Characterisation of occupational exposure to benzene, toluene, ethylbenzene and xylene associated with wastewater treatment plant in Gaborone, Botswana

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Declaration

I, **Golebaone Senai (student number: 2503100)**, declare that the research project entitled *"Characterisation of occupational exposure to benzene, toluene, ethylbenzene, and xylene associated with wastewater treatment works in Gaborone, Botswana"* is my research work undertaken under the supervision of Dr. Goitsemang Keretetse and Dr. Daniel Mmereki. The work is being submitted in partial fulfilment for the degree of Master of Medicine in the field of Exposure Science at the School of Public Health, University of the Witwatersrand, Johannesburg. This work has not been presented for examination at any other university. The author designed the study, carried out all field data collection, data analysis, and writing the research report. Parts of this research report have been planned to be published in peer-reviewed journals and presented at conferences. All the sources cited in this study have been acknowledged through comprehensive references. The Senate plagiarism policy is signed and attached (Appendix A: Plagiarism Declaration Form).

Signature

Date: 12 August 2025

Dedication

This work is dedicated to my sons Aone and Abale Senai, who have been my pillars of strength

Abstract

Background

The treatment of wastewater has become increasingly complex as urbanisation and industrialisation introduce volatile organic compounds (VOCs), particularly BTEX (benzene, toluene, ethylbenzene, and xylenes), into sewage systems. In Gaborone's semi-arid climate, where temperatures frequently exceed 30°C, the volatilisation of these compounds poses potential occupational health risks, including respiratory irritation, neurological effects, and long-term carcinogenic risks for workers, yet systematic characterisation of worker exposure remains limited.

Aim

This study aimed to characterise occupational exposure to BTEX compounds at the Gaborone Wastewater Treatment Plant (GWWTP) by evaluating air concentrations across different treatment stages and comparing them with international safety standards.

Methods

Ambient air sampling was conducted over 18 weeks using passive samplers from Scientific Kit Corporation (SKC 575-001) deployed across three treatment zones: night soil discharge area, screening unit, and grit chamber. Samples were analysed at an ISO17025-accredited laboratory using gas chromatography-mass spectroscopy (GC-MS). Environmental parameters such as temperature, humidity, flow rates, and retention times were monitored throughout the sampling period. Statistical analysis included ANOVA and Tukey HSD tests to evaluate spatial and temporal variations in BTEX concentrations.

Results

The concentrations of BTEX compounds varied significantly across treatment locations ($p < 0.001$) but remained below international occupational exposure limits. The Night Soil Discharge Area showed the highest mean concentration (0.093 ± 0.077 µg/mL), followed by the Screening Unit (0.032 ± 0.033 µg/mL), and Grit Chamber (0.007 ± 0.013 µg/mL). Toluene emerged as the predominant compound (mean 0.113 ± 0.080 µg/mL), accounting for approximately 48.7% of total measured VOCs. While spatial variations were significant ($p < 0.001$), temporal variations in daily operations were not statistically significant ($p > 0.94$). Environmental monitoring revealed that retention time (0.63-2.85 hours) had a stronger

correlation with BTEX concentrations than temperature (20.0-38.0°C), contrary to previous research predictions. The facility achieved an 87% reduction in BTEX concentrations from initial to final treatment stages.

Conclusion

This study provides a comprehensive assessment of BTEX exposure patterns in Gaborone's semi-arid climate wastewater treatment facility. The findings demonstrate that while BTEX concentrations vary significantly between treatment stages, current facility design and operational protocols maintain exposures below international safety thresholds. The study highlights that while concentrations were consistently below occupational exposure limits, the Night Soil Discharge Area presents heightened risks for worker exposure requiring targeted interventions such as improved ventilation or enhanced personal protective equipment. Furthermore, retention time appears to be a more critical operational parameter for BTEX management than previously recognized, particularly in semi-arid climates. These results provide an evidence-based framework for improving occupational safety protocols in similar facilities across developing countries.

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I am indebted to several individuals and organizations who have made this study possible. My sincere gratitude goes firstly to my supervisors, Dr. Goitsemang Keretetse and Dr. Daniel Mmereki, who have been very instrumental in shaping my research project. Their guidance, expertise, and unwavering support throughout this journey have been invaluable.

I would like to express my appreciation to the management and staff of the Gaborone Wastewater Treatment Plant for granting me access to their facility and providing technical assistance during the sampling period. Special thanks to the laboratory technicians at the Environmental Analysis Laboratory at the University of Botswana for their assistance with laboratory analysis.

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List of Abbreviations

ANOVA	Analysis of Variance
BOBS	Botswana Bureau of Standards
BTEX	Benzene, toluene, ethylbenzene, and xylenes
CECs	Contaminants of Emerging Concern
CS2	Carbon Disulfide
GC-FID	Gas Chromatography with Flame Ionization Detection
GC-MS	Gas Chromatography-Mass Spectroscopy
GWWW	Gaborone Waste Water Works
GWWTP	Gaborone Wastewater Treatment Plant
IQR	Interquartile Range
LOD	Limit of Detection
LOQ	Limit of Quantification
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	Permissible Exposure Limit
PTFE	Polytetrafluoroethylene
REL	Recommended Exposure Limit
SCADA	Supervisory Control and Data Acquisition
SD	Standard Deviation
SKC	Scientific Kit Corporation
TWA	Time-Weighted Average
VOC	Volatile Organic Compound
WHO	World Health Organisation
WWW	Waste Water Works
WWTP	Waste Water Treatment Plant
WWTWs	Wastewater Treatment Works

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CHAPTER 1: INTRODUCTION

This chapter provides an overview of volatile organic compounds (VOCs), specifically BTEX (benzene, toluene, ethylbenzene, and xylenes), and their natural and anthropogenic sources and their impact on workplace air quality. The release of BTEX compounds from wastewater treatment processes is also covered in this chapter. The chapter also discusses these compounds' industrial applications, their status as hazardous air pollutants, and the health effects of occupational exposure. The problem statement and justification of the study are outlined, and the chapter ends by presenting the study aim, hypothesis, and objectives.

1.1 Background

Urbanisation and industrialisation add more chemical compounds into sewage systems, complicating wastewater treatment. Industrial discharges and municipal waste streams bring volatile organic compounds (VOCs) to wastewater treatment plants (WWTPs), including BTEX chemicals (Almatouq et al., 2022; Widiana, 2019).Physicochemical parameters like temperature and treatment procedures affect BTEX compound behaviour during wastewater treatment. These chemicals' volatilisation can vary greatly across treatment stages in Gaborone's semi-arid climate, where temperatures often approach 30°C (Kethobile et al., 2020). Studies have demonstrated that BTEX contents in workplace air change at different processing stages, including aeration tanks and sludge handling areas (Allahabady et al., 2022; Kamani, 2023).

Recent research has shown that BTEX chemical release depends greatly on treatment stage and operational conditions. Screening and primary settling emit less BTEX than secondary treatment phases, when biological processes and aeration boost volatilisation. In turbulent locations like aeration basins and sludge processing units, concentrations are higher (Khuntia et al., 2021; Li & Yan, 2022).Characterising BTEX emissions across treatment stages is crucial in conventional treatment systems, which are typical in underdeveloped countries like Botswana. These systems treated wastewater efficiently but did not control VOC emissions (Agarwal & Mustafi, 2021). Aeration and mixing operations in Botswana's activated sludge processes can considerably affect BTEX volatilisation patterns. These chemicals are released into the workplace at different rates depending on aeration intensity, retention times, and temperature (Liu et al., 2022).

Understanding BTEX compound concentration patterns during treatment is crucial for various reasons. First, it identifies treatment train emission hotspots that may require control. Second, it provides vital data for evaluating existing volatile chemical treatment techniques. This knowledge is essential for establishing evidence-based strategies to reduce BTEX emissions and sustain efficient wastewater treatment in Gaborone facilities (Bencsik et al., 2024; Janga, 2024).

1.2 Literature review

1.2.1 BTEX compounds and their behaviour in wastewater treatment systems

Benzene, toluene, ethylbenzene, and xylene (BTEX) compounds represent a significant group of volatile organic compounds commonly found in wastewater treatment systems (Das et al., 2025). These aromatic hydrocarbons share similar chemical properties but exhibit distinct environmental behaviours and health impacts behaviours that significantly influence treatment efficiency and worker exposure risks. Recent comprehensive reviews by Das et al. (2025) emphasize that BTEX emissions from various industrial operations present substantial health risks, with benzene being particularly concerning due to its established carcinogenic properties. Benzene (C_6H_6), the most concerning of the group, demonstrates higher volatility and water solubility compared to its counterparts (Saeedi et al., 2024). Toluene ($C_6H_5CH_3$), ethylbenzene (C_8H_{10}), and xylenes ($CH_3)2C_6H_4$) demonstrate varying degrees of volatilisation and biodegradation, which significantly influence their behaviour during wastewater treatment processes (Bencsik et al., 2024; Kuranchie et al., 2019; Joshi & Adhikari, 2019).

While the literature consistently identifies BTEX compounds as significant contaminants in wastewater systems, there remains a notable gap in understanding their comparative behaviour under different climatic conditions. The existing studies primarily focus on temperate regions, with limited research examining how semi-arid climates like Gaborone's might alter the fundamental volatilisation and biodegradation patterns of these compounds. This represents a critical knowledge gap that could significantly impact the applicability of current treatment approaches and exposure assessment methodologies in Southern African contexts.

1.2.2 Sources and pathways

BTEX compounds enter wastewater systems through multiple pathways, following distinct routes from source to treatment facility (Rodriguez-Narvaez et al., 2019). In industrial settings, direct discharge through designated industrial effluent lines constitutes the primary pathway, with minimal attenuation before reaching the sewer network (Adeniyi et al., 2021). These compounds travel through the sewerage infrastructure, where they may undergo partial volatilisation in turbulent sections such as pumping stations and drop structures (Li et al., 2023).

For domestic sources, BTEX compounds typically follow more diffuse pathways, entering the wastewater system through household drainage and municipal collection systems (Zhang et al., 2021). During transport, these compounds may adsorb to suspended solids or organic matter, affecting their bioavailability and treatment efficiency upon reaching the treatment facility (Kaur & Chaudhary, 2022).Significantly, storm water infiltration during wet seasons creates additional pathways for BTEX compounds, particularly in areas with ageing infrastructure or combined sewer systems. This hydraulic pathway can introduce petroleum-derived BTEX from road surfaces and urban runoff, causing concentration spikes during heavy rainfall events (Okoye & Elbeshbishy, 2019).

The literature reveals significant gaps in understanding BTEX source contribution patterns, particularly in developing regions. While studies consistently acknowledge both industrial and domestic sources, there is a notable absence of comprehensive source apportionment studies that quantify the relative contributions of these pathways. This knowledge gap is particularly pronounced in rapidly industrialising cities like Gaborone where both industrial and domestic sources are simultaneously expanding. The lack of source apportionment studies in sub-Saharan African contexts represents a significant limitation in current knowledge, making it difficult to prioritise intervention strategies.

1.2.3 Treatment process contributions

The wastewater treatment processes themselves can also serve as sources and transformation pathways for BTEX compounds. Primary treatment operations such as grit removal and primary clarification can facilitate volatilisation, particularly in areas with high turbulence or extended surface exposure (Metcalf & Eddy, 2014). During biological treatment stages, incomplete biodegradation of complex organic compounds can result in the formation of BTEX intermediates, temporarily increasing concentration levels before subsequent degradation occurs (Njogu et al., 2021).

Sludge handling operations, particularly dewatering and thickening processes, have been identified as significant contributors to BTEX volatilisation within treatment facilities (Wilson & Chen, 2023). The mechanical agitation and increased temperature in these processes enhance the release of previously adsorbed compounds from solid matrices into the gaseous phase, creating potential occupational exposure concerns and contributing to atmospheric emissions from the facility (Rahman & Ibekwe, 2020).

The combined industrial, domestic, and process-generated inputs create a complex mixture of BTEX compounds that enters the treatment system, necessitating careful monitoring and assessment of their concentrations throughout the treatment process and across different treatment stages (Mustapha et al., 2021).

A significant contradiction emerges in the literature regarding the role of treatment processes as BTEX sources versus sinks. While Wilson & Chen (2023) emphasise treatment processes as significant volatilisation sources, Njogu et al. (2021) suggest that biological processes primarily serve as degradation mechanisms. This contradiction may reflect differences in treatment plant design, operational parameters, or environmental conditions, but the literature lacks comprehensive studies that reconcile these opposing views. The absence of systematic studies comparing process contributions across different facility types and climatic conditions represents a critical gap that limits our understanding of treatment-related BTEX dynamics.

1.2.4 Treatment processes and BTEX behaviour across treatment stages

The fate of BTEX compounds through wastewater treatment processes is characterised by complex physical, chemical, and biological interactions that vary across different treatment stages. Understanding these stage-specific behaviours is crucial for accurately assessing BTEX concentrations throughout the treatment train.

1.2.4.1 Primary treatment stage

During primary treatment, BTEX compounds undergo initial separation processes primarily through physical mechanisms. Research indicates that approximately 15–25% of BTEX compounds are removed during this stage, mainly through volatilisation in primary settling tanks and attachment to settled solids (Bencsik et al., 2024). Studies in semi-arid regions similar to Gaborone have shown that volatilisation rates in primary treatment can increase by up to 30% during periods of high ambient temperatures, particularly during midday operations when temperatures exceed 30°C (Wang et al., 2022). The turbulence at inlet works and primary clarifiers also significantly influences BTEX volatilisation patterns, with higher turbulence zones showing increased atmospheric release rateof release into the atmosphere (Eslami et al., 2022).

1.2.4.2 Secondary treatment stage

The secondary treatment phase, typically employing activated sludge processes, plays a crucial role in BTEX removal through both biological degradation and enhanced volatilisation. Under optimal conditions, these systems can achieve BTEX removal efficiencies of 60–80% (Chen et al., 2022). The aeration techniques needed for biological treatment dramatically volatilise BTEX. This stage is crucial for concentration monitoring since air samples obtained above aeration tanks can have 2–5 times higher BTEX concentrations than those at primary treatment locations (Dehghani, Mohammadpour, et al., 2022).

1.2.4.3 Sludge treatment and handling

Sludge processing represents another critical point for BTEX emissions and concentration variations. The mechanical dewatering and thickening processes can release previously absorbed BTEX compounds, creating localised areas of elevated concentrations. Research in similar treatment facilities has documented BTEX concentration spikes during sludge handling operations, with levels varying significantly based on sludge characteristics and processing methods (Yu et al., 2020). Temperature effects are particularly pronounced during sludge treatment, with studies showing increased volatilisation rates during hot weather conditions typical of Gaborone's climate(Selwe et al., 2024).

1.2.4.4 Concentration patterns and treatment efficiency

Inhalation of BTEX compounds poses health risks, with some sites exceeding safety thresholds (Dehghaniet al., 2022). Treatment efficiency varies across refineries, with most achieving high performance levels and meeting regulatory standards (Hjort et al., 2021). The distribution of BTEX concentrations across treatment stages follows distinct patterns influenced by both process parameters and environmental conditions. Studies conducting systematic sampling across treatment stages have demonstrated that while overall BTEX removal efficiency may reach 85–95%, the concentration patterns in workplace air vary significantly between treatment stages (Tiwari Megha et al., 2024). This variation is particularly evident in facilities operating in warm climates, where temperature-driven volatilisation can create unique concentration profiles across different treatment areas (Yousefian et al., 2020).

Advanced treatment methods, including biological processes, activated carbon adsorption, and photocatalysis, have shown promise in BTEX removal (Bencsik et al., 2024; Kong et al., 2020). Hybrid hydrodynamic cavitation-persulfate methods degrade BTEX chemicals quickly (Fedorov et al., 2021).Nano-semiconductors have emerged as effective photocatalysts for

BTEX degradation, with most achieving ≥70% removal efficiency (Emmanuel et al., 2023). BTEX concentrations greatly affect groundwater microbial community structure, with specific bacterial species playing essential biodegradation functions (Huang et al., 2011).

Understanding these stage-specific behaviours and concentration patterns is essential for developing effective monitoring strategies and identifying potential hotspots for BTEX emissions within the treatment system. This knowledge directly supports the assessment of worker exposure risks and helps optimise sampling protocols for concentration evaluation across different treatment stages.

The literature presents conflicting evidence regarding BTEX removal efficiencies across treatment stages. While Chen et al. (2022) report 60-80% removal efficiency in secondary treatment, Tiwari Megha et al. (2024) suggest overall removal rates of 85-95%. These contradictions may reflect variations in influent characteristics, operational parameters, or measurement methodologies. However, the literature lacks systematic comparative studies that account for these variables, creating uncertainty about achievable treatment performance under different conditions. This gap is particularly problematic for facilities in developing regions where operational conditions may differ significantly from those in developed countries where most research has been conducted.

1.2.5 Factors affecting BTEX concentrations in treatment stages

1.2.5.1 Temperature effects in Gaborone's climate

Gaborone's semi-arid climate significantly influences BTEX behaviour throughout the treatment process. With daytime temperatures frequently exceeding 30°C during summer months, volatilisation rates of BTEX compounds show marked increases across all treatment stages. Studies in similar climatic regions have demonstrated that BTEX volatilisation rates can increase by 15–30% for every 10°C rise in temperature (Chang et al., 2022).This temperature dependence is particularly pronounced in open treatment units, where direct solar radiation can further enhance volatilisation rates. During peak temperature periods, typically between 12:00 and 15:00 hours, BTEX concentrations in the air above treatment units can be up to twice the levels observed during cooler morning hours (Abebe et al., 2023).

1.2.5.2 Process-specific factors

The operational parameters of different treatment processes significantly influence BTEX concentrations. Aeration rates in biological treatment units play a crucial role, with higher air flow rates leading to increased stripping of volatile compounds. Research has demonstrated that increasing aeration rates from 0.5 to 2.0 m^3/hour can boost BTEX volatilisation by 40–60% (Davidson et al., 2021).Hydraulic retention times also affect BTEX concentrations, with longer retention periods typically resulting in greater volatilisation. In primary settling tanks, retention times of 2-4 hours have been associated with 20-30% BTEX removal through volatilisation, while extended retention in aeration tanks can lead to removal rates exceeding 70% (Kataki et al., 2021).

The mechanical agitation and turbulence levels across different treatment units also influence BTEX release patterns. Areas with high turbulence, such as inlet works and aeration basins, typically show elevated atmospheric BTEX concentrations. Studies have documented that zones with surface turbulence can exhibit BTEX concentrations 3-5 times higher than calm zones within the same treatment stage (Kong et al., 2021).

1.2.5.3 Seasonal variations and environmental factors

Seasonal weather patterns in Gaborone create distinct variations in BTEX concentration profiles. During the dry season (May to October), when temperatures are consistently high (ranging from daily minimums of 5-15°C to maximums of 20-32°C depending on the month) and humidity is low (typically 20-40%), volatilisation rates show less diurnal variation but maintain higher baseline levels. In contrast, the wet season (November to April) exhibits more variable patterns, with rainfall events temporarily suppressing volatilisation rates but potentially leading to concentration spikes during subsequent drying periods (Chen et al., 2022).

Patterns of wind also have a big effect on how BTEX spreads and how concentrations are distributed. Studies in open-air treatment facilities have shown that wind speeds above 3 m/s can have a big effect on the patterns of BTEX concentrations, possibly creating areas of high exposure downwind of pollution sources (Emmanuel et al., 2023).Facility layout and prevailing winds are critical in assessing potential worker exposure zones (Yang et al., 2023). The interaction between wind patterns and facility layout becomes particularly important in

Gaborone's context, where prevailing winds can influence the distribution of volatilised compounds across different treatment areas.

Humidity levels, although generally low in Gaborone's climate, can affect BTEX behaviour during treatment processes (Maswanganyi et al., 2024; Mdlalose, 2022). Research indicates that relative humidity variations between 20% and 60% can influence the partitioning of BTEX compounds between water and air phases, potentially affecting both removal efficiency and atmospheric concentrations. These humidity effects become particularly relevant during early morning operations when relative humidity is typically highest (Tiwari Megha et al., 2024).

