Health and Safety (SAOHS) for various pollutants, primarily VOCs, measured in parts per billion (ppb). These pollutants include benzene, toluene, ethylbenzene, and xylene isomers (m, p-xylene and o-xylene). The table also provides the mean concentration of these pollutants in micrograms per cubic meter (µg/m³) and parts per million (ppm).

The table begins by listing pollutants with their corresponding mean concentrations in µg/m³ and ppm. Benzene has a mean concentration of 204.9 µg/m³ and 64.0 ppm. Toluene shows a significantly higher mean concentration of 596.81 µg/m³ and 158.0 ppm. Ethylbenzene is measured at 272.3 µg/m³. The m, p-xylene has a mean concentration of 521.6 µg/m³ and 119.8 ppm, while o-xylene is recorded at 280.7 µg/m³ and 64.5 ppm.

The table further presents the occupational exposure limits as set by SAOHS and NIOSH. For benzene, SAOHS sets a limit of 1 ppm (500.0 ppb), whereas NIOSH's limit is 101.0 ppb, significantly lower than SAOHS's standard. For toluene, SAOHS allows an exposure of 50 ppm (46,432 ppb), while NIOSH sets a much higher limit of 99,498.0 ppb. Ethylbenzene has an SAOHS limit of 100 ppm. In the case of m, p-xylene, SAOHS and NIOSH both set an identical exposure limit of 100 ppm (100,186.0 ppb).

Table 12: TWA-OELs of NIOSH and South African Occupational Health and Safety (SAOHS) limits, in ppb.

Pollutant	Mean Concentration µg/m3	Mean Concentration ppm	Mean concentration Occupational Exposure limit (OEL)		
			SAOHS ppm	SAOHS ppb	NIOSH ppb
Benzene	**204.9**	**64.0**	1	500.0	101.0
Toluene	**596.81**	**158.0**	50	46 432	99 498.0
Ethylbenzene	**272.3**	**62.0**	100	n/d	n/d
m, p-xylene	**521.6**	**119.8**	100	100 186.0	100 186.0
O-xylene	**280.7**	**64.5**		No info	No info

4.2 HUMAN HEALTH RISK ASSESSMENT

As it is shown that the employees in the municipal WWTP are exposed to certain amount of BTEX concentration emitted from the treatment plants. It is important to undertake the inhalation risk analysis in order to determine the potential exposure of employees to this chemicals. This will assist in determining the carcinogenity or non-carcinogenity based on the threshold level of exposure. The calculations will be for both cancer risk and hazard risk of potential inhalation of the BTEX and the results were compared with United States Environmental Protection Agency acceptable standards. For the exposure assessment, we have considered an estimated dose, expressed as a chronic daily intake (mg/kg/day). The route of entry in the WWTP is inhalation during the occupational activities, for adults who are workers working 8 hour per day for 5 days a week, excluding weekends using US.EPA's risk assessment , while the female and males years of life expectancy was adopted from www.statssa.gov.za.

Following the US.EPA risk assessment framework and related equations from equation 1 to 7, were adopted and used to calculate the outcomes of the risk assessment calculations following the summary of equations for female and male employees as illustrated as in Table 13.

Table 13: Equations used for risk assessments in the study.

Female Employees		
CDI(averaged daily intake) = (C × CF × IR × ED)/(BW × AT)	**HQ** = CDIadj.((mg/kg)/day)/(RfC(mg/mˆ3) × 20m3/(60 kg))	
CDIadj = CDI (25 years average dose)/ life expectency for female	**ED** =(Actual exposure duration/24h) × 240	**CR**= CDIadj × SF

Male Employees										
CDI(averaged daily intake) = (C × CF × IR × ED)/(BW × AT)				**HQ** = CDIadj.((mg/kg)/day)/(RfC(mg/mˆ3) × 20m3/(70 kg))						
CDIadj = CDI (25 years average dose)/ life expectency for male				**ED** =(Actual exposure duration/24h) × 240				**CR**= CDIadj × SF		

The results in Table 14 indicate the carcinogenic (CR) and non-carcinogenic (HQ) risk assessment calculations for female adults, focusing on various pollutants found in wastewater treatment plants (WWTP) of different sizes. The columns in the table include parameters such as BAS WWTP Sizes, Pollutant, Average Concentration (µg/m^3), CF, IR (m^3/day), ED (Year), RfC, YE, BW (kg), AT, CDI (mg/kg/day), CR, SF, and HQ.

The rows are categorized based on the size of the WWTP, including small-scale, medium-scale, large-scale, and macro-scale plants. Each category lists various pollutants like Benzene, Toluene, Ethylbenzene, and Xylene, along with their respective average concentrations and calculated risk values.

This table provides detailed information on the exposure risks associated with different pollutants in wastewater treatment plants of varying sizes. It highlights both carcinogenic and non-carcinogenic risks for female adults based on specific parameters such as concentration levels, intake rates, exposure duration, body weight, and other factors. This data is crucial for understanding the potential health impacts of these pollutants on female adults and can be used to inform risk assessments and mitigation strategies.

Table 14: Carcinogenic and non-carcinogenic risks for adult females employees in BAS WWTP

Carcinogenic and non-carcinogenic risks															
BAS WWTP Sizes	**Pollutant**	**Average Concentration**	**CF**	**IR**	**ED**	**RfC**	**YE**	**BW**	**AT**	**CDI $_{year}$**	**CDI $_{25\ years}$**	**CDI$_{adj.}$**	**SF**	**CR**	**HQ**
		ug/m3		**m3/day**	**Year**			**kg**		**mg/kg/day**	**mg/kg/day**	**mg/kg/d**			
Small scale (0.5-2ML/day capacity)	Benzene	91	0,001	20	80	0,029	25	60	67	3,62E-02	9,05E-01	1,35E-02	0,0273	3,69E-04	0,155
	Toluene	459,75	0,001	20	80	5	25	60	67	1,83E-01	4,57E+00	6,83E-02	N/A	N/A	0,005
	Ethylbenzene	240,5	0,001	20	80	1	25	60	67	9,57E-02	2,39E+00	3,57E-02	N/A	N/A	0,012
	m,p-xylene	0	0,001	20	80	0,1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	O-xylene	101,5	0,001	20	80	0,1	25	60	67	4,04E-02	1,01E+00	1,51E-02	N/A	N/A	0,050
Medium scale (2-10ML/day capacity)	Benzene	0	0,001	20	80	0,029	25	60	67	0,00E+00	0,00E+00	0,00E+00	0,0273	0,00E+00	0,000
	Toluene	0	0,001	20	80	5	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	Ethylbenzene	0	0,001	20	80	1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	m,p-xylene	0	0,001	20	80	0,1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	O-xylene	0	0,001	20	80	0,1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
Large scale (10-25ML/day capacity)	Benzene	0	0,001	20	80	0,029	25	60	67	0,00E+00	0,00E+00	0,00E+00	0,0273	0,00E+00	0,000
	Toluene	0	0,001	20	80	5	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	Ethylbenzene	0	0,001	20	80	1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	m,p-xylene	0	0,001	20	80	0,1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	O-xylene	0	0,001	20	80	0,1	25	60	67	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
Macro Size Plants (>25ML/Day capacity)	Benzene	227,7	0,001	20	80	0,029	25	60	67	9,06E-02	2,27E+00	3,38E-02	0,0273	9,23E-04	0,389
	Toluene	631,1	0,001	20	80	5	25	60	67	2,51E-01	6,28E+00	9,37E-02	N/A	N/A	0,006
	Ethylbenzene	282,9	0,001	20	80	1	25	60	67	1,13E-01	2,81E+00	4,20E-02	N/A	N/A	0,014
	m,p-xylene	521,6	0,001	20	80	0,1	25	60	67	2,08E-01	5,19E+00	7,75E-02	N/A	N/A	0,258
	O-xylene	460	0,001	20	80	0,1	25	60	67	1,83E-01	4,58E+00	6,83E-02	N/A	N/A	0,228
BAS WWTP Average	Benzene	204,9	0,001	20	80	0,029	25	60	67	8,16E-02	2,04E+00	3,04E-02	0,0273	8,31E-04	0,350
	Toluene	596,81	0,001	20	80	5	25	60	67	2,38E-01	5,94E+00	8,86E-02	N/A	N/A	0,006
	Ethylbenzene	272,3	0,001	20	80	1	25	60	67	1,08E-01	2,71E+00	4,04E-02	N/A	N/A	0,013
	m,p-xylene	521,6	0,001	20	80	0,1	25	60	67	2,08E-01	5,19E+00	7,75E-02	N/A	N/A	0,258
	O-xylene	280,7	0,001	20	80	0,1	25	60	67	1,12E-01	2,79E+00	4,17E-02	N/A	N/A	0,139