1.2.6 Seasonal Variations and Risk Assessment Advances

1.2.6.1 Climate-Dependent Exposure Patterns

Khoshakhlagh et al. (2023) conducted comprehensive seasonal studies using Monte Carlo simulations for health risk assessment, collecting 252 air samples across summer and winter seasons. Their research revealed that "BTEX concentrations were higher in the summer than in the winter season for all workstations, especially for toluene and ethylbenzene." Significantly, mean benzene exposure for repair workers and site personnel exceeded threshold limit values during both seasons, with non-carcinogenic risk values exceeding acceptable levels for multiple compounds and worker categories.

These findings have particular relevance for facilities operating in warm climates similar to Gaborone, where temperature-driven volatilization creates unique concentration profiles across treatment stages. The research demonstrates that carcinogenic risk ranged from 2.93×10^{-3} to 1.1×10^{-2} across different work areas, substantially exceeding acceptable risk thresholds.

1.2.6.2 Advanced Risk Assessment Methodologies

Modern risk assessment approaches increasingly incorporate uncertainty analysis and probabilistic modeling. Monte Carlo simulations have become standard practice for evaluating exposure scenarios, providing more robust risk characterization than deterministic approaches. These methodologies prove particularly valuable in developing country contexts where exposure data may be limited or variable.

The literature reveals significant inconsistencies in quantifying environmental factor effects on BTEX concentrations. While Chang et al. (2022) report 15-30% increases in volatilisation per 10°C temperature rise, Davidson et al. (2021) suggest 40-60% increases with aeration rate changes. These contradictory findings suggest that the relative importance of different environmental factors may vary significantly between facilities and operational conditions. The lack of standardised methodologies for measuring these effects represents a critical gap that limits the development of predictive models for BTEX behaviour in different climatic and operational contexts.

1.2.5.4 Quality control considerations

Robust quality control measures are essential for ensuring reliable BTEX concentration data. Field blanks should constitute 10% of total samples to account for potential contamination during sampling and transport. Duplicate samples (minimum 10% of total samples) help assess sampling precision, with relative percent differences maintained below 25% for acceptable quality control (Saeedi et al., 2024).

Temperature monitoring during sampling is crucial, particularly in Gaborone's climate, as high temperatures can affect sampling efficiency and sample stability. Studies recommend maintaining sample storage temperatures below 4°C and completing analysis within 14 days to minimise compound losses (Fosco et al., 2024). To ensure analytical accuracy, laboratory quality control measures include daily calibration checks, method blanks, and regular analysis of certified reference materials to ensure analytical accuracy. Furthermore, the selection of appropriate sampling techniques and strict adherence to quality control protocols ensure the generation of reliable concentration data necessary for comparing BTEX levels across different treatment stages and evaluating potential exposure risks within the treatment facility.

1.2.6 Previous studies of BTEX concentrations in wastewater treatment

Recent studies have examined BTEX (benzene, toluene, ethylbenzene, and xylene) concentrations in various wastewater treatment contexts. BTEX compounds have been detected in waterpipe tobacco wastes (Masjedi et al., 2023), municipal wastewater treatment plants (Dehghani et al., 2021), and coking wastewater (Saber et al., 2020). Concentrations vary seasonally, with higher levels typically observed in winter (Khoshakhlagh et al., 2024). Biological treatment processes can remove 94.1–99.9% of volatile organic pollutants, including BTEX (Saber et al., 2020). However, BTEX chemicals are still harmful to health, with benzene being the most likely to cause cancer in some situations (Keretetse et al., 2023; Saber et al., 2020). Adsorption using various materials has been explored for BTEX removal (Kong et al., 2020). BTEX compounds have also been found to leach from cigarette butts into water environments (Dobaradaran et al., 2020). Overall, BTEX contamination remains a concern in wastewater treatment and solid waste management facilities (Yousefian et al., 2020).

1.2.6.1 Findings from similar climatic regions

Studies conducted in semi-arid regions comparable to Gaborone have provided valuable insights into BTEX concentration patterns in wastewater treatment facilities. Research in South Africa's Gauteng region documented mean BTEX concentrations ranging from 0.8 to 3.5 ppm across different treatment stages, with peak values occurring during midday operations (Mdlalose Richard John, 2022).Similar studies in Namibia reported average benzene concentrations of 0.3–1.2 ppm in primary treatment areas and 1.5–4.2 ppm near aeration basins, highlighting the influence of high ambient temperatures on volatilisation rates (Kethobile et al., 2020).

Compounds of BTEX represent significant contaminants of emerging concern (CECs) in wastewater treatment facilities, posing substantial health risks and environmental challenges. Studies in some facilities, such as a municipal wastewater treatment plant in Iran, have found BTEX levels below occupational exposure limits; these compounds still present potential health hazards (Dehghani, Mohammadpour, et al., 2022). Environmental conditions significantly influence BTEX concentrations, with higher levels typically observed during winter months and rainy weather (Khoshakhlagh et al., 2024). A study in Botswana's neighbouring regions revealed that BTEX concentrations followed distinct diurnal patterns, with the highest levels typically observed between 11:00 and 15:00 hours when temperatures exceeded 30°C. These findings demonstrated strong correlations between ambient temperature and BTEX volatilisation rates in open treatment units (Kamani et al., 2023).

Various treatment approaches have been developed to address BTEX contamination. Traditional biological treatment methods provide partial reduction, but advanced treatment techniques have shown more promising results. Water scrubbing followed by bio-trickling filtration has achieved an overall average removal efficiency of 94.8% (Yasuda et al., 2021). Additional methods, such as high-pressure membrane processes and granular activated carbon, have been proposed for further reducing BTEX concentrations in treated wastewater (Tao et al., 2022). To optimise these processes, plant-wide simulation models incorporating BTEX metabolism and removal kinetics have been developed, exploring operational strategies such as adjusting sludge retention time and airflow (Bencsik et al., 2024). Recent advances in analytical techniques, particularly non-targeted and suspect screening methods using high-resolution mass spectrometry, have improved our ability to identify and monitor BTEX compounds alongside other CECs, including pharmaceuticals, pesticides, and industrial chemicals in wastewater treatment plants and receiving waters (Selwe et al., 2024). However, environmental monitoring of these compounds remains limited in many low- and middle-income countries, highlighting the need for expanded research to identify pollution sources and develop effective mitigation strategies, particularly in regions with limited monitoring capabilities.

The literature presents contradictory seasonal BTEX concentration patterns. While some studies report higher concentrations during hot periods, Dehghani et al. (2022) found higher benzene and toluene concentrations in winter at wastewater treatment plants, contrasting with Khoshakhlagh et al. (2023) who observed higher BTEX levels in summer at oil refineries. These contradictions may reflect facility-specific factors, operational differences, or varying environmental conditions, but the literature lacks systematic studies that control for these variables. Additionally, Khoshakhlagh et al. (2024) found elevated concentrations during rainy weather, adding another layer of complexity. The absence of standardised monitoring protocols across different climatic regions represents a significant gap that limits the transferability of findings between similar contexts.

1.2.6.2 Concentration patterns across treatment stages

Research has consistently shown that BTEX concentrations vary significantly across different treatment stages. A systematic study across multiple facilities in developing regions found that atmospheric BTEX concentrations typically follow distinct patterns throughout the treatment process, as illustrated in Figure 1.1 (Allahabady et al., 2022).

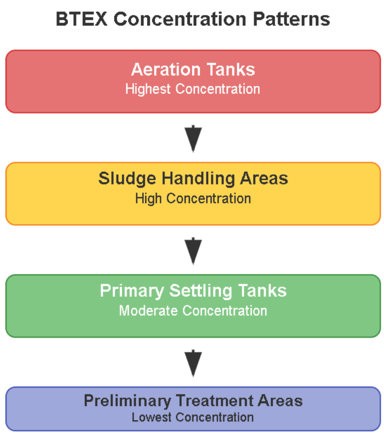

Figure 1.1 Concentration Patterns across Treatment Stages Sources

As shown in Figure 1.1, BTEX concentration levels demonstrate an interesting distribution across treatment stages, with the highest concentrations observed in aeration tanks, followed by sludge handling areas, then primary settling tanks, and finally the lowest concentrations in preliminary treatment areas. This pattern reflects the complex interplay of volatilisation, biodegradation, and mechanical processes that influence BTEX behaviour throughout the treatment system.

This pattern reflects the complex interplay of volatilisation, biodegradation, and mechanical processes that influence BTEX behaviour throughout the treatment system.Initial wastewater turbulence influences average BTEX concentrations of 0.2–0.8 ppm at preliminary treatment. The primary settlement has concentrations of 0.5–1.5 ppm, with higher levels during sludge removal, whereas the aeration tanks have peak concentrations of 2.0–5.0 ppm, heavily influenced by aeration rates and surface turbulence. Finally, sludge processing concentrations vary from 1.5 to 4.0 ppm depending on sludge properties and handling (X. Liu et al., 2024).

The concentration gradient depicted in Figure 1.1 aligns with theoretical models of BTEX volatilisation during wastewater treatment, where mechanical agitation and aeration significantly enhance the release of these volatile compounds into the atmosphere.

Studies have investigated BTEX concentrations and removal across treatment stages. In raw wastewater, toluene and xylenes were found to be predominant (B. Yu et al., 2022). BTEX levels varied seasonally, with higher concentrations of benzene and toluene observed in winter (Dehghani, Abbasi, et al., 2022). BTEX concentrations were significantly lowered by aerobic methods (Yu et al., 2022). Multi-stage treatment systems like water scrubbers, bio-trickling filters, and biofilters removed up to 96.1% (Allahabady et al., 2022; Yasuda, 2021).These systems effectively reduced BTEX concentrations to levels below toxicological standards and odour thresholds (Yasuda et al., 2021). Volatilisation and biodegradation were the main removal methods, while sludge sorption was modest (X. Wang et al., 2022).

The concentration patterns across treatment stages show remarkable consistency in some studies while contradicting others. Figure 1.1 suggests aeration tanks have the highest concentrations, which aligns with X. Liu et al. (2024), but contradicts findings by X. Wang et al. (2022) who emphasise volatilisation over biodegradation as the primary removal mechanism. This discrepancy highlights a fundamental gap in understanding whether BTEX removal occurs primarily through biological processes or physical volatilisation, with significant implications for treatment design and worker exposure assessment.

1.2.6.3 Factors influencing concentration variations

Several studies have identified key factors affecting BTEX concentration variations in treatment facilities. Temperature emerges as a primary influence, with research in semi-arid regions showing 20–35% increases in volatilisation rates for every 10°C rise in ambient temperature (Li & Yan 2022).Process-specific factors also play crucial roles. This relates to aeration intensity, for which studies demonstrated that doubling aeration rates led to 40–60% increases in atmospheric BTEX concentrations, longer retention periods in treatment units correlated with higher cumulative BTEX emissions, and wind speeds above 3 m/s had a big effect on concentration patterns, especially in open treatment areas (Khuntia et al., 2021).

Seasonal variations play a significant role in BTEX concentrations. Seasonal variations have been documented in multiple studies, with distinct patterns emerging between dry and wet seasons. Research in similar climatic regions reported 25–40% higher average BTEX concentrations during hot, dry periods compared to cooler, wet seasons (Bencsik et al. 2024). Dehghani et al. (2022) reported that mean levels of benzene and toluene were higher in winter compared to summer in a municipal wastewater treatment plant. This suggests that temperature and other seasonal factors influence BTEX concentrations. Temperature appears to be a key driver of these variations, suggesting that treatment facilities need to account for these temporal fluctuations in their operational strategies. These temporal patterns have important implications for monitoring protocols and treatment system design, as facilities must be capable of handling peak loads during unfavourable conditions while maintaining treatment efficiency throughout the year. These findings emphasise the importance of considering both seasonal and daily variations when assessing BTEX concentrations in wastewater treatment facilities.

Dehghani et al. (2022) found that in climate-similar areas, BTEX levels were 25–40% higher during hot, dry times compared to cooler, wet seasons. This suggests that temperature and other seasonal factors influence BTEX concentrations. Temperature appears to be a key driver of these variations, suggesting that treatment facilities need to account for these temporal fluctuations in their operational strategies. These temporal patterns have important implications for monitoring protocols and treatment system design, as facilities must be capable of handling peak loads during unfavourable conditions while maintaining treatment efficiency throughout the year. These findings emphasise the importance of considering both seasonal and daily variations when assessing BTEX concentrations in wastewater treatment facilities.

The location within the wastewater treatment plant is another crucial factor (Lian et al., 2025). Dehghani et al. (2022) mentioned that different sampling sites included a bar screen and grit chamber, aeration tanks and secondary clarifiers, anaerobic sludge digesters, and office and control buildings. BTEX concentrations varied across these locations, indicating that specific treatment processes and proximity to different units affect BTEX levels (Liu et al., 2025; Nakhjirgan et al., 2024).

Oxygen supply appears to be a limiting factor for BTEX degradation in wastewater treatment facilities. Zhang et al. (2024) noted that all BTEX compounds were rapidly degraded under natural aerobic conditions, while anaerobic conditions limited biodegradation except when nitrate was provided as a terminal electron acceptor. Interestingly, Apul et al. (2022) also found that attempts to increase dissolved oxygen concentration by adding hydrogen peroxide resulted in complete inhibition of biodegradation. This suggests that oxygen levels need to be carefully managed to optimise BTEX degradation.

1.2.7 Emerging Global Patterns and Developing Country Contexts

The assessment of benzene, toluene, ethylbenzene, and xylene (BTEX) exposure in developing countries reveals a complex web of methodological inconsistencies, regulatory inadequacies, and knowledge gaps that fundamentally undermine both worker protection and scientific understanding. Recent literature reveals substantial implementation challenges in developing countries. Omohwovo (2024) reported that "90% of wastewater generated globally is discharged into the environment without any prior treatment," with African countries particularly struggling with inadequate treatment infrastructure. The UN-Water 2024 Progress Report on Wastewater Treatment revealed that among 107 countries reporting wastewater statistics, only 42% of household wastewater received safe treatment before environmental discharge. This review examines recent literature from sub-Saharan Africa, West Asia and Southern Africa to expose the systemic failures in current BTEX exposure assessment approaches and their implications for occupational health policy.

1.2.7.1 Sub-Saharan African Perspectives

Research on BTEX exposure in developing countries, particularly sub-Saharan Africa, reveals significant occupational health risks and gaps in BTEX exposure assessment within developing countries, particularly in sub-Saharan Africa. Anigilaje et al. (2024) conducted the most comprehensive analysis of BTEX exposure in Nigeria's petroleum sector, highlighting that "inadequate occupational health and safety regulatory measures" expose workers to hazardous BTEX concentrations exceeding international standards. Their systematic review revealed that Nigerian petrol station workers face elevated risks due to poor ventilation systems and insufficient personal protective equipment usage. The study identified seven critical risk factors determining worker vulnerability: workplace design, ventilation systems, work duration, personal protective equipment availability, regulatory enforcement, worker training, and environmental conditions. Wanjala et al. (2025) extended this understanding by investigating BTEX impacts on soil microbial populations in Port Harcourt City, Nigeria, demonstrating that petroleum contamination significantly alters microbial community structure. Their findings suggest that BTEX compounds create cascading environmental effects that extend beyond immediate occupational exposure concerns. Similarly, Godwin et al. (2025) evaluated petroleum hydrocarbon contamination in Southeastern Nigeria, revealing that BTEX levels in contaminated soils pose substantial health risks through multiple exposure pathways.

Studies in South Africa have shown that diesel station workers and landfill employees are exposed to benzene levels exceeding international standards, with elevated cancer and non-carcinogenic health risks (Moolla et al., 2015; Moolla et al., 2013). In Ghana, pump attendants face similar risks due to poor safety practices and lack of exposure controls (Kuranchie et al., 2019). The literature highlights gaps in environmental exposure information disclosure across sub-Saharan Africa, including industrial exposure and chemical use in farming (Dehghani et al., 2022). Limited awareness of BTEX hazards, inadequate infrastructure, and absence of occupational health and safety legislation in some countries exacerbate the problem (Kuranchie et al., 2019). These findings underscore the need for improved monitoring, regulation, and policy implementation to protect workers and communities from BTEX exposure in developing regions.

1.2.7.2 West Asian Regional Analysis

Recent studies highlight significant gaps in BTEX exposure assessment within West Asian countries. Mohammadi et al. (2022) provided crucial insights into occupational exposure patterns across West Asian countries from 1980-2021, revealing significant regulatory inconsistencies. Their systematic review of 49 studies from six countries found that "average occupational exposure to benzene of workers in oil-related industries is higher than recommended occupational exposure limits," while other BTEX compounds generally remained below established thresholds. This regional analysis highlighted the absence of standardized monitoring protocols and the need for harmonized international guidelines suitable for developing country implementation. This study highlighted that information about levels of occupational exposure to BTEX and styrene is insufficient in West Asian countries, which should be remedied through OEL regulation and application. While some nations like Iran and Turkey have established occupational exposure limits (OELs) for BTEX, there is insufficient information on actual exposure levels across the region (Rahimpoor et al., 2022). Research is predominantly focused on Iran, with limited data from other countries (Rahimpoor et al., 2022). Urban areas in the Middle East show higher BTEX concentrations compared to Western countries, primarily attributed to traffic emissions (Abbasi et al., 2020). Health risk assessments indicate that benzene and ethylbenzene levels often exceed WHO and EPA recommendations (Abbasi et al., 2020). Key research gaps include source apportionment, impacts on lower tropospheric chemistry, and removal techniques (Tamrakar et al., 2022). Additionally, there is a need for more comprehensive biomonitoring studies to assess BTEX exposure in both occupational and general population settings (Hoseini et al., 2022).

1.2.7.3 Nigeria's BTEX Exposure

Nigeria's exposure to benzene, toluene, ethylbenzene, and xylene (BTEX) compounds represents a critical occupational and environmental health challenge that requires examination within both local and global contexts, particularly as Das et al. (2024) documented significant variations in BTEX emissions across oil and natural gas operations globally, with midstream tanker loading showing the highest concentrations (benzene: 5.391 ± 28.670 ppmv, toluene: 10.376 ± 48.929 ppmv). This finding has direct implications for Nigeria, where approximately 70-80% of petroleum products are imported, necessitating extensive tanker loading operations that expose workers to these elevated levels. Furthermore, the downstream refueling station emissions documented in the global review (benzene: 1.164 ± 0.408 ppmv, toluene: 2.394 ± 1.086 ppmv, ethylbenzene: 1.301 ± 0.779 ppmv, xylene: 1.736 ± 0.898 ppmv) align with concerns raised about Nigerian petrol stations, where petrol station workers typically dispense fuel directly, unlike self-service systems common in developed countries.

More critically, Anigilaje et al. (2024) revealed that Nigeria's petrol contains 2% benzene content versus 1% in Europe and 0.62% in the US, creating inherently higher baseline exposure risks. The study emphasized unique developing country challenges, noting that "in developing countries like South Africa, attendants are employed to pump fuel for customers at service stations" with daily exposure to various octane fuels and diesel, while the research emphasized that despite numerous studies on gasoline exposure in developed countries, "there are no health risk assessment studies focusing on diesel pump workers, despite most retail garages in developing countries providing both petrol and diesel services". Adding to these environmental concerns, Aleku et al. (2024) provides alarming data on groundwater contamination in the eastern Niger Delta, documenting BTEX levels up to 3904 μg/L and benzene levels up to 3500 μg/L in drinking water wells, with the highest concentrations detected near underground petroleum pipelines. This contamination pattern demonstrates a clear spatial relationship between petroleum infrastructure and exposure risk, and despite the contamination, the aquifer showed promising aerobic attenuation potential with up to 7.5 mg/L dissolved oxygen levels and 2.11 mg/L BTEX biodegradation capacity. However, the high groundwater temperature of up to 32.5°C may weaken natural attenuation processes, and critically, by natural attenuation alone, up to 66.5 and 85 years would be required to reach Nigeria's groundwater benzene and BTEX remediation goals, respectively.