CDI_{year}: the estimated daily intake corresponding to an annual dose; $CDI_{25\ year}$: cumulative average 25-year dose;

CDIadj. is the cumulative intake dose; CR: carcinogenic risk; HQ: hazard quotient; IR: Inhalation rate; SF: Slope factor

The results presented in

Table 15 indicate the carcinogenic (CR) and non-carcinogenic (HQ) risk assessment calculations for male adults, focusing on BTEX pollutants found in wastewater treatment plants (WWTP) of different sizes. The columns in the table include parameters such as BAS WWTP Sizes, Pollutant, Average Concentration (µg/m3), CF, IR (m3/day), ED (Year), RfC, YE, BW (kg), AT, CDI (mg/kg/day), CR, SF, and HQ.

The rows are categorized based on the size of the WWTP, including small-scale (<2MLD capacity), medium-scale (>2MLD-<10MLD capacity), large-scale (>10MLD capacity), and macro-sized plants. Each category lists various pollutants like Benzene, Toluene, Ethylbenzene, and Xylene, along with their respective average concentrations and calculated risk values.

This table provides a comprehensive overview of the health risks posed by different pollutants in water treatment plants of varying sizes. It highlights both carcinogenic and non-carcinogenic risks for male adults based on specific parameters such as concentration levels, intake rates, exposure duration, body weight, and other factors. This information is crucial for understanding the potential health impacts of these pollutants on male adults and can be used to inform risk assessments and mitigation strategies.

Table 15: Carcinogenic and non-carcinogenic risks for adult males employees in BAS WWTP

Carcinogenic and non-carcinogenic risks															
BAS WWTP Sizes	**Pollutant**	**Average Concentration**	**CF**	**IR**	**ED**	**RfD**	**YE**	**BW**	**AT**	**CDI $_{year}$**	**CDI $_{25\ years}$**	**CDI$_{adj.}$**	**SF**	**CR**	**HQ**
		ug/m3			**year**			**kg**		**mg/kg/day**	**mg/kg/day**	**mg/kg/d**			
Small scale (0.5-2ML/day capacity)	Benzene	91	0,001	20	80	0,029	25	70	60	3,47E-02	8,67E-01	1,44E-02	0,029	4,19E-04	0,142
	Toluene	459,75	0,001	20	80	5	25	70	60	1,75E-01	4,38E+00	7,30E-02	N/A	N/A	0,004
	Ethylbenzene	240,5	0,001	20	80	1	25	70	60	9,16E-02	2,29E+00	3,82E-02	N/A	N/A	0,011
	m,p-xylene	0	0,001	20	80	0,1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	O-xylene	101,5	0,001	20	80	0,1	25	70	60	3,87E-02	9,67E-01	1,61E-02	N/A	N/A	0,046
Medium scale (2-10ML/day capacity)	Benzene	0	0,001	20	80	0,029	25	70	60	0,00E+00	0,00E+00	0,00E+00	0,0273	0,00E+00	0,000
	Toluene	0	0,001	20	80	5	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	Ethylbenzene	0	0,001	20	80	1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	m,p-xylene	0	0,001	20	80	0,1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	O-xylene	0	0,001	20	80	0,1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
Large scale (10-25ML/day capacity)	Benzene	0	0,001	20	80	0,029	25	70	60	0,00E+00	0,00E+00	0,00E+00	0,0273	0,00E+00	0,000
	Toluene	0	0,001	20	80	5	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	Ethylbenzene	0	0,001	20	80	1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	m,p-xylene	0	0,001	20	80	0,1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
	O-xylene	0	0,001	20	80	0,1	25	70	60	0,00E+00	0,00E+00	0,00E+00	N/A	N/A	0,000
Macro Size Plants (>25ML/Day capacity)	Benzene	227,7	0,001	20	80	0,029	25	70	60	8,67E-02	2,17E+00	3,61E-02	0,0273	9,87E-04	0,356
	Toluene	631,1	0,001	20	80	5	25	70	60	2,40E-01	6,01E+00	1,00E-01	N/A	N/A	0,006
	Ethylbenzene	282,9	0,001	20	80	1	25	70	60	1,08E-01	2,69E+00	4,49E-02	N/A	N/A	0,013
	m,p-xylene	521,6	0,001	20	80	0,1	25	70	60	1,99E-01	4,97E+00	8,28E-02	N/A	N/A	0,237
	O-xylene	460	0,001	20	80	0,1	25	70	60	1,75E-01	4,38E+00	7,30E-02	N/A	N/A	0,209
BAS WWTP Average	Benzene	204,9	0,001	20	80	0,029	25	70	60	7,81E-02	1,95E+00	3,25E-02	0,0273	8,88E-04	0,320
	Toluene	596,81	0,001	20	80	5	25	70	60	2,27E-01	5,68E+00	9,47E-02	N/A	N/A	0,005
	Ethylbenzene	272,3	0,001	20	80	1	25	70	60	1,04E-01	2,59E+00	4,32E-02	N/A	N/A	0,012
	m,p-xylene	521,6	0,001	20	80	0,1	25	70	60	1,99E-01	4,97E+00	8,28E-02	N/A	N/A	0,237
	O-xylene	280,7	0,001	20	80	0,1	25	70	60	1,07E-01	2,67E+00	4,46E-02	N/A	N/A	0,127

4.2.1. *Non Carcinogenic risk for female*

The Benzene Hazard Quotient (HQ) stands out as the highest among all the BTEX pollutants. This is particularly evident in macro-scale WWTPs and the BAS WWTP average, where HQ values approach 0.4. Such a high HQ suggests a considerable non-cancer health risk for female employees exposed to benzene in these wastewater treatment environments. The elevated HQ values highlight the necessity for stricter exposure controls, especially in large-scale facilities.

Both Toluene HQ and Ethylbenzene HQ show relatively low values across all WWTP scales, indicating that these pollutants pose minimal non-cancer health risks for female employees. Their consistently low HQ values suggest that exposure to toluene and ethylbenzene in these work environments is unlikely to cause significant health concerns compared to other pollutants, such as benzene and xylene isomers. Despite this, continued monitoring is essential to ensure exposure levels remain within safe limits.

The m, p-Xylene HQ values are notably high, especially in macro-scale WWTPs and the BAS WWTP average, where the HQ values approach 0.3. This indicates a potential health concern for female employees exposed to these compounds, though the risk remains lower than that of benzene.

Similarly, the o-Xylene HQ values show a significant trend, with macro-scale WWTPs displaying the highest values, followed closely by the BAS WWTP average. While not as high as benzene HQ, the presence of elevated xylene HQ values suggests that prolonged exposure could still contribute to adverse health effects. These findings emphasize the need for further investigation and possible control measures to limit xylene exposure in wastewater treatment plants.

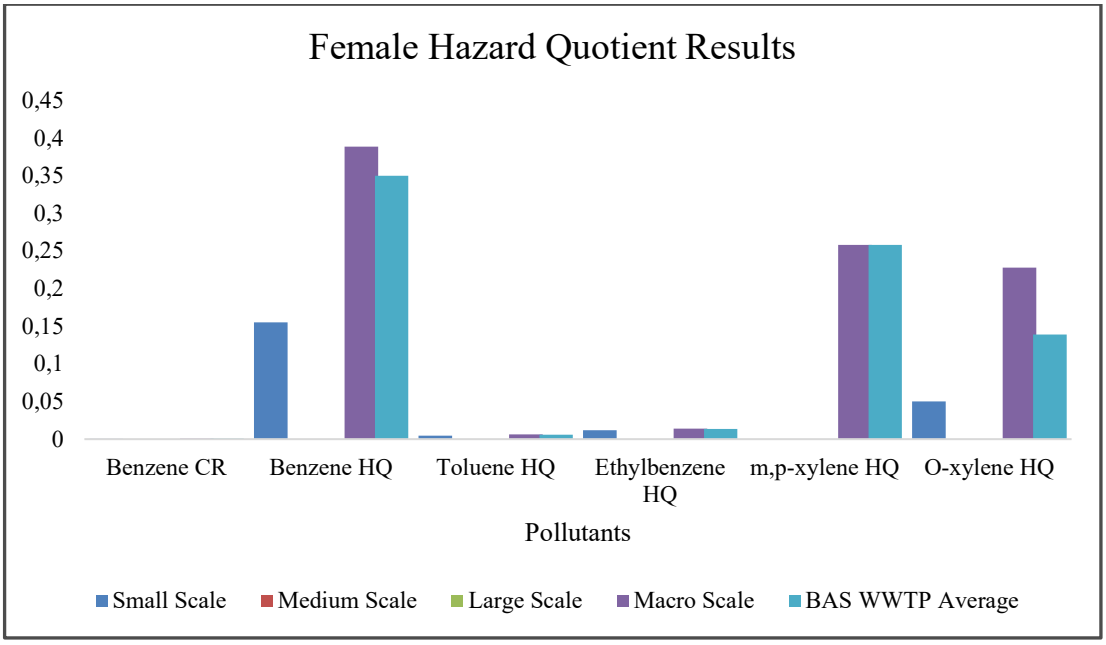


Figure 17: Female employees Hazard Quotient Results in BAS WWTP.

4.2.2. *Carcinogenic risk for female*

The carcinogenic risk of benzene to female adults is depicted in Figure 18 which provides a visual representation of the cancer risk (CR) associated with benzene exposure for females across different scales of wastewater treatment plants (WWTP). The x-axis represents the cancer risk compared with the US.EPA threshold risk limit of 1×10^{-4} or/ 0.0004 as unacceptable CR. The y-axis categorizes the WWTP scales into Small Scale, Medium Scale, Large Scale, Macro Scale, and BAS WWTP Average of all the plant sizes.

For Small Scale WWTPs, the cancer risk is approximately 0.00037 which is below the threshold risk limit of 0.0004. Medium and large scale there are no data available. Macro Scale WWTPs have a higher cancer risk of approximately 0.00092 which is 56% higher than the threshold limit of 0.0004. The BAS WWTP Average is 0.00083 which is also 51% higher than the threshold limit, which indicated approximately 2 additional cancer case per 10 000 individuals exposed.

This chart is significant as it highlights the potential cancer risk especially for female workers in the macro scale plant and how cancer risk due to benzene exposure varies depending on the scale of the wastewater treatment plant. The data suggests that larger and more extensive WWTPs tend to have higher associated cancer risks for females. This information can be crucial for public health assessments and environmental safety regulations, as it underscores the need for targeted interventions and stricter controls in larger WWTPs to mitigate the health risks associated with benzene exposure.

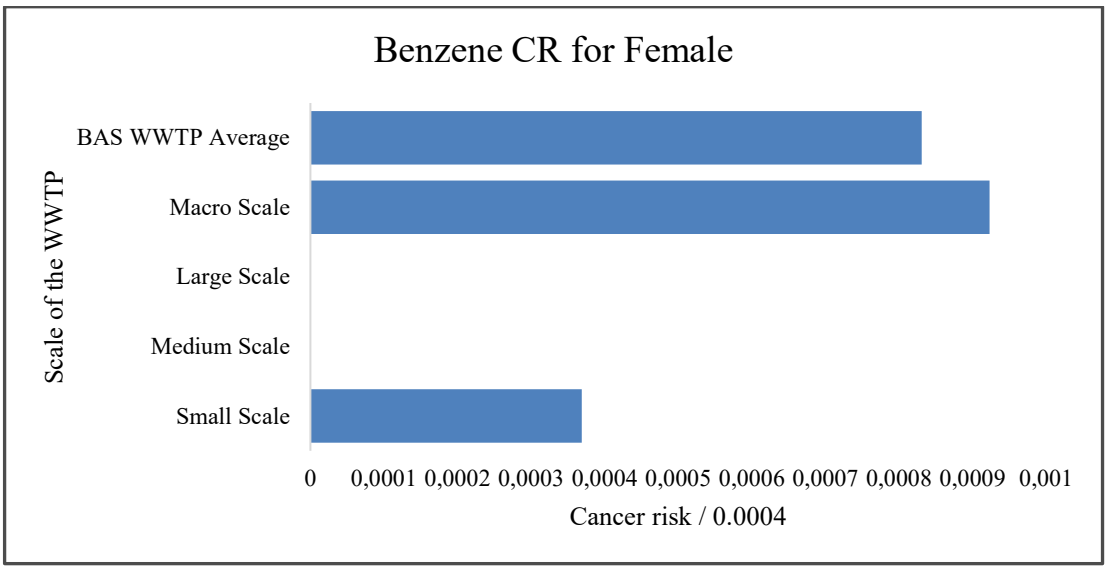


Figure 18: Benzene Carcinogenic risk for female employees in BAS WWTP.