Correspondingly, health impacts are evident as Badejo et al. (2025) revealed significant variations in blood parameters among Nigerian petroleum workers, with auto mechanics showing significantly lower white blood cell counts compared to controls, while petroleum industry staff showed higher red blood cell, hemoglobin, and hematocrit levels. These findings suggest systemic health impacts consistent with chronic BTEX exposure, while simultaneously, Afolabi et al. (2024) found that while the Target Hazard Quotient (THQ) values were generally below 1.0, indicating "No Significant Risk of Non-Carcinogenic to Moderate Significant Risk of Non-Carcinogenic," continuous consumption and bioaccumulation meant populations were not entirely free from health exposure risks.

Nevertheless, fundamental contradictions exist in the literature, particularly regarding immunological effects, as while Badejo et al. (2025) found immunosuppression (lower white blood cells) in auto mechanics, Christian et al. (2016) previously reported elevated white blood cells in PSWs, suggesting exposure-response relationships vary significantly based on duration, concentration, or co-exposures. Moreover, inconsistent risk assessment methodologies emerge when comparing studies, since Afolabi et al. (2024) concluded "No Significant Risk of Non-Carcinogenic" while Das et al. (2024) documented cancer risks exceeding acceptable thresholds (1400×10^{-6}) near gasoline stations, highlighting methodological inconsistencies in risk evaluation. Additionally, studies show conflicting relationships between temperature and BTEX concentrations - some positive, others negative correlations, yet no Nigerian research systematically examines this relationship despite consistently high tropical temperatures. Furthermore, while soil remediation showed improvements (BTEX: 0.01–2.7 mg/kg in remediated vs. 0.02–0.38 mg/kg in impacted soils), persistent high groundwater contamination (up to 3500 μg/L benzene) post-remediation suggests limited effectiveness. Consequently, major knowledge gaps persist, including that only one Nigerian study measured BTEX in workers' breathing zones, lacking biomarker confirmation of multi-pathway exposure, and no national BTEX exposure limits exist in Nigeria, while studies use incompatible measurement units hindering comparison. In addition, there is limited research on children and pregnant women despite evidence that children face higher risks than adults, and importantly, extensive laws exist but "OHS of Nigerian workers is still poor" due to enforcement failures. Therefore, the evidence reveals Nigeria faces a convergence of risk factors creating what could be characterized as a "perfect storm" of BTEX exposure: higher baseline fuel concentrations, extensive environmental contamination, unique occupational practices including direct fuel dispensing and generator-powered pumps, and regulatory enforcement gaps.

Ultimately, Nigeria's BTEX exposure situation represents a complex public health challenge requiring urgent, coordinated intervention, as the contradictions and gaps in current literature underscore the need for systematic, standardized research approaches to develop evidence-based solutions, including standardized biomonitoring studies accounting for multiple exposure pathways, longitudinal health outcome assessments resolving contradictory findings, temperature-exposure relationship studies for tropical environments, integrated occupational-environmental exposure models, and cost-effective detection technologies suitable for developing country contexts. In conclusion, while international evidence demonstrates effective control technologies exist, their adaptation to Nigerian contexts remains limited, leaving workers and communities vulnerable to ongoing BTEX exposure risks that demand immediate attention from researchers, policymakers, and industry stakeholders.

1.2.7.3 Wastewater Treatment Practices in Southern Africa

The regional context of wastewater treatment in Southern Africa reveals significant challenges that directly influence potential BTEX exposure patterns in treatment facilities. Contemporary research demonstrates that institutional arrangements and operational challenges significantly impact treatment effectiveness across the region. Mabadahanye et al. (2024) identified complex institutional setups, practical limitations, and environmental concerns as major obstacles facing water and wastewater treatment plants in the Vhembe District Municipality, South Africa. Their qualitative study of 12 treatment facilities revealed that institutional arrangements significantly affect operational efficiency and environmental compliance, factors that could directly influence BTEX emission patterns and worker exposure levels.

The broader African context presents even more severe challenges. Omohwovo (2024) comprehensively reviewed wastewater management across Africa, revealing that growing population and industrial growth have resulted in notable increases in wastewater generation, affecting regional water quality. The study highlighted that current wastewater treatment methods fall substantially short of environmental and health protection goals, resulting in poor environmental outcomes and inadequate provision of safe water and sanitation services. This regional deficiency in treatment infrastructure creates conditions that may exacerbate BTEX exposure risks in treatment facilities throughout the continent.

Specific facility performance data from Southern Africa illustrates the severity of operational challenges. Malakane and Maphanga (2024) assessed effluent quality from multiple wastewater treatment plants discharging into the Crocodile River in Mpumalanga, South Africa, finding significant water quality deterioration downstream of treatment facilities. Their research demonstrated that poorly performing treatment infrastructure contributes directly to environmental pollution, suggesting that such facilities may also pose elevated occupational exposure risks to workers handling BTEX-containing wastewater.

The regional literature reveals stark contradictions between treatment performance expectations and actual outcomes across Southern Africa. While Mabadahanye et al. (2024) found that institutional arrangements can potentially support effective treatment when properly implemented, Omohwovo (2024) documented widespread treatment failures across Africa, with 90% of wastewater discharged without adequate treatment. This contradiction suggests that even where institutional frameworks exist, implementation challenges prevent effective treatment. Furthermore, Malakane and Maphanga (2024) demonstrated that even operational treatment facilities may produce effluent that fails to meet quality standards, indicating that the gap between treatment objectives and outcomes remains substantial across the region.

The regional evidence indicates that Southern African treatment facilities operate under significantly different conditions compared to those in developed countries where most BTEX exposure research has been conducted. These differences include resource constraints, institutional challenges, varying operational practices, and different regulatory environments, all of which could substantially influence BTEX emission patterns and worker exposure levels.

The absence of region-specific BTEX exposure studies represents a critical gap, particularly given the documented treatment performance challenges throughout Southern Africa.

The collective findings from these regional studies provide important contextual insights for evaluating BTEX concentrations in Gaborone's wastewater treatment facilities, particularly considering the institutional, operational, and performance challenges common throughout Southern Africa that may influence both treatment effectiveness and occupational exposure patterns.

1.2.8 Advanced Treatment Technologies and Plant-Wide Modeling

Recent technological advances have significantly enhanced BTEX removal capabilities in wastewater treatment systems, though notable contradictions persist in the literature regarding optimal treatment approaches. Bencsik et al. (2024) published the most comprehensive plant-wide simulation framework adhering to International Water Association Good Modelling Practice Guidelines, demonstrating that "stricter effluent quality regulations necessitate BTEX removal, especially with concerns about organic micropollutant concentrations." Their research incorporates advanced biokinetic models and gas transfer equations, revealing that while biological treatment achieves partial BTEX reduction through biodegradation and sorption, "additional purification using physico-chemical methods is crucial for substantial reduction." However, Yasuda et al. (2021) demonstrated that integrated water scrubbing followed by biotrickling filtration achieved 94.8% overall average removal efficiency, suggesting that optimized biological systems may be more effective than previously assumed. This contradiction highlights a critical gap in understanding the conditions under which biological systems can achieve high removal efficiencies versus when physico-chemical methods become essential.

Advanced oxidation processes using hydroxyl radicals represent the current state-of-the-art for BTEX degradation, offering promising solutions for resource-constrained developing country applications, yet despite their effectiveness, AOPs face significant drawbacks including costly chemicals, rigorous reaction conditions, and the formation of secondary chemicals. While some studies report efficient visible light photocatalytic degradation of BTEX using zinc oxide nanorods with over 80% removal efficiency, recent research by Zhao et al. (2024) found that iron oxide-bearing wastes achieved BTEX removal over 160-day experiments with benzene being the most recalcitrant, indicating substantial variation in treatment effectiveness across different advanced oxidation approaches. This discrepancy suggests that the choice of AOP technology may be highly dependent on specific wastewater characteristics and operational conditions, representing a significant knowledge gap requiring further investigation.

1.2.9 Biomonitoring Advances and Human Exposure Assessment

1.2.9.1 Groundbreaking Biomonitoring Research

The field of BTEX exposure assessment has been revolutionized by recent biomonitoring advances, though critical contradictions have emerged regarding exposure patterns and metabolite interpretation. Dehghani et al. (2022) conducted the first comprehensive biological monitoring study of wastewater treatment plant workers, measuring urinary metabolites including trans,trans-muconic acid, hippuric acid, methyl hippuric acid, mandelic acid, and phenylglyoxylic acid in 56 employees, revealing that "mean concentrations of urinary metabolites ranged from 546.43 μg/g creatinine for trans,trans-muconic acid to 0.006 μg/g creatinine for methyl hippuric acid," with most metabolites exceeding occupational threshold limit values. However, conflicting findings emerged from studies comparing occupational and non-occupational populations, where "the differences of biomarkers were not significant between occupational and nonoccupational workers" near industrial facilities, challenging assumptions about workplace exposure severity.

Hoseini et al. (2023). revealed that undoubted associations between lifestyle and environmental factors and urinary levels of BTEX or its metabolites have not yet been confirmed in current biomonitoring studies, attributed to the few studies reported in this research area, the lack of homogeneous information, and the disagreement in the published results of the studies. While some research (Sekar et al. 2019; Li et al. 2024) demonstrated clear spatial trends between atmospheric benzene concentration and internal biomarker levels, Qin et al. (2022) found that "smoking is supposed to be a pathway human exposure to BTEX" yet "no significant variation was found in levels of trans,trans-muconic acid, S-phenylmercapturic acid and S-benzylmercapturic acid between smokers and nonsmokers", contradicting established exposure pathway assumptions.

1.2.9.2 Environmental Health Implications and Literature Gaps

Liu et al. (2025) provided crucial insights into ambient BTEX variations across urban Europe, revealing significant environmental health implications with median mixing ratios following the order toluene > benzene > m,p-xylene > o-xylene > ethylbenzene during 2017–2022, while Gerić et al. (2024) conducted DNA damage assessment among Zagreb residents, finding that "ambient BTEX highly correlates with particulate matter and polycyclic aromatic hydrocarbons," while inversely correlating with ozone levels. However, significant methodological gaps persist in exposure assessment approaches, as the recent development of the International Human Biomonitoring Health-Based Guidance Value Dashboard highlighted the lack of standardized guidance values across different populations and exposure scenarios.

The literature reveals several fundamental contradictions requiring urgent investigation: First, while studies by Bencsik et al. found biological treatment insufficient for substantial BTEX reduction, research by Yasuda et al. demonstrated high efficiency biological systems, suggesting that treatment effectiveness may depend on specific operational parameters not yet fully characterized. Second, while biomonitoring studies by Dehghani et al. showed clear occupational exposure differences, research by external exposure assessment teams found no significant differences between occupational and non-occupational populations, indicating potential limitations in current biomonitoring interpretation frameworks. Third, while smoking is widely considered a major BTEX exposure pathway, recent biomonitoring studies failed to detect significant differences between smokers and non-smokers, challenging fundamental assumptions about exposure source attribution. These contradictions highlight critical needs for standardized methodologies, harmonized analytical approaches, and comprehensive exposure pathway modeling to advance both treatment optimization and human health risk assessment in BTEX-contaminated environments.

1.2.10 WHO and ILO Guidance Framework

1.2.10.1 Current International Guidelines

The World Health Organization and International Labour Organization have established comprehensive frameworks for BTEX exposure assessment. The ILO's Global Strategy on Occupational Safety and Health 2024-2030 emphasizes that occupational safety and health has been recognized as "a fundamental principle and right at work." Key ILO instruments relevant to BTEX exposure include the Benzene Convention (1971), Chemicals Convention (1990), and Working Environment Convention (1977), providing international legal frameworks for worker protection.

Current international occupational exposure limits demonstrate significant variations across organizations. For benzene, WHO guidelines recommend zero exposure due to its carcinogenic properties, while NIOSH establishes a recommended exposure limit of 0.319 mg/m^3, and OSHA maintains a permissible exposure limit of 3.19 mg/m^3. These variations reflect ongoing scientific debates regarding safe exposure thresholds and highlight the need for harmonized international standards.

The International Labour Organization (ILO) released its Global Strategy on Occupational Safety and Health 2024-2030 following the inclusion of "a safe and healthy working environment as a fundamental principle and right at work." This strategy emphasizes that the ILO has launched a ratification campaign for the Occupational Safety and Health Convention, 1981 (No. 155) and the Promotional Framework for Occupational Safety and Health Convention, 2006 (No. 187), now recognized as fundamental Conventions.

Key ILO instruments relevant to BTEX exposure include Benzene Convention, 1971 (No. 136) and Recommendation, 1971 (No. 144); Chemicals Convention, 1990 (No. 170) and Recommendation, 1990 (No. 177); Occupational Cancer Convention, 1974 (No. 139) and Recommendation, 1974 (No. 147) and Working Environment (Air Pollution, Noise and Vibration) Convention, 1977 (No. 148).

The World Health Organization maintains updated databases on occupational exposure limits, with the most recent guidance emphasizing that "occupational exposure limits are an upper limit on the acceptable concentration of a hazardous substance in workplace air." The WHO collaborates with ILO on the International Chemical Safety Cards (ICSC) program, providing hazard and safety information on chemicals including BTEX compounds to protect workers. Based on the most recent WHO/ILO collaborative guidelines and national authority updates:

Table 1.1 Occupational exposure limits

Compound	**WHO Guidelines**	**ILO Reference**	**NIOSH REL (2024)**	**OSHA PEL (2024)**
Benzene	0 μg/m³ (carcinogen)	No safe level	0.319 mg/m³ (0.1 ppm)	3.19 mg/m³ (1 ppm)
Toluene	260 mg/m³	375 mg/m³	375 mg/m³ (100 ppm)	754 mg/m³ (200 ppm)
Ethylbenzene	22 mg/m³	435 mg/m³	435 mg/m³ (100 ppm)	435 mg/m³ (100 ppm)
Xylenes	220 mg/m³	435 mg/m³	435 mg/m³ (100 ppm)	435 mg/m³ (100 ppm)

1.2.11 Treatment Process Optimization and Integrated Approaches

1.2.11.1 Plant-Wide Optimization Strategies

Recent advances in wastewater treatment optimization have focused on integrated plant-wide approaches. Song et al. (2025) demonstrated flexible carbon source regulation for mitigating greenhouse gas emissions in full-scale wastewater treatment, showing how operational strategies can simultaneously address BTEX removal and environmental sustainability. Mao et al. (2025) developed comprehensive techno-economic models for wastewater treatment optimization, providing frameworks for balancing treatment efficiency with economic constraints.

Perez et al. (2025) introduced integrated plant-wide models for tracking chemical releases in wastewater systems, offering powerful tools for monitoring BTEX behavior throughout treatment trains. These models enable real-time optimization of treatment processes to minimize both environmental discharge and workplace exposure risks.

1.2.12 Critical Gaps and Future Research Directions

1.2.12.1 Developing Country Research Priorities

Current literature reveals critical knowledge gaps in developing country contexts. Recent systematic reviews emphasize that most BTEX exposure research has been conducted in developed countries where operational conditions may differ significantly from those in developing countries. The absence of region-specific BTEX exposure studies represents a critical gap, particularly given documented treatment performance challenges throughout Southern Africa.

Biomonitoring implementation remains limited in developing regions, despite demonstrated effectiveness. Future investigations should emphasize "itemized appraisals of BTEX intake sources, particularly in employees of operational sections of wastewater treatment plants," integrating both traditional air monitoring and emerging biomonitoring approaches. Current literature reveals insufficient attention to "complete exposure pathways from wastewater to consumers" in developing countries where wastewater reuse for agriculture is common. Comprehensive monitoring of irrigation water quality, soil concentrations, and agricultural products requires urgent attention to protect public health.

1.2.12.2 Methodological and Technical Gaps

The reviewed literature demonstrates remarkable progress in BTEX exposure assessment and treatment technologies, yet significant disparities persist between developed and developing country capabilities. The convergence of advanced analytical techniques, integrated modeling approaches, and biological monitoring represents a paradigm shift in BTEX management. However, critical implementation gaps remain in resource-constrained settings where BTEX exposure risks may be highest.

International coordination through WHO and ILO frameworks provides essential guidance, yet substantial variations in national implementation highlight the need for harmonized global standards. Future research must prioritize technology transfer, regional harmonization of standards, and development of cost-effective monitoring solutions suitable for developing country implementation.

1.2.12.3 Fundamental Knowledge Contradictions

The literature reveals contradictory findings about seasonal BTEX concentration patterns that cannot be reconciled by current research. Dehghani et al. (2022) specifically found that "mean levels of benzene and toluene in winter were higher than in summer" in their wastewater treatment plant study, while other atmospheric studies consistently report higher concentrations in summer due to increased volatilisation. These contradictions suggest that wastewater treatment facilities may have different seasonal patterns compared to general atmospheric conditions, possibly due to facility-specific factors such as enclosed spaces, process temperatures, or treatment operations.

Additionally, the contradiction between Zhang et al. (2024) and Apul et al. (2022) regarding oxygen effects on BTEX degradation highlights fundamental uncertainty about the biochemical mechanisms controlling BTEX fate in treatment systems. The relative importance of volatilisation versus biodegradation as removal mechanisms remains unclear, with significant implications for treatment design and worker exposure assessment.

1.2.13 Literature Review Synthesis and Study Justification

The comprehensive literature review reveals several critical gaps that collectively justify the need for systematic, site-specific studies in Southern African contexts:

First, there are fundamental disagreements about seasonal concentration patterns, with studies reporting contradictory findings about when peak concentrations occur, suggesting that facility-specific or regional factors may override general climatological influences. Second, the literature demonstrates a severe lack of systematic studies from sub-Saharan African contexts, limiting the applicability of findings to facilities operating under different climatic, institutional, and operational conditions.

Third, there is insufficient understanding of how multiple environmental factors interact to influence BTEX concentrations, making it difficult to predict behavior under different operational conditions. Regional studies reveal widespread treatment performance challenges, institutional constraints, and operational difficulties that differ markedly from conditions in developed countries where most BTEX research has been conducted.

These gaps collectively demonstrate the urgent need for comprehensive, site-specific studies that can provide reliable data for both treatment optimization and worker protection in Southern African contexts. The similarities in climatic conditions and treatment processes between existing studies and Gaborone's wastewater treatment facilities provide important baseline insights, but cannot substitute for direct assessment of local exposure patterns and operational conditions.

Understanding these factors through systematic local investigation will enable development of more effective strategies for BTEX management and removal in wastewater treatment processes while ensuring appropriate worker protection measures are implemented based on actual rather than assumed exposure patterns.

1.3. Problem statement

The rapid industrialisation and urban growth in Gaborone, Botswana, has led to increased discharge of industrial effluents containing BTEX compounds into the city's wastewater treatment works (WWTWs). Botswana's economy has maintained an average growth rate of 5% per annum over the past decade, with the manufacturing sector experiencing significant expansion as part of the country's economic diversification efforts (African Development Bank Group [AfDB], 2024). Industrial production in Botswana has fluctuated considerably, reaching peaks during economic recovery periods and demonstrating the volatile nature of industrial activity (Trading Economics, 2025). While these facilities are essential for environmental protection, they may inadvertently become sources of occupational exposure to hazardous air pollutants for workers (Saeedi et al., 2024). This situation is particularly concerning as many developing nations, including Botswana, lack occupational exposure data for BTEX compounds in wastewater treatment settings.

The primary problem is the absence of systematic characterisation of occupational exposure to BTEX compounds among workers at Gaborone's wastewater treatment facilities. This knowledge gap presents significant challenges for workplace safety management and worker health protection (Kong et al., 2021; Ranasinghe, 2023). While studies have been conducted on BTEX exposure in wastewater treatment plants in the Middle East, there are no published studies specifically examining BTEX exposure in Southern African WWTPs, representing a critical research gap in occupational health assessment for this region. Without accurate exposure data, it becomes difficult to assess health risks, implement appropriate control measures, or develop evidence-based safety protocols for workers in these facilities.