Figure 17 shows non-carcinogenic risk, while Figure 18 displays carcinogenic risk for female employees exposed to BTEX in the BAS WWTP. In these figures, benzene is used as an indicator of carcinogenic risk, highlighting the potential long-term health effects such as cancer due to exposure. On the other hand, the hazard quotient represents non-carcinogenic risk, which refers to other adverse health impacts excluding cancer.

For small and macro-sized WWTPs, the analysis revealed a measure of carcinogenic risk, implying that female workers might experience adverse health effects from their exposure to BTEX at these sites. However, due to lack of data, medium and large WWTPs had no data analysis. And the BAS WWTP shows an average level of risk across the board, indicating that there might be some concerns regarding both carcinogenic and non-carcinogenic risks, but not at critical levels. This baseline data can be instrumental in evaluating current safety protocols and implementing further improvements to ensure the health and safety of all employees working in various capacities within these treatment plants.

4.2.3. *Non Carcinogenic risk for male*

The Figure 19 provides a comparison of the hazard quotients (HQ) which is non-carcinogenic risk for various pollutants affecting males. The x-axis lists the pollutants, which include Benzene HQ, Toluene HQ, Ethylbenzene HQ, m-p-xylene HQ, and O-xylene HQ. The y-axis represents the hazard quotient values, ranging from 0 to 0.4.

The graph uses different colours to represent five scales of WWTP. Small Scale (blue), Medium Scale (red), Large Scale (green), Macro Scale (purple), and BAS WWTP Average (light blue). Each pollutant has multiple bars indicating the hazard quotient for each scale.

For Benzene HQ, the graph shows a significant value only in the Small Scale category. Toluene HQ has very low or negligible values across all scales, indicating minimal risk. Ethylbenzene HQ shows some variation but remains relatively low across all scales. The m-p-xylene HQ and O-xylene HQ have higher values in the Macro Scale compared to other scales, suggesting a greater risk associated with these pollutants in larger WWTPs. All these values are below the threshold of <1, which suggest that the exposure level for the employees is below the reference dose, there is low probability to cause adverse health effects and the exposure is within the acceptable safety limits.

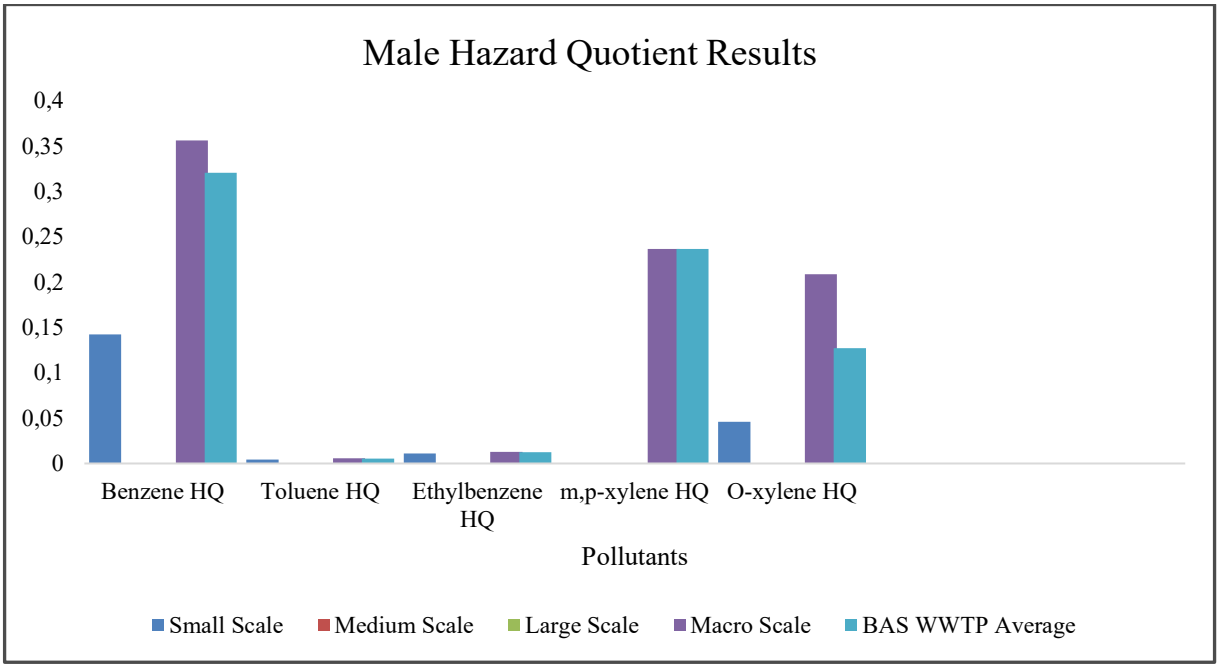


Figure 19: Male employees Hazard Quotient Results in BAS WWTP.

4.2.4. *Carcinogenic risk for male*

The horizontal part of the carcinogenic risk for male bar chart of Figure 20 illustrates the cancer risk (CR) associated with benzene exposure for males across different scales of WWTP and an average value for all the sizes. The x-axis represents the cancer risk values, ranging from 0 to 0.0012, while the y-axis lists five categories: BAS WWTP Average, Macro Scale, Large Scale, Medium Scale, and Small Scale WWTP.

The Figure 20 shows that both the BAS WWTP Average and Macro Scale have a cancer risk of approximately 0.0009 which is 55% higher than the unacceptable threshold limit of 0.0004

or/ 1 x 10^{-4} , meaning there is approximately 2 additional cancer case added per 10 000 individuals exposed. The Small Scale category has a lower cancer risk of approximately 0.0004, which means there is atleast 1 additional cancer case added per 10 000 individuals exposed. Notably, there are no data for both Large Scale and Medium Scale categories.

This Figure 20 highlights the variation in benzene-related cancer risk among males based on different scales of the plant and exposure or measurement methods, with significant differences between the small scale and other categories. This information is crucial for understanding the potential health impacts of benzene exposure and can inform public health assessments and safety regulations.

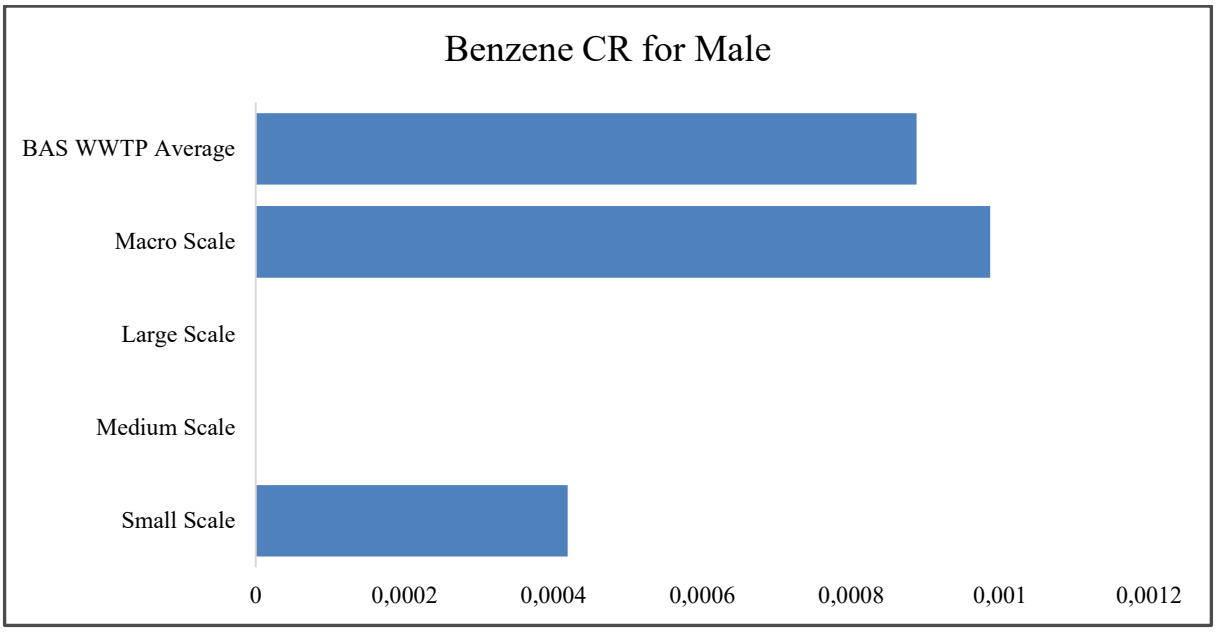


Figure 20: Benzene Carcinogenic risk for male employees in BAS WWTP.

Figure 19 shows the non-carcinogenic risk, while Figure 20 displays the carcinogenic risk for male employees exposed to BTEX in the BAS WWTP. Benzene indicates carcinogenic risk, and the hazard quotient denotes non-carcinogenic risk for small, macro scale and average. Medium and large sizes have no data from the literature.

In more detail, Figures 20 and 21 comprehensively illustrate how different sizes of WWTPs impact the health risks posed to employees. Specifically, benzene, a well-known carcinogen, is used as an indicator to measure the potential cancer risk associated with exposure. The hazard quotient, on the other hand, provides a measure of non-carcinogenic risks, which are particularly relevant for smaller and macro-sized WWTPs where such hazards might be more prevalent. Additionally the BAS WWTP Average serves as a benchmark by representing the average risk levels observed across various plant sizes.

CHAPTER FIVE: DISCUSSION

This chapter discusses and contrasts the objectives findings reported in this study with the similarities and differences of the previous studies that have been conducted elsewhere. It further shows in-depth the results of mean concentration against the available legislative limits. The study further indicate the findings of the health risk assessment and comparison with the threshold limit for carcinogenic and non-carcinogenic risk present. The chapter concludes with the limitations and suggestions on what is recommended moving forward to advance the relevancy of the study.

5. DISCUSSION

5.1 RETRIEVED ARTICLES AND ABSTRACTS

Benzene, toluene, ethylbenzene, and xylene, collectively known as BTEX, are volatile organic compounds commonly found in municipal wastewater. (Bencsik *et al.*, 2024) highlights that BTEX compounds are significant emerging contaminants in municipal wastewater and emphasizes the need for stricter effluent quality regulations and additional purification using physico-chemical methods to substantially reduce BTEX levels. These compounds are of significant concern due to their potential health risks and environmental impact (Dehghani, Mohammadpour, *et al.*, 2022b).

While numerous studies have been conducted globally to investigate the concentration of BTEX emissions from municipal wastewater treatment plants, South Africa remains underrepresented in this research area, whereby there is a notable lack of research in South Africa as in Annexure D. From this study, it can be confirmed that there are no studies which were undertaken specifically in South Africa investigating the concentration of BTEX emissions from the Municipal wastewater treatment plant in the reporting duration, despite the fact that this technology is mostly used in South Africa. (Muradi and Vaghani, 2020) found that BTEX emissions varied significantly over time and space in the municipal WWTP, indicating the need for continuous monitoring and tailored treatment strategies.

However, on the global scale there are number of studies which were found related to BTEX concentration from municipal wastewater treatment plant. Globally it has been found that the biological activated sludge wastewater treatment technology is highly used due to its effectivity and efficiency in treating the wastewater from the municipal sector (Bencsik *et al.*, 2024).

Despite the BTEX concentration subject being extensive studied in other microenvironment such as petroleum, urban environment and roads which indicated high concentration and human exposure with the high probability of development health effects (Dörter *et al.*, 2022). This study results have indicated that there are only six (6) studies globally that have assessed the concentration of BTEX in biological activated sludge WWTP. This limited data signifies a substantial gap in the literature, which is crucial for a comprehensive understanding of the exposure risks faced by wastewater treatment plant operators and supervisors. This sparse existing body of literature on the concentration of BTEX in biological activated sludge, present a significant lack of data that can provide a clear picture of the occupational exposure levels in wastewater treatment facilities. This dearth of information constrains the ability of researchers and policymakers to fully comprehend the implications of BTEX exposure on workers' health.

Considering the fact that the operators and supervisors in wastewater treatment plants typically spend around 8 hours per day in this microenvironment. The limited availability of data on BTEX concentration poses a risk to their occupational health and safety. BTEX compounds are known for their toxic effects, which include respiratory issues, skin irritation, and potential carcinogenicity (Davidson, Hannigan and Bowen, 2021). The lack of comprehensive studies makes it difficult to establish effective safety measures and interventions, thereby leaving workers vulnerable to these health risks. The BTEX emissions vary significantly over time and space, indicating the need for continuous monitoring and tailored treatment strategies. Hence it is important to ensure ventilation is available and using of safety aids such as face masks for workers (Muradi and Vaghani, 2020; Bencsik *et al.*, 2024).

5.2 BTEX CONCENTRATIONS FROM BAS MUNICIPAL WWTP

The concentration of the BTEX from the municipal wastewater treatment plants was recorded from different studies conducted to investigate the subject and the BTEX mean concentrations were calculated whereby benzene was found to be 204.9 µg/m^3 (64 ppm) which is 64 times higher than the SAOHS exposure limit of 1 ppm. The average Toluene on the other hand was found to be 596.81 µg/m^3 (158ppm) which is three times higher than the SAOHS exposure limit of 50ppm. The average ethylbenzene concentrations is 272.3 µg/m^3 (62.0ppm) which is below the SAOHS exposure limit of 100ppm. The average m, p-xylene was calculated to be 521.6 µg/m3 (119.8ppm) which is slightly above the 100ppm exposure limit in South Africa. And lastly the o-xylene was calculated to have a mean of 280.7 µg/m^3 (64.5ppm). The results indicate that emissions from the WWTP exceed both South African

and international Occupational Exposure Limits as in Table 12, posing a higher risk to employees.

Comparing with other studies results which focused on landfill microenvironment, studies reveals some difference with Benzene concentrations in landfill gas been reported to be around 140.3 µg/m³1, which is lower than the levels found in WWTP emissions. Toluene concentration in landfills gas been significantly higher, with some studies reporting levels around 1271.7 µg/m³. Ethylbenzene concentrations in landfill gas have been found to be around 239.9 µg/m³1, which is comparable to the levels in WWTP emissions. Xylene concentrations in landfill gas have been reported to be around 341.3 µg/m³1, which is lower than the levels found in WWTP emissions. Landfills: Specific data for o-xylene is often grouped with other xylene isomers, but overall xylene concentrations in landfill gas are generally lower than those in WWTP emissions (Durmusoglu, Taspinar and Karademir, 2010).