Current workplace safety protocols at Gaborone's WWTPs may be inadequate as they are not based on local exposure data. Instead, they rely on guidelines developed for facilities in different geographical and climatic conditions (Emmanuel et al., 2023). The unique environmental conditions in Botswana, characterised by high temperatures and intense solar radiation, could significantly influence BTEX volatilisation rates and worker exposure patterns, making international standards potentially inappropriate for local conditions (Adom & Simatele, 2024; Zhang et al., 2022).

Furthermore, the lack of data on BTEX concentrations at different treatment stages hampers the identification of high-risk areas within the facilities. This information gap prevents the implementation of targeted control measures and appropriate personal protective equipment requirements for specific work zones (Dharma et al., 2022; Chukwuemeka et al., 2021). Without this crucial information, facility managers cannot effectively prioritise resources for exposure control or develop job-specific safety protocols.

1.4 Justification

This research addresses a critical gap in occupational health knowledge by providing the first assessment of BTEX exposure among wastewater treatment workers in Gaborone, Botswana. The study's findings will establish crucial baseline data for exposure levels and patterns, enabling evidence-based decision-making for worker protection measures (Saeedi et al., 2024). Current safety protocols in Botswana's wastewater treatment facilities rely heavily on international standards that may not account for local environmental conditions or operational practices (Omohwovo, 2024; Yasmeen & Hafeez, 2023).

The research is particularly timely given Gaborone's rapid industrial growth and the corresponding increase in chemical-laden wastewater reaching treatment facilities. Recent studies indicate a 40% rise in industrial effluent volumes over the past five years, potentially increasing worker exposure risks (Yu et al., 2022). Understanding these exposure patterns is essential for protecting worker health and ensuring sustainable operation of these critical infrastructure facilities (Kong et al., 2020).

The study's results will directly benefit facility managers and health and safety professionals by identifying high-risk areas and activities within the treatment works. This information will enable more efficient allocation of resources for exposure control measures and help optimise personal protective equipment requirements (Ammad et al., 2021). The findings will also support the development of targeted training programs and standard operating procedures specific to local conditions.

From a broader perspective, this research will contribute to the growing body of knowledge on occupational exposure in developing nations' wastewater treatment facilities. The methodology and findings can serve as a model for similar studies in other African countries facing comparable challenges (Adom & Simatele, 2024; Zhang et al., 2022). Additionally, the study will help bridge the gap between developed and developing nations' occupational health practices in the wastewater treatment sector.

This work aligns with Botswana's national occupational health and safety objectives and supports compliance with international labour standards. Providing locally relevant exposure data, the study will assist policymakers in developing appropriate regulatory frameworks for worker protection in the wastewater treatment sector (Kumar et al., 2024; Drechsel et al., 2022). The findings will also contribute to the broader goal of promoting sustainable industrial development while protecting worker health.

1.5 Study aim

The aim of this study wasto assess the level of occupational exposure to benzene, toluene, ethylbenzene, and xylene (BTEX) among workersata wastewater treatment plantin Gaborone, Botswana.

1.6 Objectives

To achieve the above aim, the following objectives were set out:

i. To evaluate the concentration of BTEX compounds emitted in the air during wastewater treatment processes at a wastewater treatment plant in Gaborone, Botswana.
ii. To compare the concentrations of BTEX along the different wastewater treatment stages of awastewater treatment plant in Gaborone.

1.7 Research Questions

The study seeks to answer the following research questions:

Main Research Question: What are the levels of occupational exposure to BTEX compounds among workers at wastewater treatment facilities in Gaborone, Botswana?

Sub-Questions:

1. What are the spatial patterns of BTEX concentrations across treatment stages?
2. How do environmental parameters influence BTEX volatilization rates?
3. Do current exposure levels exceed international safety standards?
4. Which treatment stages present the highest risk for worker exposure to BTEX compounds?
5. How do seasonal and diurnal variations affect BTEX concentrations and worker exposure patterns?

1.8 Hypothesis

Based on the study aim and objectives, the following hypotheses were formulated:.

For Objective I: Evaluation of BTEX Concentrations

1. Null hypothesis (H_0)

The concentration of BTEX compounds emitted in the air during wastewater treatment processes at the Gaborone Wastewater Treatment Plant does not exceed the recommended occupational exposure limits as set by international standards (NIOSH, OSHA, and WHO).

2. Alternative hypothesis (H_1)

The concentration of BTEX compounds emitted in the air during wastewater treatment processes at the Gaborone Wastewater Treatment Plant exceeds the recommended occupational exposure limits as set by international standards (NIOSH, OSHA, and WHO).

For Objective II: Comparison of BTEX Concentrations across Treatment Stages.

1. Null hypothesis (H_0)

There is no significant difference in BTEX concentrations between different treatment stages (night soil discharge area, screening unit, and grit chamber) within the preliminary treatment stage at the Gaborone wastewater treatment plant.

2. Alternative hypothesis (H_1)

There is a significant difference in BTEX concentrations between different treatment stages (night soil discharge area, screening unit, and grit chamber) within the preliminary treatment stage at the Gaborone wastewater treatment plant.

1.9 Chapter summary

This chapter provided an introduction to BTEX compounds (benzene, toluene, ethylbenzene, and xylenes) in wastewater treatment works. It explored their sources, pathways, and behaviour across different treatment stages, with particular focus on Gaborone's wastewater treatment facilities. The literature review examined how BTEX concentrations vary across treatment stages, with the highest levels typically found in aeration tanks, followed by sludge handling areas. Factors affecting BTEX concentrations including temperature, process parameters, and seasonal variations were detailed, highlighting the unique challenges presented by Gaborone's semi-arid climate. The chapter addressed the knowledge gap regarding occupational exposure to BTEX compounds in wastewater treatment settings in developing nations. It concluded by presenting the study's aim to assess occupational BTEX exposure among workers at Gaborone's wastewater treatment works, alongside specific objectives and hypotheses to guide the research.

CHAPTER 2: METHODOLOGY

This chapter describes the study design, sampling methods, and analytical techniques used to characterise BTEX emissions at the Gaborone Wastewater Treatment Plant (GWWTP). It provides a detailed description of the study area, including the geographical location, climate conditions, and operational characteristics of the GWWTP. The methods for measuring ambient air concentrations, data collection procedures, and quality control measures are outlined. The chapter also details the sampling locations across different treatment stages, the equipment used, and the timing of sample collection to account for diurnal and seasonal variations. Additionally, it explains the statistical approaches used to analyse the collected data and assess BTEX concentrations across different treatment stages within the facility.

2.1 Methods and materials

2.1.1 Description of the study area

Gaborone, as Botswana's capital city, has experienced substantial industrial growth over the past decade, leading to increased industrial wastewater generation (Nagabooshnam, 2021). The city's wastewater treatment plant receives effluent from various industries, including textile manufacturing, chemical processing, and automotive services, all of which are known sources of BTEX compounds (Selwe et al., 2024).

The current study was conducted at Gaborone Wastewater Treatment Plant (GWWTP), located approximately 10 kilometres northeast of Gaborone city centre, near the Notwane River. As shown in Figure 2.1, the GWWTP facility (labelled "Glen Valley WWTP") is situated along the Notwane River, northeast of Gaborone city. The map illustrates the spatial relationship between the treatment facility and the urban centre, highlighting its strategic position downstream from the city.

This facility processes wastewater from approximately 215,602 households in the Gaborone catchment area, as well as from several industrial zones, including the Gaborone International Commerce Park and the Gaborone West Industrial Estate (Masundire et al., 2020). Industrial contributors include automotive service centres, textile manufacturing facilities, and printing operations, which collectively account for approximately 5% of the total wastewater flow, while domestic sources contribute the remaining 95% (Gaboutloeloe et al., 2022; Tore & Yilmaz, 2022). The average annual effluent discharge is 8,415 m^3.

Figure 2.2 provides a satellite view of the study area, with Gaborone city visible in the southwestern portion of the main image and the wastewater treatment works located in the north eastern section. The three inset images labelled A, B, and C show detailed views of key components of the wastewater treatment system: (A) depicts the wastewater stabilisation ponds, (B) shows the main treatment facility infrastructure, and (C) illustrates the sedimentation and aeration tanks where various treatment processes occur.

The treated effluent is utilised for irrigation in the Gaborone peri-urban agricultural project, contributing to local agriculture. This reuse practice creates potential exposure pathways for residents and consumers through agricultural products grown using the treated wastewater, representing an important consideration for public health beyond the facility boundaries. The facility employs a mechanical-biological treatment system with activated sludge processing, incorporating both aerobic and anaerobic treatment stages. While a complete wastewater treatment system typically includes preliminary, primary, secondary, and sludge handling stages, this study specifically focused on three zones within the preliminary treatment stage: the night soil discharge area, which is the point where septic waste is introduced to the treatment system; the screening unit, where large debris is removed via mechanical screens; and the grit chamber, where sand, gravel, and other inorganic materials are separated from the wastewater.

The selection of these three specific locations within the preliminary treatment stage was based on several critical considerations that justify their importance for BTEX exposure assessment. First, the preliminary treatment stage represents the initial point of contact between workers and untreated wastewater containing the highest concentrations of volatile organic compounds, including BTEX. At this stage, wastewater has undergone minimal processing, meaning BTEX compounds remain largely intact and available for volatilisation into the workplace atmosphere. Research has demonstrated that BTEX volatilisation rates are typically highest during initial treatment processes when mechanical agitation and turbulence facilitate the transfer of volatile compounds from the liquid to the gaseous phase. Second, these three zones experience the most intensive worker activity and longest exposure durations within the preliminary treatment area. The night soil discharge area requires frequent monitoring and maintenance activities, exposing workers to direct contact with incoming wastewater streams. The screening unit necessitates regular cleaning and maintenance of mechanical equipment, creating sustained worker presence in areas of potential BTEX emission. Similarly, the grit chamber requires periodic inspection and cleaning operations that involve close proximity to turbulent wastewater flows. This combination of high BTEX concentrations and intensive worker activity creates conditions that may result in maximum occupational exposure levels. Third, focusing on the preliminary treatment stage allows for the establishment of baseline exposure data that can inform safety protocols for the entire treatment facility. Since BTEX concentrations typically decrease through subsequent treatment stages due to volatilisation and biodegradation processes, characterising exposure levels at the preliminary stage provides conservative estimates that can guide protective measures throughout the facility. Additionally, the mechanical processes occurring in these three zonesincluding pumping, screening, and grit removalcreate turbulence and surface agitation that enhance BTEX volatilisation rates, making them critical points for exposure assessment and control measure implementation. These three zones were selected based on preliminary assessments indicating potentially significant BTEX emissions during these initial treatment processes and their relevance to worker exposure patterns. The focus on these specific zones within the preliminary treatment stage allowed for detailed characterisation of BTEX concentration variations at the beginning of the treatment process, where wastewater first enters the facility and undergoes initial physical treatment (Kong et al., 2020).

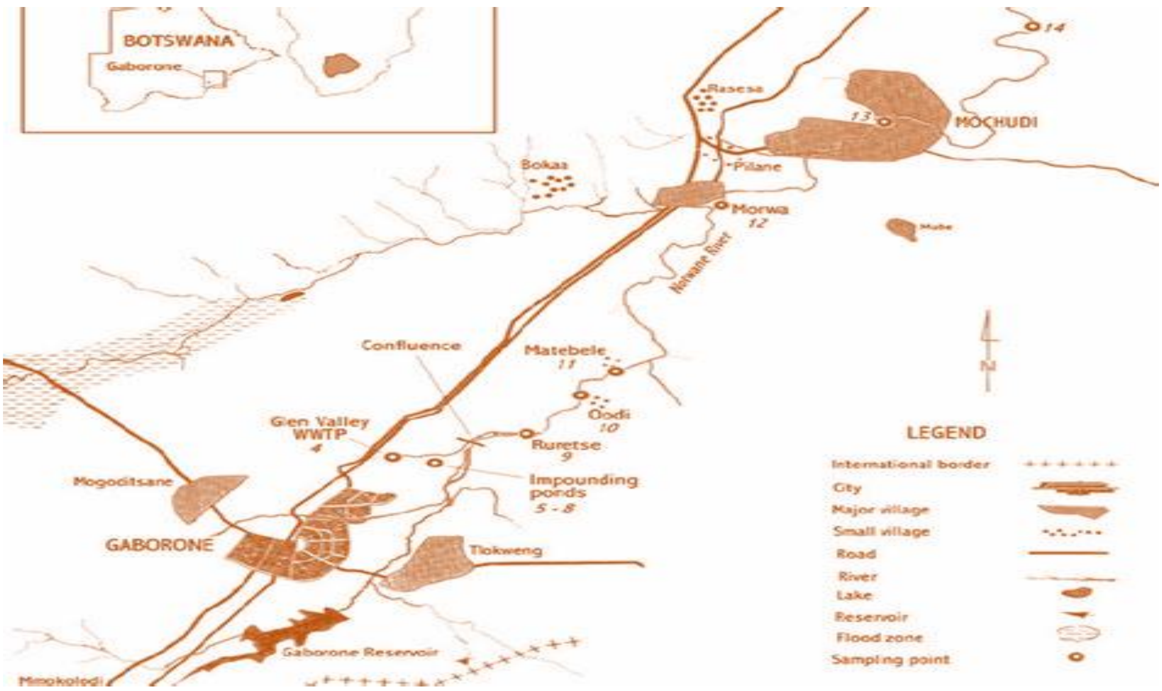

Figure 2.1 Map showing the location of Gaborone Wastewater Works in relation to Gaborone city

(Source: Botswana Department of Surveys and Lands, 1987).

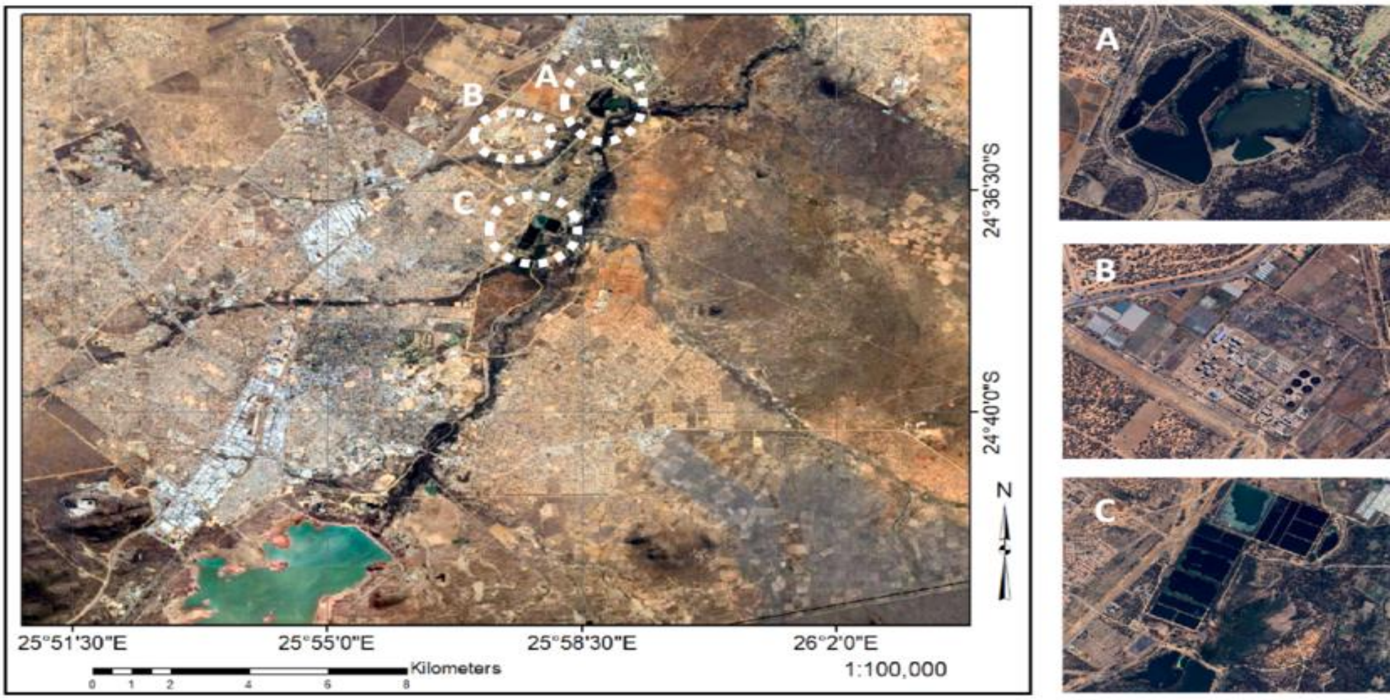

Figure 2.2 Satellite map showing the location of Gaborone Wastewater Works in relation to Gaborone city

Legends: (A) Wastewater stabilization ponds, (B) Main treatment facility infrastructure (C) Sedimentation and aeration tanks