Overall, while some BTEX concentrations in landfill emissions are lower than those in WWTP emissions, toluene levels in landfills can be significantly higher. This indicates that both WWTPs and landfills pose different levels of risk for BTEX exposure to workers.

Comparing the BTEX concentrations from municipal WWTP to those found in major emitting industries such as oil and natural gas (ONG) reveals some significant differences particularly during midstream operations like tanker loading, Benzene can reach up to 5.391 ppm, Toluene (10.376 ppm), Ethylbenzene (1.583ppm), and Xylene and other isomers (2.067 ppm) which all are significantly lower than the levels found in WWTP emissions. In overall, the BTEX concentrations in WWTP emissions are notably higher than those typically found in major emitting industries, particularly in midstream petroleum operations. This indicates a higher risk for employees at WWTPs compared to those in the petroleum industry (Das, Giri and Manjunatha, 2024).

Overall, the BTEX concentrations in WWTP emissions are notably higher than those typically found in different major emitting industries such as petroleum, automative, painting, cleaning and landfills. This indicates a higher risk for employees at WWTPs compared to those in major emitting industry operations.

5.3 HEALTH RISK ASSESSMENT

The BTEX concentrations from various sized BAS WWTPs globally were analyzed as part of a systematic review. The findings showed BTEX concentrations in studies related to small-scale WWTPs (1) and macro-scale WWTPs (5), with no data for medium and large-scale WWTPs. This indicates a limitation in studies on BTEX emissions from municipal

WWTPs globally. The results for small-scale WWTPs indicated the cancer risk for females to be 0.00037 which is below the threshold risk limit of 0.0004/ 1 x 10^{-4} and for male of 0.00042 which is slightly higher than the threshold limit. The Medium and large scale there were no data available from the systematic review literature search. Macro Scale WWTPs have a higher cancer risk of approximately 0.00092 for females and 0.00098 for males which is 56% higher than the threshold limit of 0.0004/1 x 10^{-4}. The BAS WWTP Average is 0.00083 which is also 51% higher than the threshold limit for females. While for male both the BAS WWTP Average and Macro Scale have a cancer risk of approximately 0.0009 which is 55% higher than the unacceptable threshold limit of 0.0004 or/ 1 x 10-4. Therefore, on average there is a risk of two additional cancer case per 10 000 individuals exposed BAS WWTPs activities, irrespective of the plant size and could face some degree of cancer risk.

Comparing with the other studies such as one conducted at Urban Areas in Rajasthan, India which indicated the Lifetime Cancer Risk (LCR) which ranged from 6.04×10^{-6} to 1.92×10^{-5} for males, 1.09×10^{-6} to 2.24×10^{-5} for females, and 1.17×10^{-5} to 3.73×10^{-5} for children. This indicated cancer risk values in urban areas are generally lower than those found in macro-scale WWTPs but still pose a significant risk (Tiwari *et al.*, 2024).

The other study in Burnt Oil Recycling Factory in Iran indicated a definite Cancer Risk (CR) for benzene and probable carcinogenic risk for ethylbenzene, which indicated the overall cancer risk in the burnt oil recycling factory being higher for certain compounds compared to WWTPs, indicating a significant occupational hazard (Ghobakhloo *et al.*, 2024). Whilst the risk of BTEX exposure at gasoline stations varies but can be significant, particularly in areas with high refueling activity. The cancer risk at gasoline stations is generally lower than that at macro-scale WWTPs but still poses a health concern (Chaiklieng, 2021).

Overall, the cancer risk associated with BTEX exposure in WWTPs, particularly macro-scale and BAS WWTPs, is higher than in many other industrial settings. This highlights the need for stringent monitoring and control measures to protect workers in these environments.

The hazard quotient (HQ) is crucial for assessing and managing potential health risks from non-carcinogenic pollutants. By comparing estimated exposure to a reference dose, HQ provides a measurable risk assessment. For small-scale WWTPs, the BTEX exposure HQ results were 0.155, 0.005, 0.012, 0.00, and 0.050 for females, and 0.142. 0.004, 0.011, 0.00, and 0.046 for males, all below the threshold of 1, implying low probability of adverse health effects.

For macro-scale WWTPs, the BTEX exposure HQ results were 0.389, 0.006, 0.014, 0.258, and 0.228 for females, and 0.356, 0.006, 0.013, 0.237, and 0.209 for males, all below the threshold of 1, suggesting low probability of adverse health effects and exposure within acceptable safety limits. The average scale WWTP results indicated that the BTEX exposure HQ results were 0.349, 0.006, 0.013, 0.258, and 0.139 for female employees, and 0.320, 0.005, 0.012, 0.237, and 0.127 for male employees, all within acceptable safety limits of exposure as the HQs are 1. This suggests that TEX exposure for employees at BAS WWTPs is within acceptable limits with low probability of causing adverse health effects.

In urban areas of Rajasthan, India, the HQ values ranged from 0.052 to 0.15 for males, and 0.056 to 0.17 for females. These values are higher than those in small-scale WWTPs but comparable to macro-scale WWTPs, indicating a moderate risk of adverse health effects. In a burnt oil recycling factory in Iran, the HQ values for benzo[a]pyrene exceeded the acceptable level in all operational units, suggesting a significant non-carcinogenic risk. At gasoline stations, the HQ values for BTEX exposure vary but can be significant, particularly in areas with high refueling activity. Generally, the HQ values at gasoline stations are lower than those at macro-scale WWTPs but still pose a health concern (Chaiklieng, 2021; Tiwari *et al.*, 2024; Das, Giri and Manjunatha, 2024; Ghobakhloo *et al.*, 2024). Overall, the HQ values for BTEX exposure in WWTPs, particularly macro-scale and average-scale WWTPs, are within acceptable safety limits, indicating a low probability of adverse health effects. However, the HQ values in other industrial settings, such as burnt oil recycling factories, can be significantly higher, highlighting the need for effective risk management and control measures.

Studies show that BTEX concentrations in municipal wastewater treatment plants vary across different regions. In some areas, concentrations are below occupational exposure limits, while in others, they exceed national and international standards, which could affect employee health and the environment.

5.1 LIMITATIONS

The study was based on published literature search, due to unavailability of data of exposure assessment from Department of employment and labour whereby only one study related to BTEX concentration emissions from Municipal BAS WWTP was found in South Africa during this systematic review.

Due to this gap, the literature search was extended to global level to include studies which can be used as proxy for South Africa to undertake the risk assessment associated with Municipal BAS WWTP. Only six (6) studies globally that have assessed the concentration of BTEX in BAS WWTP. This limited data signifies a substantial gap in the literature, which is crucial for a comprehensive understanding of the exposure risks faced by wastewater treatment plant operators and supervisors. This sparse existing body of literature on the concentration of BTEX in biological activated sludge, present a significant lack of data that can provide a clear picture of the occupational exposure levels in wastewater treatment facilities. This dearth of information constrains the ability of researchers and policymakers to fully comprehend the implications of BTEX exposure on workers' health.