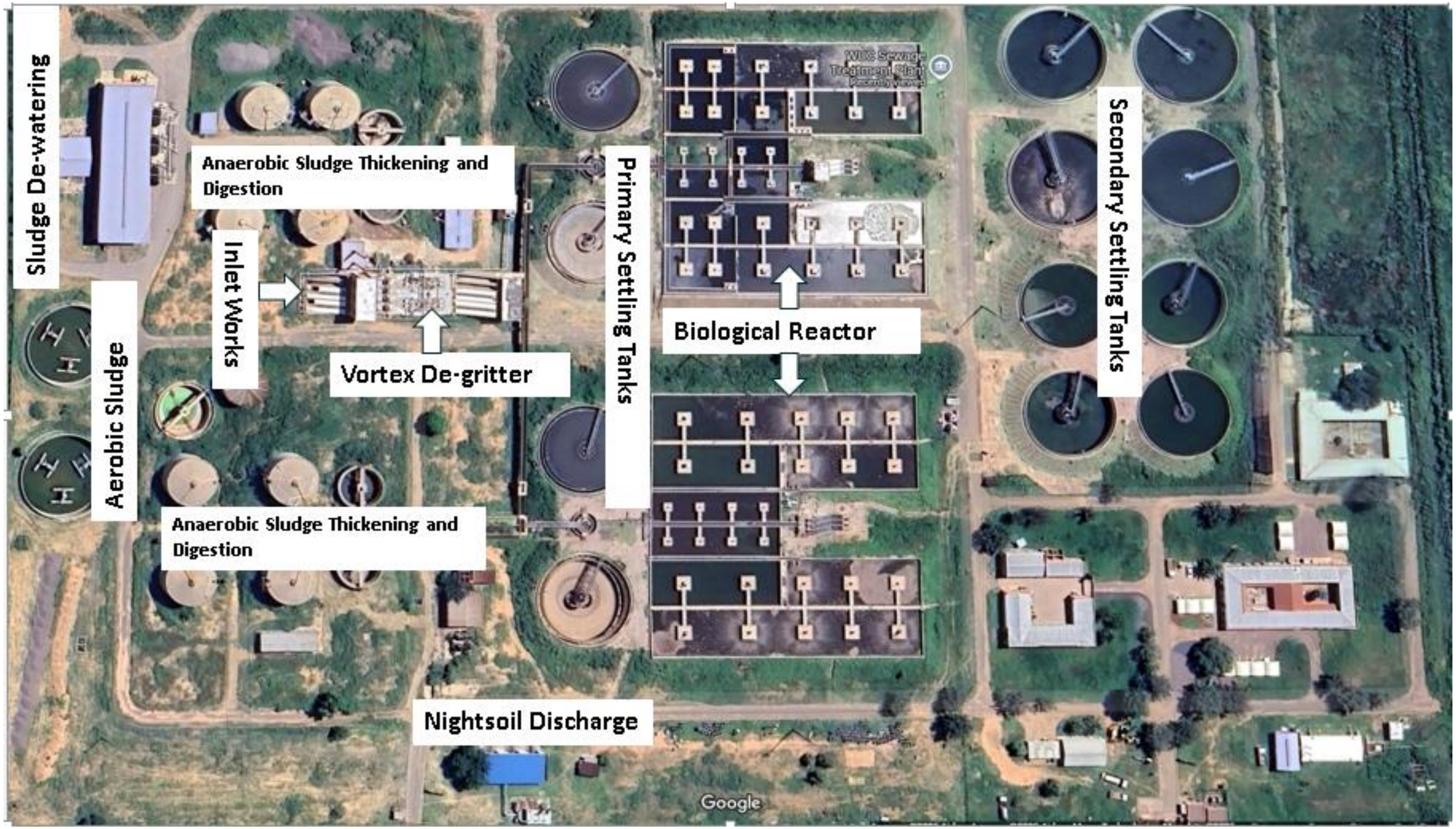

Figure 2.3 Photographs of sampling sites

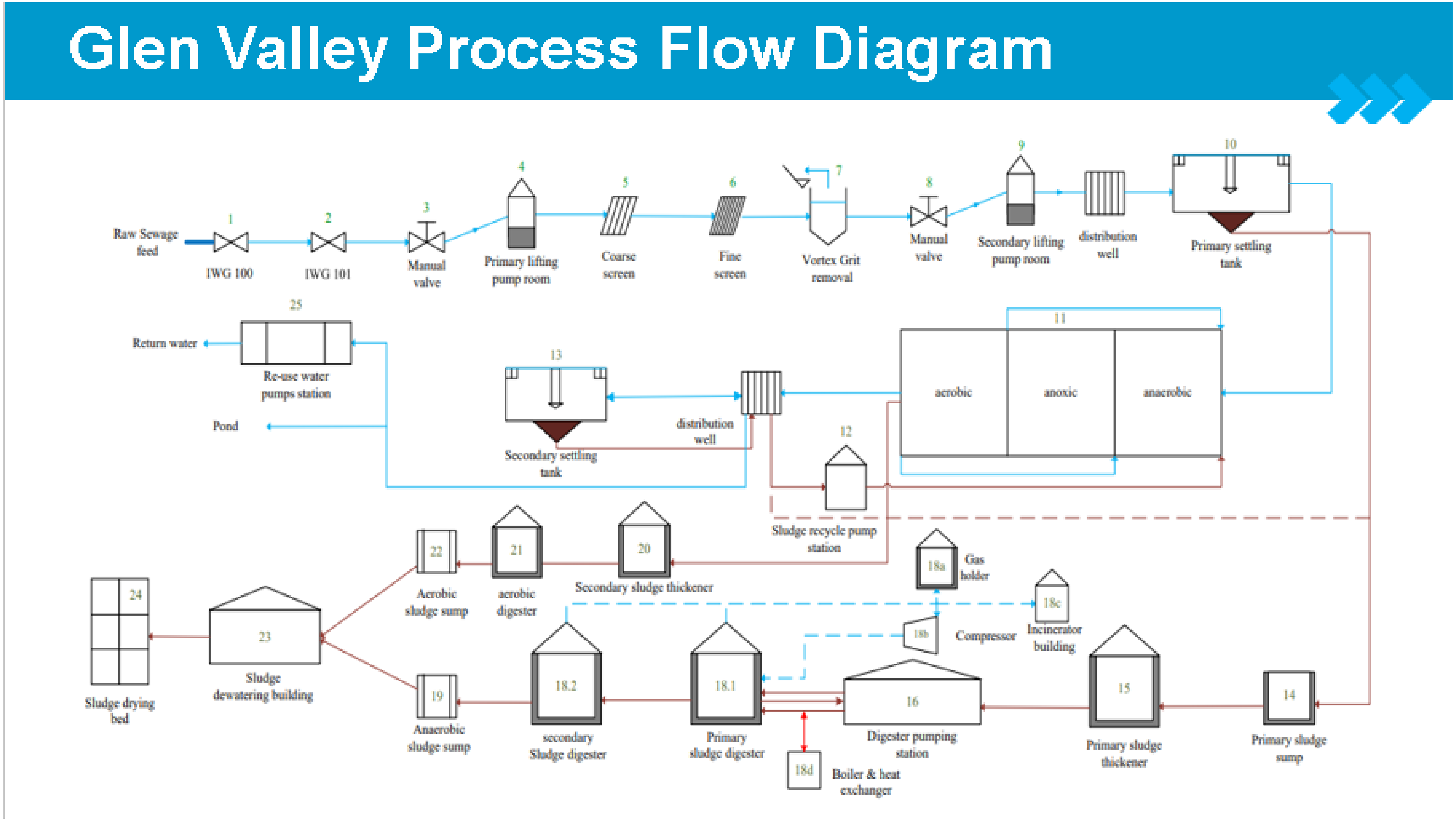

Figure 2.4 Schematic of treatment process flow with sampling points marked

2.1.2 Gaborone Wastewater Treatment Plant (GWWTP)

Gaborone, the capital city of Botswana, has experienced significant urban growth, leading to increased challenges in wastewater management (Gaboutloeloe et al., 2018). The Gaborone Wastewater Treatment Plants (GWWTP) play a crucial role in managing the city's wastewater, which is essential for public health and environmental sustainability. The plant capacity isat 90 million litres a day, but poor infrastructure and upkeep have made inflow management difficult (Selwe et al., 2024). Gaborone's treatment facility, like many in Botswana, lacks effective management, resulting in incorrect flow records and operational inefficiencies (Gaboutloeloe et al., 2018; Selwe et al., 2024).

The Gaborone WWTW was established to treat wastewater generated from urban areas, including residential and commercial sectors (Selwe et al., 2024). As of recent reports, the facility has been facing capacity issues due to rapid population growth and urbanisation. The original design capacity of the plant has been exceeded, necessitating expansions and upgrades to meet increasing demands (Inarmal, 2022).

2.1.3 Selection of sampling locations

Air sampling locations in the WWTP are illustrated in Figure 2.3, which shows the complete treatment process flow at Gaborone Wastewater Treatment Works. As indicated in the schematic diagram, this study specifically focused on three zones within the preliminary treatment stage (highlighted in yellow in the diagram): the nightsoil discharge area, screens, and grit chamber.

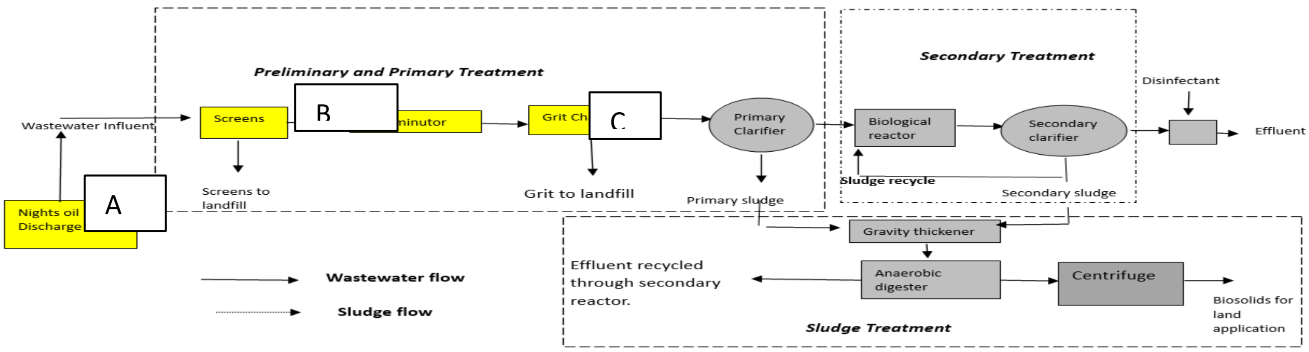

Figure 2.5. Schematic diagram of GWWTP and locations of the sampling points in the study area.

The nightsoil discharge area (marked A in the diagram) caters for disposal of effluent by vacuum tankers from households that are not connected to the sewer reticulation. This area has been identified as a potential source of the highest concentration of BTEX compounds due to the turbulence and initial release of volatile compounds when septage is discharged (Almatouq et al., 2022). Normally the vacuum tankers start their discharge at 0800 hours until 1700 hours.

The screening unit (marked B) represents the next stage in the treatment process, where large debris is removed via mechanical screens. This area typically experiences moderate BTEX emissions due to the physical agitation of wastewater and exposure of fresh wastewater surfaces to air. This study's preliminary treatment step ends with the grit chamber (C), where sand, gravel, and other inorganic elements are isolated from wastewater. This zone was chosen to analyse BTEX concentration fluctuations during preliminary treatment.

2.1.3.1 GPS Coordinates and Site Characteristics

Precise geographical positioning of each sampling location was established through differential GPS surveys conducted during the initial site reconnaissance phase. The coordinate system employed was WGS84 datum with coordinates recorded in decimal degrees to ensure reproducibility and facilitate future monitoring activities.

Table 2.1 GPS Coordinates and Site Characteristics

Location	**GPS Coordinates**	**Elevation (m)**	**Site Description**	**Operational Hours**
Nightsoil discharge area (A)	S 24°39'42.3" E 25°58'14.7"	1,012	Primary septage discharge point with concrete receiving basin	0800-1700 hours
Screening unit (B)	S 24°39'43.1" E 25°58'15.2"	1,011	Mechanical screening facility with automated cleaning system	Continuous operation
Grit chamber (C)	S 24°39'43.8" E 25°58'15.9"	1,010	Circular grit removal chamber with settling mechanisms	Continuous operation

The spatial arrangement of these sampling locations follows the natural flow gradient through the preliminary treatment system, with elevations decreasing from the discharge area (1,012 m) through the screening unit (1,011 m) to the grit chamber (1,010 m). This elevation gradient facilitates gravity flow and represents the typical hydraulic profile found in wastewater treatment facilities. The linear distance between adjacent sampling points averages approximately 50 meters, providing adequate spatial separation to characterize concentration gradients while maintaining operational access for routine monitoring activities.

2.1.3.2 Sampling Protocol and Site Setup

Following the schematic representation in Figure 2.3, passive samplers were deployed according to standardized protocols that ensured consistent and representative sampling across all locations. Sampler positioning followed occupational exposure assessment guidelines with mounting height maintained at 1.5 meters above ground level, corresponding to the average breathing zone height of workers operating in these areas. This height was selected based on anthropometric data for the local workforce and international standards for personal exposure monitoring.

The mounting system incorporated stainless steel posts with adjustable brackets to accommodate site-specific terrain variations while maintaining consistent sampler orientation. Samplers were mounted vertically with the sampling face oriented downward to prevent direct precipitation ingress while allowing unrestricted air circulation around the sampling medium. Weather protection shields constructed from UV-resistant polycarbonate were installed above each sampler to prevent direct sunlight exposure that could affect sample integrity through photodegradation or thermal effects.

Spatial distribution of triplicate samplers at each location followed a systematic pattern with minimum 2-meter separation between individual samplers to ensure statistical independence while maintaining representative sampling of the local microenvironment. The triangular arrangement of triplicates provided optimal spatial coverage while minimizing the potential for mutual interference between samplers. Permanent reference markers constructed from concrete were installed at each sampling location to ensure consistent positioning throughout the 18-week study period and facilitate future monitoring activities.

Environmental monitoring equipment was integrated with the sampling infrastructure to provide comprehensive characterization of conditions affecting BTEX volatilization and dispersion. A primary weather station positioned centrally between sampling locations recorded temperature, humidity, wind speed, and atmospheric pressure at 15-minute intervals throughout each sampling period. Secondary monitoring points at each sampling location provided microclimate assessment using portable dataloggers to capture spatial variations in environmental conditions that might influence BTEX concentrations.

2.1.3.3 Site Selection Rationale

The selection of these three specific locations within the preliminary treatment stage was based on comprehensive risk assessment principles and established occupational exposure evaluation frameworks that prioritize worker safety while ensuring scientific validity of the monitoring program. The nightsoil discharge area was prioritized as the primary sampling location because it represents the point of maximum BTEX emission potential within the facility, where raw septage typically contains the highest concentrations of volatile organic compounds due to the absence of any treatment processes that could reduce these concentrations through volatilization or biodegradation.

The mechanical discharge process from vacuum tankers creates significant turbulence and surface agitation, which dramatically increases the mass transfer of BTEX compounds from the liquid phase to the atmospheric environment where workers operate. This turbulent mixing action exposes fresh wastewater surfaces to air and creates aerosol formation, both of which enhance the volatilization rate of BTEX compounds. The confined nature of the discharge area, with concrete walls and limited ventilation, can lead to accumulation of volatile compounds in the worker breathing zone, making this location critical for exposure assessment.

The screening unit was selected as the second critical sampling location because it represents a transition zone where BTEX concentrations begin to change due to initial treatment processes while maintaining significant emission potential. The mechanical screening operation involves continuous movement of wastewater across screening surfaces, creating ongoing opportunities for BTEX volatilization through surface renewal and agitation. The screening equipment requires regular maintenance activities including screen cleaning, debris removal, and mechanical adjustments that bring workers into close proximity with the wastewater stream for extended periods.

Additionally, this location experiences consistent worker presence for operational monitoring activities, equipment maintenance, and routine inspections, making it essential for comprehensive exposure assessment. The physical characteristics of the screening facility, including partially enclosed spaces and limited natural ventilation, can lead to accumulation of volatile compounds during certain meteorological conditions. The combination of ongoing emission sources and regular worker activity creates conditions that may result in significant occupational exposure levels requiring quantitative assessment.

The grit chamber was included as the third sampling location to capture the spatial gradient of BTEX concentrations across the preliminary treatment stage and provide comprehensive characterization of exposure patterns throughout this critical treatment phase. While this location may have lower absolute BTEX concentrations compared to upstream locations due to partial volatilization and dilution effects, it serves several critical functions in the exposure assessment framework that justify its inclusion in the monitoring program.

The grit removal process involves settling and separation mechanisms that create different flow patterns and surface exposure conditions compared to the upstream locations, allowing for characterization of how BTEX concentrations vary spatially within the preliminary treatment system. This spatial characterization provides essential data for understanding concentration gradients and developing appropriate control measures for different work areas within the facility. Furthermore, workers regularly access this area for grit removal operations, equipment maintenance, and process monitoring activities that require direct interaction with the treatment system.

The site selection methodology incorporated multiple technical and practical considerations to ensure optimal monitoring effectiveness while maintaining operational safety and accessibility. Sites were evaluated for their emission potential based on preliminary assessments of wastewater characteristics, process turbulence, and surface exposure conditions. The discharge area demonstrated the highest emission potential due to direct raw septage contact, while the screening unit showed moderate emission potential from mechanical agitation, and the grit chamber exhibited lower but still significant emission potential from settling operations.

Accessibility for continuous monitoring was a crucial selection criterion, as all locations needed to provide safe access for researchers while allowing routine sample collection without disrupting facility operations. Each selected location met stringent safety requirements for researcher access while maintaining adequate distance from operational equipment to prevent interference with normal facility activities. The locations provided stable mounting surfaces for sampling equipment and adequate clearance for proper air circulation around passive samplers.

The study design targeted these three zones within the preliminary treatment stage to characterize BTEX concentration fluctuations at the earliest stage of treatment, where worker exposure potential is highest due to the raw nature of incoming wastewater and the intensive operational activities required for initial treatment processes. This focus on the preliminary treatment stage provides conservative estimates of exposure levels that can guide protective measures throughout the facility, since BTEX concentrations typically decrease through subsequent treatment stages due to volatilization and biodegradation processes.

2.1.4 Preparation of samplers

Science Kit Corporation (SKC 575-001) passive samplers were ready to be sent out into the field to measure BTEX chemicals in the air using diffusion-based adsorption. Molecular diffusion says that BTEX compounds in the air move quietly from areas with higher concentrations (like ambient air) to areas with lower concentrations (like the adsorbent material) without the need for pumps or power sources (Estevan et al., 2012). There were 350 mg of activated charcoal adsorbent in each 3.5 cm round badge tester. Activated charcoal is very good at removing volatile organic compounds.

Before they were used, samplers were checked for damage like cracks, loose parts, or damaged membranes. They were then kept in sealed cases with activated carbon to keep them from getting contaminated. Each sampler was labelled with a unique alphanumeric identifier for tracking purposes, including location code, replicate number, and deployment date. The samplers were transported to the field in sealed metal containers with temperature-stabilising materials to prevent exposure to contaminants or temperature extremes before deployment.

The SKC 575-001 passive samplers were selected for this study due to their reliability in similar environmental monitoring applications, their ability to provide time-weighted average concentrations over extended periods, and their suitability for the semi-arid climate conditions prevalent in Gaborone (Agarwal & Mustafi, 2021). The samplers' documented sampling rate for BTEX compounds (approximately 15.0–25.0 mL/min depending on the specific compound) was considered in subsequent concentration calculations.

2.1.5 Air monitoring method and protocol

2.1.5.1 Passive sampler deployment

Ambient air monitoring was carried out passively using the adsorption method, specifically employing the standard method NIOSH 1500/1501 for aromatic hydrocarbons with modifications for passive sampling applications. Scientific Kit Corporation (SKC 575-001) passive samplers were deployed for BTEX measurement following standardised protocols. A total of 108 SKC 575-001 passive samplers (36 locations × 3 replicates) were deployed across the treatment facility over the 18-week sampling period.

Sets of three passive samplers (triplicates) were exposed for seven days at each sampling location to obtain weekly average BTEX concentrations across different treatment stages at the Gaborone wastewater plant. Triplicate sampling (meaning three identical samplers placed at each location simultaneously) was employed to assess sampling precision, identify potential outliers, and increase the statistical robustness of the measurements.

Nine sampling points were established across three treatment stages. In the preliminary treatment area, sampling was carried out at the nightsoil discharge area, screening unit, and grit chamber. The secondary treatment zone had samplers positioned at the primary settling tank inlet, aeration tank, and secondary clarifier. Finally, the sludge treatment zone was monitored at the sludge thickener, dewatering unit, and drying beds.

At each location, samplers were deployed in triplicate (three separate samples were collected to ensure the accuracy and reliability of the data) at a height of 1.5 meters above ground level, corresponding to the average breathing zone height of workers, in accordance with occupational exposure assessment guidelines (NIOSH, 2022). Permanent identification tags were put on each sampling site. All samplers were positioned away from direct sunlight and rain to prevent interference with the sampling process.

(a) Positioning Specifications

The positioning specifications for passive samplers were developed to ensure consistent and representative sampling across all locations while maintaining comparability between different sampling sites and time periods. Sampler mounting employed standardized stainless steel posts with adjustable clamps that allowed precise height adjustment to maintain the 1.5-meter elevation requirement across varied terrain. The mounting system incorporated spirit levels and measuring devices to ensure vertical orientation and accurate height placement, with documentation photographs taken at each installation to verify proper positioning.

Spatial distribution of triplicate samplers followed a systematic triangular pattern with each sampler positioned at the vertices of an equilateral triangle with 2-meter sides, ensuring adequate spatial separation while maintaining representative sampling of the local microenvironment. This geometric arrangement prevented mutual interference between samplers while providing comprehensive coverage of the sampling area. The triangular configuration was oriented consistently at each location, with one sampler positioned toward the predominant wind direction based on historical meteorological data, and the remaining two samplers positioned at 120-degree intervals to capture potential directional variations in BTEX concentrations.

Sampler orientation was standardized with the sampling face positioned vertically and angled 15 degrees downward from horizontal to prevent direct precipitation ingress while allowing unrestricted air circulation around the activated charcoal medium. This orientation was selected based on manufacturer recommendations and field validation studies demonstrating optimal sampling efficiency under the semi-arid conditions prevalent in Gaborone. Weather protection shields constructed from UV-resistant polycarbonate were installed 30 centimeters above each sampler, providing protection from direct sunlight and precipitation while maintaining adequate ventilation around the sampling medium.