Considering the fact that the operators and supervisors in wastewater treatment plants typically spend around 8 hours per day in this microenvironment. The limited availability of data on BTEX concentration poses a risk to their occupational health and safety. BTEX compounds are known for their toxic effects, which include respiratory issues, skin irritation, and potential carcinogenicity (Masih *et al.*, 2016; Davidson, Hannigan and Bowen, 2021). The paucity of comprehensive studies hinders the development of evidence-based safety measures and targeted interventions, thereby increasing the vulnerability of workers to occupational health risks.

The key differences in BTEX concentrations between various studies do come as a limitation to conclude on the exposure risk. The differences can be attributed to several factors, including geographical location, sampling methods, and the specific conditions of the wastewater treatment plants being studied. Studies conducted in different regions shown varying BTEX concentrations due to differences in industrial activities, environmental regulations, and wastewater treatment practices. For example, the study from Surat, India, highlights significant temporal and spatial variability in BTEX emissions. The methodology used to measure BTEX concentrations can also impact the results, with some studies were using passive sampling methods, while others used active sampling or advanced oxidation processes, influencing the accuracy and comparability of the data. Additionally, the specific conditions of the WWTPs, such as some additional treatment technology used, the scale of the plant, and the characteristics of the influent wastewater, do affect BTEX concentrations (Bencsik *et al.*, 2024).

5.2 RECOMMENDATIONS

Given the limitations identified in the study, several recommendations can be made to address the gaps and improve the understanding of BTEX exposure risks in wastewater

treatment plants (WWTPs) such as enhanced data collection, standardized sampling method, geographical and temporal variability, WWTP conditions, health risk assessment; and policy and regulation development:

There is a need for more comprehensive and localized studies on BTEX concentrations in South African WWTPs to enhance the data collection. Collaboration between academics and Department of Employment and Labour to gather exposure assessment data would be beneficial to understand the BTEX exposure risks to workers.

The implementation of a standardized sampling methods across studies will improve the accuracy and comparability of BTEX concentration data. This includes either using both or one method between passive and active sampling techniques. This will allow a better determination and understanding on the available concentration for workers to inhale. Also conducting studies in various regions and over different time periods will help account for geographical and temporal variability in BTEX emissions. This will provide a more holistic understanding of the factors influencing BTEX concentrations.

The investigation on this subject should also covers the specific conditions of WWTPs, such as the type of treatment technology used, the scale of the plant, and the characteristics of the influent wastewater, will help identify the most effective methods for reducing BTEX concentrations. As all these factors determine the emissions of the BTEX into the microenvironment for the workers exposure. Additionally, conducting detailed health risk assessments for WWTP operators and supervisors, considering their prolonged exposure to BTEX compounds, is crucial. This will aid in developing targeted safety measures and interventions to protect workers' health.

Finally the finding from all these comprehensive studies will inform policy and regulation development to ensure that effective air pollution control measures are implemented, reducing the health risks associated with BTEX exposure in the municipal BAS WWTP to ensure occupational health and safety for the workers, visitors and Public health. Therefore, by addressing these recommendations, researchers and policymakers in South Africa can better understand and mitigate the occupational health risks posed by BTEX exposure in municipal BAS wastewater treatment facilities.

5.3 CONCLUSION

This study aimed to obtain the concentration levels of BTEX compounds in the ambient air of municipal wastewater treatment plants using systematic review and undertake the risk assessment to determine the potential carcinogenic or non-carcinogenic risk to both females and male workers in the WWTP. This BTEX compounds have been proven to be toxic air pollutants. IARC categorised benzene as a carcinogenic agent acknowledging the adverse health effects associated with exposure to Benzene. This study recognized BTEX that were released from different capacity WWTP used globally.

Additionally the BTEX concentration and associated health risks associated with BAS WWTP activities were studied. The average BTEX concentrations levels were identified and input into US.EPA risk assessment to determine the potential carcinogenic or non-carcinogenic risk for the workers at WWTP. The CRs for benzene from macro-scale and average scale WWTP exceed the U.S.EPA threshold risk limit in ambient air of 1×10^{-4}, representing that on average there is a risk of two additional cancer case per 10 000 individuals exposed in the BAS WWTPs. The noncarcinogenic risk of all the BTEX compounds was also below 1.0 for all the size plants which indicate that employee's health is not threatened.

The lack of studies on BTEX concentration from BAS WWTP in South Africa raises uncertainty about worker exposure. More research is needed to assess the risks and help policymakers establish stringent measures to protect occupational health at WWTPs. Risk assessment is a comprehensive and iterative process that evaluates the relative risk of several exposure scenarios. It should be noted that risk assessment involves several uncertainties, and the accuracy of the results relies on proper risk identification and accurate exposure information. Despite these uncertainties, our studies aimed to define the exposure scenarios accurately for future reference in subsequent research.

In summary, during the wastewater treatment in the BAS WWTP the BTEX compounds are released into the ambient air as a results the employees in this microenvironment are exposed through possible inhalation. As such the employees might develop adverse health effects overtime. More studies related to the field are required to reduce the uncertainty and safeguard workers health.

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Appendix A (Plagiarism declaration report)

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

FACULTY OF HEALTH SCIENCES

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

I THABISO JERRY MAHMELA (Student number: 1892073) am a student registered for the degree of MSc in Medicine (Exposure science) in the academic year 2024.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature:  Date: 19/03/2025

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Appendix B (Objective's flow process)

Table 16: Research Objectives detailed below:

Research Objective 1
The Desktop review process will be undertaken by using search engines to seek existing literature. The following search engines were utilized: ScienceDirect, Scopus and PubMed journal. Only articles that are peer reviewed will be included in the Desktop review. The first step in the Desktop review is searching for articles with titles that include the search terms and keywords such as "BTEX Concentrations", "BTEX Exposure" 'Biological activated sludge", "Municipal wastewater treatment Plants", well defined synonyms "Sewage treatment plant (STP)", "Carcinogenic risk", "Non-carcinogenic risk". Articles that contain one or more key word will be included in the next step. The second step will be screening the selected articles by selecting articles that have abstracts that contain the key words; "BTEX Concentrations", "BTEX Exposure" 'Biological activated sludge", "Municipal wastewater treatment Plants", well defined synonyms "Sewage treatment plant (STP)", "Carcinogenic risk", "Non-carcinogenic risk". The articles that have abstracts that contain these key words will be included in the next step. The third step will be reviewing the selected articles, reading through them, and selecting articles that are relevant to the study to be used for analysis.
Research Objective 2
This is related to the risk assessment framework whereby the data from the average BTEX concentrations obtained from objective 1; and the data related to other parameters such the inhalation rate, exposure frequency (days/year); the exposure duration (years); body weight; will be collected from the U.S.EPA guideline for superfund compound for human factor assessment handbook while averaging time (exposure averaged over lifetime/average life expectancy for male and female) (days) from South African labour law will all be used for Health Risk Assessment to determine the carcinogenic risk and non-carcinogenic risks.