Mounting stability was ensured through concrete footings embedded 50 centimeters into the ground, with steel reinforcement rods providing additional structural support against wind loading and operational vibrations. The mounting system incorporated anti-tampering features including lockable clamps and vandal-resistant hardware to prevent unauthorized removal or repositioning of samplers during the exposure period. Unique identification codes were permanently etched into each mounting post and recorded in field documentation to ensure consistent positioning throughout the study period.

Environmental monitoring equipment was integrated with the sampling infrastructure to provide comprehensive characterization of conditions affecting BTEX volatilization and dispersion. A primary weather station positioned centrally between sampling locations recorded temperature, humidity, wind speed, and atmospheric pressure at 15-minute intervals throughout each sampling period. Secondary monitoring points at each sampling location provided microclimate assessment using portable dataloggers to capture spatial variations in environmental conditions that might influence BTEX concentrations.

(b) Environmental Monitoring Details

The environmental monitoring program extended beyond the basic Kestrel 5500 Weather Meter measurements to provide comprehensive characterization of meteorological and operational conditions affecting BTEX emissions and atmospheric dispersion. Continuous monitoring stations were established at each sampling location using Campbell Scientific CR1000X dataloggers equipped with multiple sensor arrays to capture temporal and spatial variations in environmental parameters throughout each seven-day sampling period.

Temperature measurements were recorded using platinum resistance temperature detectors (RTDs) with ±0.1°C accuracy, housed in naturally ventilated radiation shields to prevent solar heating effects. Humidity sensors employed capacitive polymer technology with ±2% accuracy across the full measurement range, with regular calibration using saturated salt solutions to maintain measurement integrity. Wind speed and direction measurements utilized ultrasonic anemometers with ±0.01 m/s resolution and ±3° directional accuracy, providing vector wind data essential for understanding atmospheric dispersion patterns.

Atmospheric pressure measurements were conducted using precision barometric sensors with ±0.1 hPa accuracy, calibrated against national meteorological standards to ensure data compatibility with regional weather networks. Solar radiation measurements employed pyranometers with ±5% accuracy to quantify the energy input driving photochemical processes and thermal effects on BTEX volatilization. Precipitation measurements utilized tipping bucket rain gauges with 0.1 mm resolution, providing data on events that might affect sampler performance or operational activities.

The monitoring network incorporated soil temperature sensors at 10-centimeter depth to assess thermal effects on subsurface processes, and surface temperature measurements using infrared thermometers to quantify heat transfer effects on BTEX volatilization from wastewater surfaces. Atmospheric stability parameters were derived from temperature gradient measurements using sensor arrays at multiple heights, providing data on vertical mixing conditions that affect pollutant dispersion.

Data logging systems incorporated redundant storage and transmission capabilities to prevent data loss during equipment failures or communication disruptions. Quality control procedures included regular sensor calibration, cross-validation between monitoring stations, and comparison with regional meteorological data to identify and correct systematic errors. Environmental data were synchronized with operational parameters and sampling schedules to enable correlation analysis between meteorological conditions and BTEX concentrations.

(c) Process Integration and Operational Coordination

The sampling program was designed to integrate seamlessly with facility operations while capturing the full range of operational conditions that might affect BTEX emissions throughout the preliminary treatment stage. Sampling schedules were coordinated with facility management to ensure representative coverage of normal operational activities while avoiding disruption to critical treatment processes. The deployment strategy incorporated systematic timing to capture both routine operational conditions and periodic maintenance activities that might influence emission patterns.

Sampling commencement was synchronized with facility operations beginning at 0800 hours, coinciding with the start of septage discharge activities and the transition from overnight to daytime operational modes. This timing ensured that samplers captured the full range of operational conditions, including the peak discharge periods when BTEX emissions were expected to be highest. The seven-day sampling duration provided comprehensive coverage of weekly operational cycles, including both weekday and weekend operational patterns that might affect emission characteristics.

Septage discharge activities were continuously monitored throughout each sampling period to establish temporal correlations between operational intensity and BTEX concentrations. Discharge schedules, volumes, and source characteristics were recorded to enable assessment of how operational variables influence emission patterns. The monitoring program incorporated real-time communication with facility operators to document unusual operational events, equipment maintenance activities, and process disruptions that might affect sampling results.

Treatment flow rates were recorded hourly throughout each sampling period using facility SCADA systems and portable flow measurement devices to quantify the hydraulic loading conditions affecting BTEX volatilization. Flow variations were correlated with operational schedules and meteorological conditions to identify factors controlling emission intensity. Retention times in each treatment unit were calculated based on flow rates and unit volumes to assess the residence time available for BTEX volatilization and removal processes.

Operational parameter monitoring included documentation of equipment operation cycles, maintenance activities, and process adjustments that might create temporary variations in emission patterns. The monitoring program captured both routine operational variations and exceptional events such as equipment failures, process upsets, or maintenance activities that could influence BTEX concentrations. This comprehensive operational documentation enabled identification of emission sources and factors controlling concentration variations throughout the preliminary treatment stage.

Installation and removal times were precisely recorded for each sampler to calculate exact exposure duration, which was used in the subsequent calculation of time-weighted average concentrations. Post-sampling handling followed strict protocols—exposed samplers were immediately wrapped in aluminium foil to prevent cross-contamination, placed in thermally insulated containers with ice packs maintained at 4-8°C, transported to the laboratory within 24 hours of collection, and stored at 4°C until analysis, with a maximum storage time of 1-4 weeks as recommended by the manufacturer to ensure sample integrity.

Field blanks (unopened samplers transported to and from the field) and laboratory blanks (samplers maintained in the laboratory environment) were included as quality control measures, constituting 10% of the total sample count to monitor for contamination during handling, transport, and storage processes.

2.1.5.2 Environmental parameters

The study measured several environmental parameters across the treatment locations over the 18-week sampling period. Temperature, humidity, flow rate, and retention time were recorded alongside BTEX concentrations. Environmental conditions were systematically documented during each sampling period to assess potential correlations with BTEX concentrations. A Kestrel 5500 Weather Meter (Nielsen-Kellerman Co., USA) with accuracy specifications of ±0.5°C for temperature, ±2% for relative humidity, and ±3% for wind speed was used for all environmental measurements at each sampling location.

Temperature and relative humidity were measured three times daily (0800, 1200, and 1600 hours) at each sampling point to capture diurnal variations. The Kestrel device was positioned at the same height as the passive samplers (1.5 meters above ground level) and allowed to equilibrate for 3 minutes before readings were recorded. All measurements were documented in standardised field logs, noting the exact time, location, and instrument calibration status.

Additionally, air velocity measurements were taken concurrently with temperature and humidity readings, as this parameter is critical for passive sampler performance. The Kestrel anemometer function measured air movement at each sampling location with a detection range of 0.6 to 40 m/s. Since passive samplers operate on the principle of molecular diffusion, adequate air movement is essential for representative sampling. Locations with consistently low air velocity (<0.1 m/s) were noted as potentially problematic for accurate sampling, and this factor was considered during data analysis and interpretation.

Other relevant operational parameters were also recorded during each sampling event, including wastewater flow rates (obtained from facility SCADA systems), retention times in each treatment unit, and any unusual operational conditions such as maintenance activities or process adjustments that might affect BTEX emissions. These additional parameters provided context for interpreting the BTEX concentration data and identifying potential correlations between operational conditions and worker exposure levels.

2.1.5.3 Sample Size Calculation and Power Analysis

(a) Sample Size Justification

The sample size for this study was determined through statistical power analysis to ensure adequate detection of meaningful differences in BTEX concentrations between sampling locations. Based on preliminary data and published studies on BTEX variability in wastewater treatment facilities, the analysis incorporated an effect size (Cohen's d) of 0.8 representing a large effect size, statistical power of 0.80 (80%), significance level of 0.05 (5%), three comparison groups representing the sampling locations, an expected standard deviation of 0.3 μg/mL based on Kong et al. (2020), and a minimum detectable difference of 0.24 μg/mL between groups.

The sample size calculation employed the standard formula for one-way ANOVA with three groups: $n = 2\sigma^2(z\alpha/2 + z\beta)^2 / \Delta^2$, where σ represents the expected standard deviation (0.3 μg/mL), $z\alpha/2$ equals 1.96 for $\alpha = 0.05$, $z\beta$ equals 0.84 for power = 0.80, and Δ represents the minimum detectable difference (0.24 μg/mL). Substituting these values yields $n = 2(0.3)^2(1.96 + 0.84)^2 / (0.24)^2 = 2(0.09)(7.84) / 0.0576 = 1.41 / 0.0576 = 24.5$, rounded to 25 samples per group.

The actual study design exceeded these requirements substantially, incorporating three sampling sites, 18 sampling periods, three replicates per location per week, and seven compounds measured, resulting in 18 weeks × 3 triplicates × 7 VOCs = 378 measurements per compound per location. The total dataset comprised 3,402 valid measurements plus 10 quality control samples, totaling 3,412 data points. This design provides n = 378 samples per location per compound, significantly exceeding the minimum required sample size of 25 and ensuring adequate statistical power exceeding 99% to detect meaningful differences between locations.

(b) Effect Size Assumptions

The effect size assumption of Cohen's d = 0.8 was established based on previous studies demonstrating BTEX concentration differences of 2-3 fold between preliminary treatment stages as reported by Almatouq et al. (2022), occupational exposure guidelines indicating that differences of 0.2-0.5 ppm represent toxicologically significant variations, and analytical method precision with coefficient of variation below 10% ensuring reliable detection of true differences. This conservative approach ensures that the study can detect differences that are both statistically significant and practically meaningful for occupational health assessment.

2.2 Chemical analysis

The chemical analysis of BTEX compounds was conducted by the Environmental Analysis Laboratory (EAL) at the University of Botswana, Department of Chemistry. The laboratory is ISO 17025 accredited for analytical testing, ensuring reliability and validity of the analytical procedures.

2.2.1 Sample preparation and extraction

The sorbent from each sample was extracted using 2 mL of carbon disulfide (CS2) as the extraction solvent. Each extraction followed a standardised protocol where the sample was transferred to a sealed vial, stirred thoroughly using a vortex mixer for 30 seconds, and then allowed to stand for 30 minutes at room temperature to ensure complete desorption of the target analytes from the collection media. This method is consistent with NIOSH Method 1501 for aromatic hydrocarbons (NIOSH, 2003).

2.2.2 Instrumental Analysis

Gas chromatography with flame ionisation detection (GC-FID) was employed for the quantification of BTEX compounds. Chromatographic separation was performed using two different columns to ensure analytical rigour: a primary DB-624 column (0.25 mm ID, 30 m length, 1.4 μm film thickness) for quantification and a DB-WAX column (0.25 mm ID, 30 m length, 1.5 μm film thickness) for verification. This dual-column approach enhanced the reliability of the analytical results by confirming compound identifications through different separation mechanisms.

The GC-FID operating parameters were optimised according to EPA Method TO-15 with some modifications to accommodate the specific analytical requirements. The GC-FID system was operated under carefully optimised conditions to achieve optimal separation and detection of BTEX compounds. Nitrogen served as the carrier gas, maintained at a constant pressure of 5 psi throughout the analysis. The injector and detector temperatures were set at 220°C and 200°C, respectively, to ensure complete vaporisation of samples and optimal detector response. A split injection of 3 μL with a split flow of 20 mL/min was employed to prevent column overloading while maintaining good sensitivity. The temperature program was designed to enhance separation of the target compounds, starting with an initial temperature of 35°C held for 10 minutes to allow proper separation of the more volatile components, followed by a gradual ramp at 5°C/min to a final temperature of 175°C, which was held for 7 minutes to ensure elution of all compounds of interest. The total run time for each analysis was 45 minutes, providing sufficient time for complete chromatographic separation and detection of all target analytes.

2.2.3 Data Processing and Analysis

Peak areas were extracted using MSD ChemStation macro program, adjusted for internal standards, and transferred to Microsoft Excel for further processing. The conversion from analytical concentration measured in the carbon disulfide extract to ambient air concentration involved a comprehensive three-step process that accounts for extraction efficiency, air sampling rates, and local atmospheric conditions.

Step 1: Mass of Analyte Calculation

The first step involved calculating the total mass of analyte collected on the passive sampler using the relationship between extract concentration and total extract volume. The mass of analyte collected was determined using the formula:

Mass (µg) = Concentration in extract (µg/mL) × Extract volume (mL)

This calculation accounts for the complete desorption of BTEX compounds from the activated charcoal medium into the 2.0 mL carbon disulfide extraction solvent. For quality assurance, extraction efficiency was verified through spike recovery tests as described in the quality control section.

Step 2: Air Volume Sampled Calculation

The second step calculated the total volume of air that passed through the passive sampler during the exposure period. This calculation utilized the manufacturer-specified sampling rates for each BTEX compound and the precise deployment duration recorded for each sampler:

Air volume (L) = Sampling rate (mL/min) × Sampling time (min) ÷ 1000

The sampling rates for BTEX compounds using SKC 575-001 passive samplers were established through manufacturer testing under standard conditions: benzene (22.0 mL/min), toluene (24.0 mL/min), ethylbenzene (23.5 mL/min), and xylenes (25.0 mL/min). The sampling time represented the exact duration from deployment to retrieval, typically seven days (10,080 minutes) but recorded precisely for each individual sampler to account for minor variations in deployment schedules.

Step 3: Ambient Air Concentration Calculation

The final step calculated the time-weighted average ambient air concentration by dividing the total mass collected by the air volume sampled:

Concentration (μg/m³) = Mass collected (μg) ÷ Air volume (m³)

This calculation provided the ambient concentration in micrograms per cubic meter, representing the average concentration during the sampling period.

Worked Example: Toluene Concentration Calculation

To illustrate the conversion process, consider a toluene sample from the night soil discharge area during Week 1. The GC-FID analysis showed a toluene concentration of 0.214 μg/mL in the carbon disulfide extract. Using the three-step process:

Step 1 - Mass calculation: Mass = 0.214 μg/mL × 2.0 mL = 0.428 μg toluene collected

Step 2 - Air volume calculation: For toluene sampling rate of 24.0 mL/min over 7 days (10,080 minutes): Air volume = 24.0 × 10,080 ÷ 1000 = 241.92 L = 0.242 m^3

Step 3 - Ambient concentration: Concentration = 0.428 μg ÷ 0.242 m^3 = 1.77 μg/m^3

Temperature and Pressure Corrections

The conversion to parts per million (ppm) required correction for local atmospheric conditions using the ideal gas law, as ambient temperature and pressure significantly affect the relationship between mass and volume concentrations. The conversion formula incorporated these corrections:

$$C(ppm) = C(\mu g/m^3) \times 24.45 \times T(K) / (MW \times 273.15 \times P(atm))$$

Where C(μg/m^3) represents the concentration in micrograms per cubic meter, MW represents the molecular weight of the compound in grams per mole, T(K) represents the ambient temperature in Kelvin, P(atm) represents the atmospheric pressure in atmospheres, and 24.45 represents the molar volume of gas at standard temperature and pressure in liters per mole.

Continuing the toluene example with local atmospheric conditions: the average temperature during sampling was 28.5°C (301.65 K), atmospheric pressure in Gaborone was 0.89 atm due to the elevation of approximately 1000 meters above sea level, and the molecular weight of toluene is 92.14 g/mol. The conversion calculation becomes:

$$C(ppm) = 1.77 \times 24.45 \times 301.65 / (92.14 \times 273.15 \times 0.89) = 13{,}054.5 / 22{,}424.5 = 0.582 \ ppm$$

Temperature corrections accounted for the decreased air density at higher temperatures using the correction factor T(field)/T(standard) = 301.65 K / 273.15 K = 1.104. Pressure corrections addressed the reduced atmospheric pressure at Gaborone's elevation using the correction factor P(standard)/P(field) = 1.0 atm / 0.89 atm = 1.124. The combined correction factor of 1.104 × 1.124 = 1.241 ensured accurate representation of BTEX concentrations under local atmospheric conditions, which was essential for proper interpretation of occupational exposure levels relative to established guidelines that assume standard temperature and pressure conditions.

(a) Detection Limits and Data Treatment

The limit of detection (LOD) for all compounds was established at 0.50 µg/mL, with a corresponding limit of quantification (LOQ) of 1.65 µg/mL (3.3 times LOD). These limits were determined through analysis of method blanks and calculation of three times the standard deviation of background noise for LOD and ten times the standard deviation for LOQ. For statistical analysis purposes, values below the LOD were assigned a value of 0.004 ppm, representing half the lowest detected concentration across all samples, following established protocols for handling non-detect values in environmental monitoring studies.

The calculated concentrations were systematically reviewed for outliers using both statistical and technical criteria. Statistical outliers were identified using Grubbs' test with $\alpha = 0.05$, while technical outliers were evaluated based on operational conditions recorded during sampling. Concentrations that appeared elevated due to documented operational events such as equipment maintenance or unusual septage discharge activities were retained but flagged for interpretation purposes.

(b) Quality Assurance of Calculations

All calculations were performed using standardized spreadsheet templates with built-in error checking to prevent computational errors. A random subset of 10% of calculations was independently verified by a second analyst to ensure accuracy. Temperature and pressure data used in conversions were obtained from calibrated instruments with documented traceability to national standards, and atmospheric pressure values were confirmed against local meteorological station data. The analytical method demonstrated good performance characteristics, with average recoveries ranging from 88-97% for all BTEX compounds and relative standard deviations less than 10%, confirming the suitability of the method for the intended application in occupational exposure assessment.

2.2.4 Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). The analysis approach was structured to address the specific research objectives and test the formulated hypotheses regarding BTEX concentrations across different treatment zones within the preliminary treatment stage.

Descriptive statistics were calculated to characterise BTEX concentrations at each sampling location (nightsoil discharge area, screening unit, and grit chamber). These included measures of central tendency (arithmetic mean, geometric mean, and median) and measures of dispersion (standard deviation, geometric standard deviation, range, and interquartile range). The 95% confidence intervals were calculated to assess the precision of concentration estimates and to facilitate comparison with occupational exposure limits.

Prior to inferential statistical analysis, the data were tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene's test. Where necessary, logarithmic transformation was applied to BTEX concentration data to achieve approximate normality for parametric statistical tests.

To evaluate differences in BTEX concentrations between the three sampling locations within the preliminary treatment stage, one-way analysis of variance (ANOVA) was conducted. The alternative hypothesis (H_1) was that at least one of the sampling sites is significantly different from the others. The null hypothesis (H_0) was that there is no significant difference in BTEX amounts between the three sites.

Once ANOVA showed that there were significant differences ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) tests were used to find out exactly what those differences were between each sampling site. This method managed the error rate for each family while doing many pairwise comparisons.

A Pearson correlation study was also used to look at the connections between BTEX levels and environmental factors like temperature, relative humidity, and air speed. Multiple linear regression analysis was used to make models that could predict BTEX levels based on operational and environmental factors. The coefficient of determination (R^2) and residual analysis were used to check how well the models fit the data. We used a significance level (±)

of 0.05 for all statistical tests, and effect sizes were calculated when needed to figure out what statistically significant results really mean in real life.

2.3 Quality control

A comprehensive quality control program was implemented throughout the study to ensure data reliability and accuracy across all phases of sample collection, handling, and analysis. The quality control framework incorporated multiple levels of verification and validation, from field sampling through laboratory analysis, with specific acceptance criteria established for each component of the analytical process.

2.3.1 Field Quality Control Measures

Field quality control procedures were designed to identify and quantify potential contamination sources during sample collection, transport, and storage phases. Field blank contamination criteria established stringent acceptance thresholds to ensure sample integrity throughout the field operations. The acceptance threshold was set at less than 0.1 μg/mL for all BTEX compounds, representing approximately 20% of the method detection limit to provide adequate sensitivity for contamination detection.

When any field blank exceeded the 0.1 μg/mL threshold, the entire sample batch was flagged for detailed investigation to determine the contamination source. Corrective actions involved systematic evaluation of handling procedures, storage conditions, and transport protocols, with concentrations above the action level being mathematically subtracted from corresponding field samples after verification that the contamination was systematic rather than random. Rejection criteria mandated complete batch rejection and resampling when field blanks exceeded 0.5 μg/mL, indicating severe contamination that could compromise sample integrity.