Appendix C (Ethical consideration certificate)

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Innovation)

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
ETHICS WAIVER

03/01/2025

Ref: W25/01/01

TO WHOM IT MAY CONCERN

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical)

Investigator: Mr TJ Maimela
Student No. (if appropriate): 1892073
Staff No. (if appropriate):

Supervisor: Dr D Mmereki, et al

School: Public Health
Department:
Division:
Faculty of Health Sciences

Project title: *BTEX concentration and risk assessment from biological activated sludge in municipal weastewater treatment plants: a systematic review*

Degree: MSc (Med)

Reason: Review of information in the public domain
No human participants will be involved in the study

Professor P Ruff
Chairperson: Human Research Ethics Committee (Medical)

Research Office Secretariat:
Third Floor, Phillip Tobias Building, corner of St Andrews and York Roads, Parktown, Johannesburg 2193
Postal address: Private Bag 3, Wits 2050
Tel Nos: +27 (0)11 717 1234/1252/2656/2700
Office E-mail: HREC-Medical.ResearchOffice@wits.ac.za
Website:
https://www.wits.ac.za/research/researcher-support/research-ethics/ethics-committees/

Appendix D (Data collection tool)

Table 6: Summary of secondary data collection from articles and reports on ScienceDirect, PubMed, ProQuest, and SCOPUS search websites:

Author	Year of Publication	Title of the article	Type of WWTP	WWTP Capacity	Local/Global	Country of study	Sampling Method	Pollutant	Concentration Summer µg/m3	Concentration Winter µg/m3	Mean Conc µg/m3	Comments/Additional Info
Mansooreh Dehghani	2022	Health risks of inhalation exposure to BTEX in a municipal wastewater treatment plant in Middle East city: Shiraz, Iran	Municipal/BAS	Population of 584,000 (an average flow rate of 1360 L/s)	Global	IRAN	Active	Benzene	103.9	131.3	117.6	
								Toluene	39.9	55.5	47.7	
								Ethylbenzene				
				117 MLD				m,p-xylene				summer (July and August)
								O-xylene				and winter (January and February).
Misaq Ahmad Muradi	2021	Tempo-spatial variability in volatile emissions from a sewage-treatment plant in Surat, India	blanket (UASB) followed by extended aeration.	100 million litres per day (MLD)	Global	India	Active handheld gas detector	Benzene	0.40 ppm	0.60ppm	500.0	November/winter), the average tempwas 32°C. Being a tropical region, Surat has a high temp of around 40°C in April Summer). Two seasons were considered for temperature variation and its influence on BTEX emissions from STP units. In an attempt to evaluate the influence of temperature, BTEX emissions were
								Toluene	0.50ppm	0.55ppm	525.0	
								Ethylbenzene	0.55ppm	0.55ppm	550.0	
								m,p-xylene	0.75ppm	0.45ppm	600.0	
								O-xylene				
Kadir Ulutaş	2021	Assessment of H S and BTEX concentrations in ambient air using passive sampling method and the health risks		Istanbul with a capacity of 250,000 m3 /day	Global	Tuzla, Istanbul, Turkey.	Passive Sampler - diffusive samplers	Benzene	Averages	2.78 µg/m3 ,	2.78	winter (November 2015), summer (August 2016)
								Toluene		11.6µg/m3	11.6	Averages in WWTP workplace air
				250 MLD				Ethylbenzene		3.72µg/m3	3.72	
								m,p-xylene		11.9µg/m3	11.9	
								O-xylene				
Seitlotli Mamonyamane Ntlatleng	2013	Estimation of Volatilization Rate of Volatile Organic Compounds from Wastewater	OSB (Pre-treatment collection point)	10.11 mega litres per day	Local	RSA	Active	Benzene	91.0	0	91.0	averages con
								Toluene	459.75	0	459.75	
								Ethylbenzene	240.5	0	240.5	
								m,p-xylene	0	0		
								O-xylene	101.5	0	101.5	
Heresh Amini	2024	Land Use Regression Models for Alkylbenzenes in a Middle Eastern Megacity: Tehran Study of Exposure Prediction for Environmental Health Research (Tehran SEPEHR)	Municipal/BAS		Global	Iran		Benzene		58 µg/m3		secondary data from study in 1993 from Ontario Canada
								Toluene		1940 µg/m3		
								Ethylbenzene		295 µg/m3		
								m,p-xylene		953 µg/m3		
								O-xylene		460 µg/m3		
Bian Yu	2022	BTEX in the environment: An update on sources, fate, distribution, pretreatment, analysis, and removal techniques	Not clear	N/A	Global	China		Benzene		No data		
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
Mohammad Ali Zahed	2022	Risk assessment of Benzene, Toluene, Ethyl benzene, and Xylene (BTEX) in the atmospheric air around the world: A review	Not Clear/Outdoor		Global	Iran		Benzene		No data		
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		

Hubert Bylińskia	2019	Differences between selected volatile aromatic compound concentrations in sludge samples in various steps of wastewater treatment plant operations	Municpal	Sludge samples not in air	Global	Poland		Benzene		No data		
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
Bian Yu	2022	BTEX in the environment: An update on sources, fate, distribution,pretreatment, analysis, and removal techniques	Not Clear	Not Available	Global	China		Benzene		No data		No BTEX concentration data available from WWTP
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
Raquel Lebrero	2013	Characterization and biofiltration of a real odorous emission from wastewater treatment plant sludge	Municipal/BAS	Not available	Global	Spain		Benzene		No data		No BTEX concentration data
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
Rasha Maal-Bared	2022	Evaluating the impacts of leachate co-treatment on a full-scale municipal wastewater treatment plant in Canada	Municipal	970 MLD	Global	Canada		Benzene		No data		No BTEX data, just physiochemical data
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
José M. Estrada	2015	Integral approaches to wastewater treatment plant upgrading for odor prevention: Activated Sludge and Oxidized Ammonium Recycling	Municipal	Not available	Global	Spain		Benzene		No data		No BTEX concentration data
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
Daniel Gonz´alez	2022	Multipoint characterization of the emission of odour, volatile organic compounds and greenhouse gases from a full-scale membrane-based municipal WWTP	Municipal	33 MLD	Global	Spain		Benzene		No data		
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
B. Mrowiec	2013	Removal of aromatic hydrocarbons (BTX) in anoxic and anaerobic wastewater treatment processes	Municipal	Not Available	Global	Poland		Benzene		No data		No BTEX concentration data in
								Toluene		No data		the air but in the water samples
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		
Kaixiong Yanga	2019	The identification, health risks and olfactory effects assessment of VOCs released from the wastewater storage tank in a pesticide plant	Pesticide Plant	Not available	Global	China	Active	Benzene		460μg/m3		Only Benzane data found
								Toluene		No data		
								Ethylbenzene		No data		
								m,p-xylene		No data		
								O-xylene		No data		

Appendix E (Turnitin Report)

Supervisor

Prof Masekameni MD

Co-Supervisor

Daniel Mmereki

TJ Maimela Research Report Final.docx

ORIGINALITY REPORT

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8	Bassam S. Tawabini, Konstantinos V. Plakas, Anastasios J. Karabelas. "A pilot study of BTEX removal from highly saline water by an advanced electrochemical process", Journal of Water Process Engineering, 2020	<1%

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by Thabiso Maimela

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