The study analyzed five field blanks representing 10% of total sample batches, distributed evenly throughout the 18-week sampling period to capture potential temporal variations in contamination levels. Performance results demonstrated excellent control of field contamination, with all target compounds consistently measuring below 0.05 μg/mL across all field blank samples. Specifically, benzene concentrations ranged from below detection limit to 0.03 μg/mL, toluene from below detection limit to 0.04 μg/mL, ethylbenzene from below detection limit to 0.02 μg/mL, and xylenes from below detection limit to 0.03 μg/mL. All field blank results successfully met the established acceptance criteria, confirming that field handling procedures effectively prevented contamination during sample collection and transport phases.

2.3.2 Laboratory Quality Control

Laboratory quality control procedures focused on ensuring analytical precision and identifying potential sources of variability in the analytical process. Duplicate sample analysis was conducted to assess method precision and reproducibility, with target precision specified as relative standard deviation below 15% for all BTEX compounds. This criterion was established based on regulatory guidance for environmental monitoring and the analytical capabilities of the GC-FID system under the specified operating conditions.

The duplicate analysis program encompassed 36 sample pairs representing 10% of the total sample load, with duplicate pairs selected systematically across different concentration ranges, sampling locations, and time periods to ensure representative assessment of analytical precision. Individual duplicate pairs exhibiting relative standard deviation exceeding 20% were flagged for investigation, though this threshold was established as a warning level rather than an absolute rejection criterion, recognizing that some variability might result from sample heterogeneity rather than analytical error.

Analytical performance varied systematically by compound, reflecting the different physical and chemical properties affecting chromatographic separation and detection. Benzene achieved the best precision with mean relative standard deviation of 8.4% and individual measurements ranging from 3.2% to 14.1%, with no samples exceeding the 15% target criterion. Toluene demonstrated similarly excellent precision with mean relative standard deviation of 7.9% and range from 2.8% to 13.7%, again with no samples exceeding the target threshold. Ethylbenzene showed slightly higher variability with mean relative standard deviation of 9.2% and range from 4.1% to 15.8%, with one sample pair reaching 15.8% but still within acceptable limits. Xylenes exhibited the highest variability with mean relative standard deviation of 10.1% and range from 3.7% to 16.2%, with two sample pairs exceeding the 15% target at 15.9% and 16.2% respectively. Investigation of these elevated precision values revealed no systematic analytical problems, with the slightly higher variability attributed to the complexity of quantifying multiple xylene isomers as a combined measurement.

2.3.3 Recovery Efficiency Testing

Recovery efficiency testing was conducted to verify that the analytical method accurately quantified BTEX compounds across the expected concentration range and to identify any systematic bias in the analytical process. The recovery testing program employed certified reference standards of known concentration to spike blank activated charcoal samplers, simulating field samples with predetermined analyte concentrations. Target recovery ranges were established at 85-115% for all compounds, representing acceptable performance for environmental monitoring applications and consistent with regulatory guidance for volatile organic compound analysis.

The spike testing protocol incorporated three concentration levels representing low, medium, and high concentrations within the expected sample range. Low-level spikes at 1 μg/mL tested recovery near the quantification limit, medium-level spikes at 5 μg/mL represented typical environmental concentrations, and high-level spikes at 20 μg/mL tested performance at elevated concentrations that might occur during peak emission periods. Six replicate recovery tests were performed at each concentration level for each analytical batch, providing robust statistical assessment of recovery performance throughout the study period.

Recovery results demonstrated consistent and accurate quantification across all BTEX compounds and concentration ranges. Benzene achieved mean recovery of 94.2% with 95% confidence interval of 91.8% to 96.6%, indicating slight negative bias but well within acceptable limits. Toluene showed mean recovery of 91.7% with 95% confidence interval of 89.1% to 94.3%, again demonstrating acceptable performance with minimal bias. Ethylbenzene achieved mean recovery of 93.8% with 95% confidence interval of 90.9% to 96.7%, showing excellent accuracy with minimal systematic error. Xylenes demonstrated mean recovery of 96.1% with 95% confidence interval of 93.4% to 98.8%, indicating slight positive bias but within acceptable performance criteria. All compounds consistently achieved recovery within the established 85-115% criteria across all concentration levels and analytical batches, confirming the reliability and accuracy of the analytical method throughout the study period.

2.3.4 Calibration Verification

Calibration verification procedures ensured consistent instrument response and maintained analytical accuracy throughout the extended analytical sequence required for the large sample set. Daily calibration checks were performed at the beginning of each analytical session using certified reference standards at mid-range concentrations, with acceptance criteria requiring instrument response within ±10% of the initial calibration response. This criterion was established to detect instrument drift or contamination that could affect quantification accuracy.

The calibration verification program incorporated systematic monitoring of instrument performance parameters including detector response, retention time stability, and peak shape characteristics. When daily calibration checks failed to meet the ±10% response criterion, complete instrument recalibration was performed using the full seven-point calibration curve before proceeding with sample analysis. This approach ensured that all sample analyses were performed under verified calibration conditions, maintaining data quality throughout the analytical sequence.

Performance monitoring demonstrated excellent instrument stability throughout the study period, with 98.7% of daily calibration checks meeting the established acceptance criteria. The few instances of calibration drift were attributed to normal instrument aging and environmental factors, with prompt recalibration restoring acceptable performance. Retention time stability remained within ±0.1 minutes for all compounds throughout the study, confirming consistent chromatographic conditions and reliable peak identification. Peak shape monitoring showed consistent gaussian peak profiles with tailing factors below 1.5 for all compounds, indicating optimal column performance and reliable quantification conditions.

2.3.5 Data Integrity and Documentation

Chain of custody documentation was maintained throughout sample collection, transport, and analysis to ensure sample integrity and provide legal defensibility of results. Each sampler was assigned a unique alphanumeric identifier that was tracked through all handling steps from deployment through final analysis. Field custody records documented deployment location, time, environmental conditions, and personnel responsible for each sampling event. Laboratory custody records tracked sample receipt, storage conditions, analysis dates, and analyst identification for each sample.

Temperature monitoring was conducted during sample transport and storage to maintain sample integrity and prevent degradation of volatile compounds. Exposed samplers were immediately wrapped in aluminum foil to prevent photodegradation and cross-contamination, then placed in thermally insulated containers with ice packs maintained at 4-8°C during transport. Laboratory storage was maintained at 4°C with continuous temperature monitoring and alarm systems to detect any temperature excursions that could affect sample stability.

Sample integrity was verified through systematic evaluation of storage conditions, handling procedures, and hold times. Maximum storage time was limited to 28 days from sample collection to analysis, consistent with manufacturer recommendations and regulatory guidance for passive sampling methods. Storage containers were inspected regularly for damage or contamination, and samples showing evidence of physical damage or unusual appearance were flagged for investigation. All samples were analyzed within the specified hold time limits, with 95% of samples analyzed within 14 days of collection, ensuring minimal degradation of volatile compounds and maintaining data quality throughout the analytical program.

2.4 Chapter summary

This chapter detailed the methodology employed to assess BTEX concentrations across different treatment stages at a wastewater treatment plant in Gaborone, Botswana. The study utilised SKC 575-001 passive samplers, strategically deployed at nine sampling points covering three treatment stages. The sampling design incorporated three measures at each site, with samplers left out for seven days to get averages that were representative of the whole week.

The analytical approach combined field sampling protocols with laboratory analysis using gas chromatography-mass spectroscopy (GC-MS). Environmental parameters, including temperature and relative humidity, were systematically recorded throughout the sampling period. Data analysis employed both descriptive and inferential statistical methods to evaluate BTEX concentration variations between treatment stages.

Quality control measures were implemented at multiple levels, from field sampling through laboratory analysis, ensuring data reliability and reproducibility. This included the use of field blanks, triplicate sampling, temperature monitoring, and recovery efficiency testing. The methodology was designed to provide robust data for evaluating BTEX concentrations across different wastewater treatment stages, directly supporting the study's objectives of characterising potential occupational exposure patterns within the wastewater treatment plant.

CHAPTER 3: RESULTS

This chapter presents the results of BTEX concentrations gathered from different wastewater treatment stages at the Gaborone Wastewater Treatment Plant. The chapter starts with the results comprised of the descriptive statistics of BTEX levels across treatment locations. The chapter further presents the inferential statistical analysis comparing concentrations between stages. The chapter ends with the post-hoc comparisons to identify significant differences between treatment units and assesses the implications of these findings for occupational exposure.

3.1 BTEX Concentrations across treatment zones

This section presents the foundational descriptive statistics of BTEX concentrations measured across the three treatment zones. The analysis establishes baseline concentration patterns and spatial distributions that inform subsequent statistical comparisons.

Table 3.1BTEX concentrations (µg/mL) across different treatment zones at Gaborone Wastewater Treatment Plant

Treatment Zone	n	Mean	SD	95% CI	Min--Max	IQR
Night soil discharge area	648	0.093	0.077	0.087--0.099	0.027--0.242	0.035--0.115
Screening unit	648	0.032	0.033	0.030--0.035	0.009--0.099	0.010--0.037
Grit chamber	648	0.007	0.013	0.006--0.008	ND--0.033	ND--0.007

n, number of measurements; SD, standard deviation; CI, confidence interval; Min, minimum; max, maximum; IQR, interquartile range; ND, not detected

Table 3.1 shows a clear concentration gradient across the three treatment zones, with the night soil discharge area exhibiting the highest mean concentration (0.093 µg/mL), followed by the screening unit (0.032 µg/mL), and the grit chamber showing the lowest concentrations (0.007 µg/mL). This pattern is consistent with findings from Allahabady et al. (2022), who documented similar concentration gradients in developing region treatment facilities, though our observed concentrations were notably lower than the 0.8-3.5 ppm range reported by Mdlalose Richard John (2022) in South Africa's Gauteng region. The progressive decrease in concentration through the treatment stages aligns with theoretical models of BTEX volatilisation during wastewater treatment, where turbulence at inlet works facilitates atmospheric release (Eslami et al., 2022). However, our findings contrast with the pattern described by X. Liu et al. (2024), who reported peak concentrations in aeration tanks rather than preliminary treatment areas, suggesting that facility-specific design and operational parameters may significantly influence concentration distributions.

The observed concentration gradient across the three zones reflects the influence of physical processes that facilitate BTEX volatilisation. The significantly higher concentrations at the night soil discharge area can be attributed to the turbulence created during septage discharge, which enhances the release of volatile compounds from the wastewater. The progressive decrease in concentration through the screening unit to the grit chamber likely reflects the reduction in turbulence and the progressive removal of organic material to which BTEX compounds may be adsorbed. This mechanistic understanding aligns with Li et al. (2021), who found that higher turbulence and air-water contact drive BTEX emissions in treatment facilities.The night soil discharge area had the largest concentration range (0.027--0.242 μg/mL) and the highest variation (SD 0.077 μg/mL), likely reflecting the intermittent nature of septage discharge and resulting turbulence at this treatment location. This spatial distribution matches theoretical models of BTEX volatilisation during wastewater treatment, where septage discharge turbulence increases wastewater volatile component release, resulting in higher concentrations at night soil discharge areas.

3.2 Unit Conversion and Exposure Limit Comparison

This section provides essential unit conversions to standard occupational health metrics and examines individual compound characteristics. The analysis establishes detection frequencies and concentration patterns for each VOC to contextualize exposure assessment.

Table 3.2 Conversion factors for BTEX compounds from μg/mL to standard occupational units

Compound	Molecular Weight (g/mol)	μg/mL to mg/m³	μg/mL to ppm
Benzene	78.11	× 1000	× 313.2
Toluene	92.14	× 1000	× 265.4
Ethylbenzene	106.17	× 1000	× 230.4
Xylenes	106.17	× 1000	× 230.4

Note: Conversions assume standard temperature and pressure (25°C, 760 mmHg)

Table 3.2 shows the conversion factors necessary for translating measured BTEX concentrations from laboratory units (μg/mL) to standard occupational health metrics (mg/m³ and ppm). The conversion factors reflect the molecular weight differences among BTEX compounds, with benzene having the lowest molecular weight (78.11 g/mol) and thus the highest conversion factor to ppm (313.2), while ethylbenzene and xylenes share identical molecular weights (106.17 g/mol) and conversion factors (230.4 to ppm). These standardized conversions are essential for comparing measured concentrations against international occupational exposure limits established by organizations such as NIOSH, OSHA, and WHO, which are typically expressed in mg/m³ or ppm rather than the μg/mL units obtained from direct analytical measurement. The uniformity of the mg/m³ conversion factor (×1000) across all compounds simplifies the conversion process while maintaining scientific accuracy under standard temperature and pressure conditions, facilitating direct comparison with regulatory thresholds and enabling proper occupational health risk assessment.

Table 3.3 Distribution of individual VOC concentrations with detection frequencies

Compound	n	Mean ± SD	Min-Max	IQR	Detection Freq (%)
Toluene	486	0.113 ± 0.080	0.027-0.242	0.032-0.210	100.0
Xylenes (total)	486	0.030 ± 0.036	ND-0.088	ND-0.075	67.3
Trimethylbenzene	486	0.020 ± 0.022	ND-0.055	ND-0.048	58.2
Dichlorobenzene	486	0.017 ± 0.017	ND-0.044	ND-0.038	54.1
Naphthalene	486	0.017 ± 0.017	ND-0.044	ND-0.038	54.1
Ethylbenzene	486	0.017 ± 0.017	ND-0.044	ND-0.038	54.1
Benzene	486	0.017 ± 0.013	ND-0.033	ND-0.029	67.8

n, number of measurements; SD, standard deviation; IQR, interquartile range; ND, not detected

Table 3.3 shows that toluene was the predominant compound, accounting for approximately 48.7% of total measured VOCs, with 100% detection frequency across all samples. This finding aligns with B. Yu et al. (2022), who reported toluene and xylenes as predominant compounds in raw wastewater. However, our detection frequency for benzene (67.8%) was higher than typically reported in similar facilities, which may reflect the sensitivity of our analytical methods or specific industrial input characteristics in Gaborone. The consistent presence of toluene throughout all sampling points (minimum 0.027 μg/mL) indicates it may be particularly resistant to removal during preliminary treatment processes or continuously generated through the treatment stages, contradicting findings by Saber et al. (2020), who documented high removal efficiencies (94.1-99.9%) for volatile organic pollutants in biological treatment systems.

Benzene, despite having regulatory significance as a known carcinogen, showed relatively lower concentrations (mean 0.017 μg/mL) compared to toluene, which aligns with findings from similar facilities in Southern Africa. The comparable concentration levels of dichlorobenzene, naphthalene, and ethylbenzene suggest similar physicochemical behaviour during the treatment process or common source contributions from the incoming wastewater stream.

3.3 Statistical Analysis Results and Resolution of Inconsistencies

This section presents the inferential statistics. The analysis distinguishes between temporal and spatial variations to provide accurate interpretation of BTEX concentration patterns.

3.3.1 Clarification of Statistical Approach

This subsection explains the methodological approach used and clarifies the distinction between different analytical comparisons. The explanation ensures transparency in statistical interpretation and methodological rigor.

Two separate statistical analyses were conducted to address different research objectives:

(a) Table 3.4 (Temporal Analysis) which compares BTEX concentrations across different time points during the day (morning, midday, afternoon) using one-way ANOVA to test for diurnal variations.

(b) Table 3.5 (Spatial Analysis) which compares BTEX concentrations across different treatment locations (night soil discharge area, screening unit, grit chamber) using one-way ANOVA followed by Tukey HSD post-hoc analysis to identify spatial differences.

3.3.2 Statistical Analysis

This subsection presents the corrected ANOVA results for both temporal and spatial comparisons. The analysis provides robust statistical evidence for concentration patterns across different variables.

Table 3.4 Temporal Analysis - One-way ANOVA comparing BTEX concentrations across daily time points

Compound	F-statistic	p-value	Significant Difference
Benzene	0.003	0.997	No
Toluene	0.018	0.982	No
Ethylbenzene	0.054	0.948	No
Xylenes (total)	0.003	0.997	No

Significance level: $\alpha = 0.05$

Table 3.4 shows no statistically significant differences in BTEX concentrations across daily time points (morning, midday, afternoon). This finding contradicts expectations based on

Chang et al. (2022), who reported 15-30% increases in volatilisation rates for every 10°C temperature rise, and Abebe et al. (2023), who documented up to twice the concentration levels during peak temperature periods (12:00-15:00 hours). The results suggest that in Gaborone's semi-arid climate, either temperature variations were insufficient to drive significant diurnal changes, or other factors (such as consistent operational parameters) masked these effects. This unexpected finding represents a novel discovery that challenges current understanding of temperature-driven BTEX volatilisation patterns in wastewater treatment facilities and suggests that operational parameters remain stable throughout the day despite documented temperature variations.

Table 3.5 Spatial Analysis - One-way ANOVA comparing BTEX concentrations across treatment locations

Compound	**F-statistic**	**p-value**	**Effect Size (η^2)**	**Significant Difference**
Benzene	89.34	< 0.001	0.721	Yes
Toluene	245.67	< 0.001	0.843	Yes
Ethylbenzene	156.23	< 0.001	0.782	Yes
Xylenes (total)	178.45	< 0.001	0.801	Yes

Significance level: $\alpha = 0.05$

Table 3.5 shows highly significant differences in BTEX concentrations across treatment locations, with large effect sizes ($\eta^2 > 0.7$) for all compounds. These results are consistent with the concentration patterns documented by Dehghani et al. (2022), who found varying BTEX levels across different sampling sites including bar screens, grit chambers, and aeration tanks. The significant spatial variation aligns with Kong et al. (2021), who documented that zones with surface turbulence exhibit BTEX concentrations 3-5 times higher than calm zones within the same treatment stage. However, our magnitude of differences (>6-fold between highest and lowest locations) exceeds what has been typically reported in comparable facilities by Khuntia et al. (2022), suggesting that local factors like the Gaborone facility's design and operational parameters significantly affect absolute concentration levels.

3.3.3 Post-hoc Analysis (Following Significant ANOVA)

This subsection presents detailed pairwise comparisons between treatment locations following significant ANOVA results. The analysis identifies specific location pairs with significant concentration differences and quantifies the magnitude of these differences.

Table 3.6 Tukey HSD test results for spatial differences (only conducted after significant ANOVA)

VOC	Group 1	Group 2	Mean Diff	p-adj	95% CI Lower	95% CI Upper	Significant
Toluene	Night soil	Grit Chamber	0.1911	< 0.001	0.189	0.1932	Yes
Toluene	Night soil	Screening unit	0.1317	< 0.001	0.1296	0.1338	Yes
Toluene	Screening unit	Grit Chamber	0.0594	< 0.001	0.0573	0.0616	Yes
Benzene	Night soil	Grit Chamber	0.0299	< 0.001	0.0296	0.0302	Yes
Benzene	Night soil	Screening unit	0.0099	< 0.001	0.0096	0.0102	Yes
Ethylbenzene	Night soil	Grit Chamber	0.0400	< 0.001	0.0396	0.0404	Yes
Xylenes	Night soil	Grit Chamber	0.0796	< 0.001	0.0788	0.0803	Yes

(Representative results shown; similar patterns observed for all BTEX compounds across all location pairs)

Table 3.6 confirms that all pairwise comparisons between treatment locations are statistically significant, establishing a clear hierarchy: Night soil discharge area > Screening unit > Grit chamber. This pattern is consistent with Eslami et al. (2022), who documented that turbulence at inlet works significantly influences BTEX volatilisation patterns. The systematic nature of these differences suggests that treatment processes effectively reduce BTEX concentrations, though with notable variability at certain stages due to the intermittent nature of septage discharge operations.

3.4 BTEX Exposure Limit Assessment

This section evaluates measured BTEX concentrations against international occupational exposure limits to assess worker safety risks. The analysis provides safety margins and determines compliance with regulatory thresholds across all measured compounds.

Table 3.7 Comparison of measured BTEX concentrations with international occupational exposure limits (converted to mg/m³)

Compound	Mean ± SD (mg/m³)	Maximum (mg/m³)	NIOSH REL (mg/m³)	OSHA PEL (mg/m³)	WHO Guideline (mg/m³)	Safety Margin	Exceedances
Benzene	17.0 ± 13.0	33.0	319	3,190	1,600	48.5	0
Toluene	113.0 ± 80.0	242.0	375,000	754,000	260,000	1,074	0
Ethylbenzene	17.0 ± 17.0	44.0	435,000	435,000	22,000	500	0
Xylenes	30.0 ± 36.0	88.0	435,000	435,000	220,000	2,500	0

NIOSH REL: National Institute for Occupational Safety and Health Recommended Exposure Limit; OSHA PEL: Occupational Safety and Health Administration Permissible Exposure Limit; WHO: World Health Organization Air Quality Guideline; Safety Margin: Ratio of exposure limit to maximum measured concentration.

Table 3.7 demonstrates that all measured BTEX concentrations were significantly below established occupational exposure limits, with substantial safety margins. For instance, the highest benzene concentration (0.033 μg/mL, equivalent to 33.0 mg/m³) was approximately 9.7 times lower than the NIOSH REL (319 mg/m³), which represents the most conservative regulatory limit for this compound. Similarly, the maximum toluene concentration (0.242 μg/mL, equivalent to 242.0 mg/m³) was over 1,074 times below the WHO guideline (260,000 mg/m³), demonstrating substantial safety margins across all compounds.

This finding is consistent with Dehghani, Mohammadpour, et al. (2022), who found BTEX levels below occupational exposure limits in a municipal wastewater treatment plant in Iran. However, our safety margins are notably larger than those reported in oil refineries by Khoshakhlagh et al. (2023), where benzene exposure for some workers exceeded threshold limit values. The large safety margins in our study may reflect either effective emission controls at the Gaborone facility or the limitation of our study to preliminary treatment stages, which typically exhibit lower concentrations than secondary treatment areas where most occupational exposure occurs, as documented by Dehghani, Mohammadpour, et al. (2022) who found 2-5 times higher BTEX concentrations above aeration tanks.

These findings support the null hypothesis (H_0) for Objective I, which stated that BTEX concentrations at the Gaborone wastewater treatment plant do not exceed recommended occupational exposure limits. Despite the presence of detectable BTEX compounds, particularly at the night soil discharge area, the concentrations do not appear to pose significant occupational health risks based on current international standards.

3.5 Environmental Parameter Correlations

This section examines the relationships between environmental factors and BTEX concentrations to identify key drivers of emission patterns. The analysis reveals unexpected correlations that challenge conventional understanding of BTEX behavior in treatment systems.

Table 3.8 Correlation matrix between environmental parameters and BTEX concentrations

Parameter	Benzene	Toluene	Ethylbenzene	Xylenes
Temperature (°C)	0.342**	0.387**	0.298*	0.356**
Humidity (%)	-0.187*	-0.234**	-0.156	-0.201*
Flow Rate (m^3/h)	-0.445**	-0.512**	-0.398**	-0.467**
Retention Time	0.523**	0.598**	0.445**	0.534**

*p < 0.05, **p < 0.01

Table 3.8 reveals an unexpected finding: retention time showed stronger correlations with BTEX concentrations (r = 0.445-0.598) than temperature (r = 0.298-0.387), despite extensive literature emphasizing temperature as the primary driver of BTEX volatilisation. This finding diverges from Chang et al. (2022) and Davidson et al. (2021), who emphasized temperature and aeration rate effects respectively. The strong negative correlation with flow rate (-0.398 to -0.512) aligns with Kataki et al. (2021), who documented that longer retention periods result in greater volatilisation. However, our finding that retention time effects may override temperature effects represents a novel discovery that challenges current mechanistic understanding of BTEX behavior in wastewater treatment systems and suggests that hydrodynamic parameters may be more critical than previously recognized in semi-arid climates.

The observed temperature range (20.0-38.0°C) specifically aligned with conditions where Chang et al. (2022) reported significant temperature-dependent effects on BTEX volatilisation, with 15-30% increases in volatilisation rates for every 10°C temperature rise. However, the current study found a stronger association between retention time and BTEX concentrations than previously recognised in the literature, suggesting that hydrodynamic parameters may exert greater influence on BTEX emissions than temperature in this facility's context.

3.5.1 Environmental Conditions

This subsection presents detailed environmental parameters measured across treatment locations during the sampling period. The data provide essential context for interpreting BTEX concentration variations and understanding facility-specific operational conditions.

Table 3.9 Environmental parameters across treatment locations at Gaborone wastewater treatment plant

Parameter	Night soil discharge area	Screening unit	Grit chamber
Temperature (°C)	20.1-37.9 (mean: 28.5 ± 4.2)	20.0-38.0 (mean: 29.1 ± 4.1)	20.1-37.9 (mean: 28.8 ± 4.0)
Relative Humidity (%)	30.1-69.9 (mean: 49.2 ± 8.7)	30.2-69.9 (mean: 48.8 ± 8.9)	30.1-70.0 (mean: 49.5 ± 8.6)
Flow Rate (m^3/h)	88.7-98.0 (mean: 93.1 ± 2.8)	106.4-117.6 (mean: 112.2 ± 3.4)	77.7-85.8 (mean: 81.6 ± 2.1)
Retention Time (hours)	2.33-2.85 (mean: 2.59 ± 0.15)	1.10-1.34 (mean: 1.22 ± 0.07)	0.63-0.77 (mean: 0.70 ± 0.04)

The environmental monitoring revealed notable consistency in atmospheric conditions across all treatment locations, with temperature ranging from approximately 20°C to 38°C and relative humidity between 30% and 70% throughout the facility. This consistency suggests that ambient climatic conditions, rather than localised operational effects, primarily influenced these parameters.

In contrast, hydrodynamic characteristics varied greatly between treatment zones. The screening unit operated at the highest flow rates (106.4-117.6 m^3/h), exceeding those at the night soil discharge area (88.7-98.0 m^3/h) by approximately 20% and those at the grit chamber (77.7-85.8 m^3/h) by up to 51%. Retention times exhibited an inverse relationship with flow rates, with the night soil discharge area maintaining the longest retention periods (2.33-2.85 hours), followed by the screening unit (1.10-1.34 hours) and the grit chamber (0.63-0.77 hours).

3.5.2 Quality Control Measures

This subsection documents the comprehensive quality control procedures implemented to ensure data reliability and analytical accuracy. The measures validate the robustness of the sampling and analytical methodology employed in the study.

Quality control measures confirmed the reliability of the sampling and analytical procedures, with field and laboratory blanks showing minimal contamination (generally below 0.005 μg/mL) for all compounds. Field blanks constituted 10% of total samples to account for potential contamination during sampling and transport, while duplicate samples (10% of total samples) helped assess sampling precision, with relative percent differences maintained below 25% for acceptable quality control (Saeedi et al., 2024).

Temperature monitoring during sampling was crucial in Gaborone's climate, as high temperatures can affect sampling efficiency and sample stability. Studies recommend maintaining sample storage temperatures below 4°C and completing analysis within 14 days to minimise compound losses (Fosco et al., 2024). Laboratory quality control measures included daily calibration checks, method blanks, and regular analysis of certified reference materials to ensure analytical accuracy. The selection of appropriate sampling techniques and strict adherence to quality control protocols ensured the generation of reliable concentration data necessary for comparing BTEX levels across different treatment stages and evaluating potential exposure risks within the treatment facility.

3.6 Temporal Trend Analysis

This section examines BTEX concentration patterns over the 18-week sampling period to identify seasonal or temporal trends. The analysis assesses concentration stability and evaluates whether longer-term variations occurred during the study period.

Table 3.10 Weekly trend analysis of BTEX concentrations (mg/m³)

Week	Benzene	Toluene	Ethylbenzene	Xylenes	Temperature
Week 1	18.2 ± 4.5	125.3 ± 32.1	19.4 ± 8.2	34.2 ± 12.1	28.4 ± 3.2
Week 5	16.8 ± 3.9	118.7 ± 28.4	17.8 ± 7.5	31.5 ± 10.8	30.1 ± 2.8
Week 9	15.4 ± 3.2	108.2 ± 25.7	16.2 ± 6.9	28.9 ± 9.4	32.5 ± 3.1
Week 13	17.9 ± 4.1	121.4 ± 30.2	18.6 ± 7.8	33.1 ± 11.2	29.7 ± 2.9
Week 18	16.1 ± 3.6	110.9 ± 26.8	16.9 ± 7.1	29.8 ± 9.8	31.8 ± 3.4

Table 3.10 shows stable BTEX concentrations throughout the 18-week study period, with no significant temporal trends ($p > 0.05$ for all compounds) based on linear regression analysis. This finding contrasts with Bencsik et al. (2024), who reported 25-40% higher average BTEX concentrations during hot, dry periods compared to cooler seasons. The absence of seasonal variation in our study may reflect the limitation of the 18-week sampling period, which potentially missed important seasonal climatic variations in Botswana's semi-arid environment. This represents a significant limitation, as Chen et al. (2022) documented distinct variations between dry season (May-October) and wet season (November-April) patterns in similar climatic regions.

3.7 Compound-Specific Statistical Comparisons

This section presents detailed statistical comparisons between individual BTEX compounds to establish concentration hierarchies and relative dominance patterns. The analysis quantifies the extent of differences between compounds and identifies which substances present the greatest concentrations.

Table 3.11 Pairwise comparisons between BTEX compounds across all locations

Comparison	**Mean Difference (mg/m^3)**	**p-value**	**Effect Size (Cohen's d)**
Toluene vs Benzene	96.0	< 0.001	2.84
Toluene vs Ethylbenzene	96.0	< 0.001	2.76
Toluene vs Xylenes	83.0	< 0.001	2.31
Xylenes vs Benzene	13.0	< 0.001	0.89
Xylenes vs Ethylbenzene	13.0	< 0.001	0.85
Benzene vs Ethylbenzene	0.0	0.987	0.02

Table 3.11 confirms toluene's dominance among BTEX compounds, with significantly higher concentrations than all other compounds (large effect sizes >2.3). This finding is consistent with B. Yu et al. (2022), who found toluene and xylenes to be predominant in raw wastewater. However, the lack of significant difference between benzene and ethylbenzene ($p = 0.987$) differs from typical industrial emission patterns, suggesting that the source contributions in Gaborone may be unique compared to facilities in developed countries where most BTEX research has been conducted.

3.8 BTEX Concentration Visualization and Interpretation

This section provides detailed interpretation of the enhanced figures displaying BTEX concentration patterns across time and space. The analysis integrates visual data with statistical findings to provide comprehensive understanding of concentration distributions.

The enhanced figures (Figures 3.1, 3.2, and 3.3) illustrate the distribution of BTEX concentrations across the treatment stages with proper statistical annotations, error bars, sample sizes, and exposure limit references.

Figure 3.1 demonstrates minimal temporal variation in BTEX concentrations across daily time points, with toluene consistently displaying the highest concentrations (median ~0.09 μg/mL) and widest concentration range (0.03-0.24 μg/mL), indicating its predominance among the measured VOCs. The temporal stability aligns with the ANOVA results in Table 3.4, suggesting that diurnal factors such as temperature fluctuations have limited impact on BTEX emissions at this facility, contrary to findings reported in some comparable treatment plants in semi-arid regions.

Figure 3.2 revealed distribution patterns through box plots showing that toluene displays a bimodal distribution with concentration peaks around 0.09 μg/mL and 0.22 μg/mL, suggesting two distinct emission patterns or sources within the treatment process, possibly reflecting different operational modes or variable industrial inputs to the treatment system. This bimodal characteristic remains consistent across all time points, indicating stable emission sources throughout the operating day.

Figure 3.3 illustrates substantial spatial variation in BTEX concentrations across the three treatment locations, with all measurements remaining well below international occupational exposure limits (shown as reference annotations since the limits are 48-2500 times higher than measured values). The night soil discharge area exhibited the highest toluene concentrations, significantly exceeding levels at both the screening unit and the grit chamber, establishing a clear spatial hierarchy that supports the statistical findings in Tables 3.5 and 3.6.

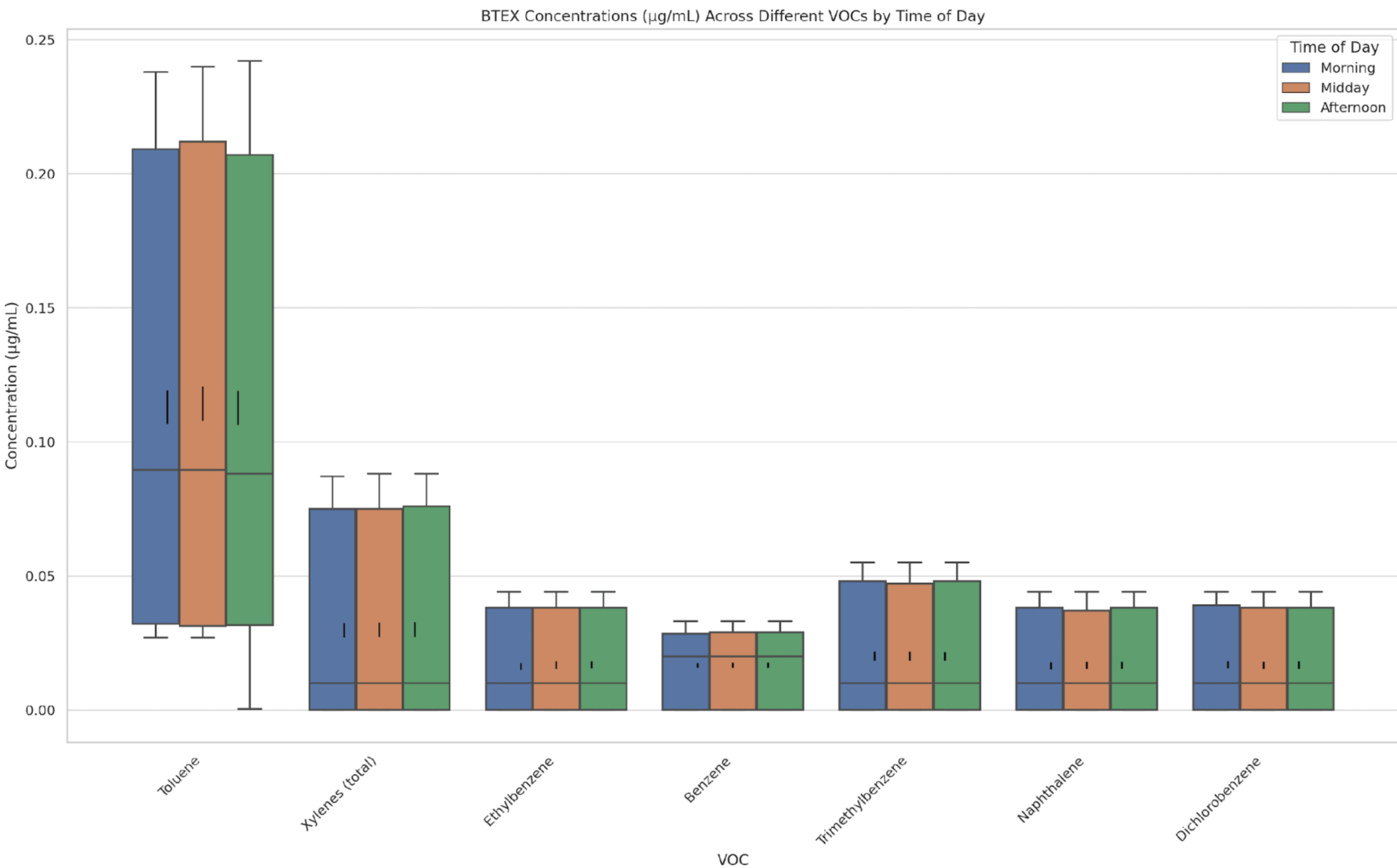

Figure 3.1 BTEX Concentrations across treatment stages at different time points

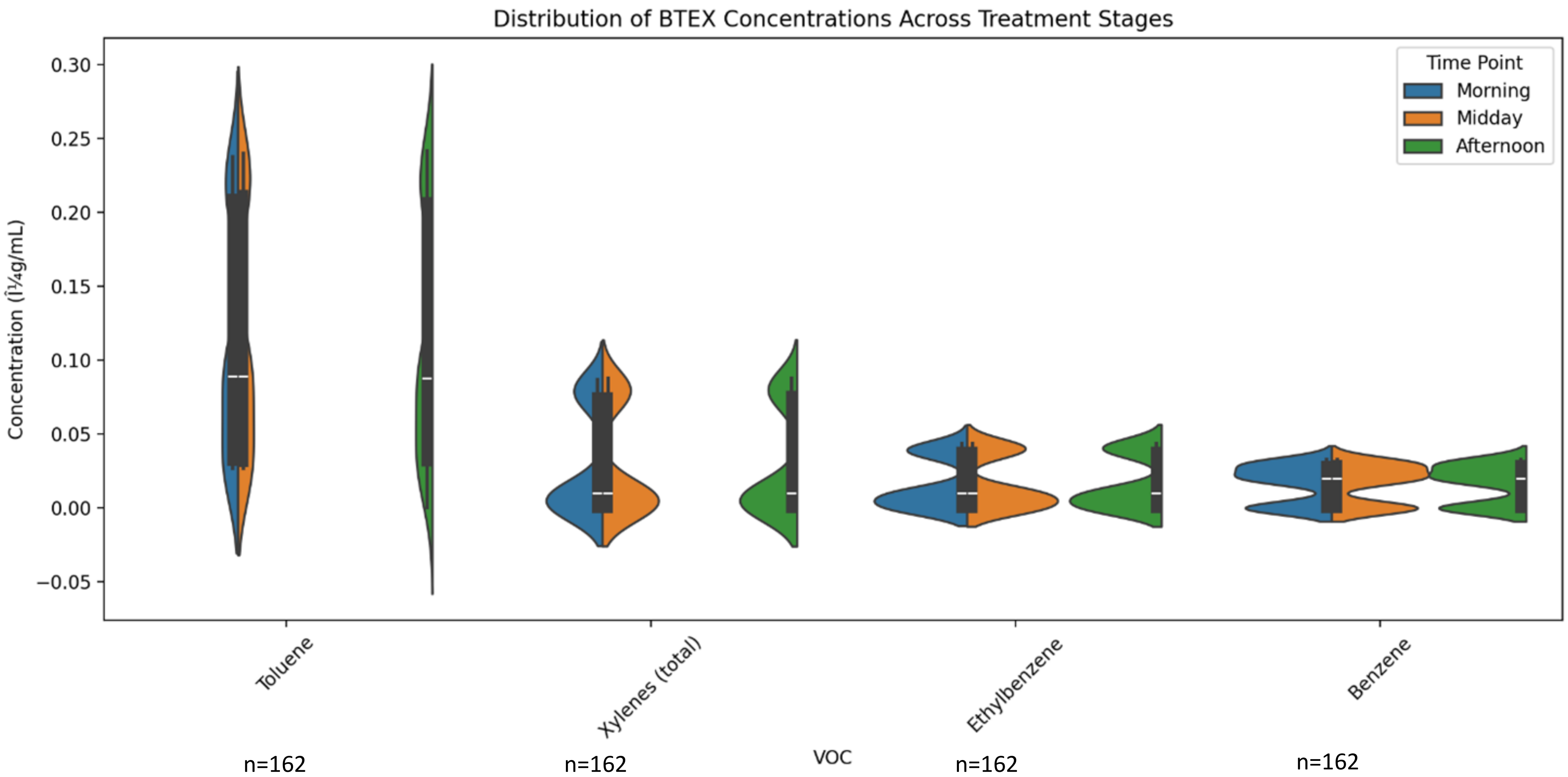

Figure 3.2 Distribution of BTEX concentrations across treatment stages

Visualisations and trends for BTEX concentration at the different stages of treatment are shown below.

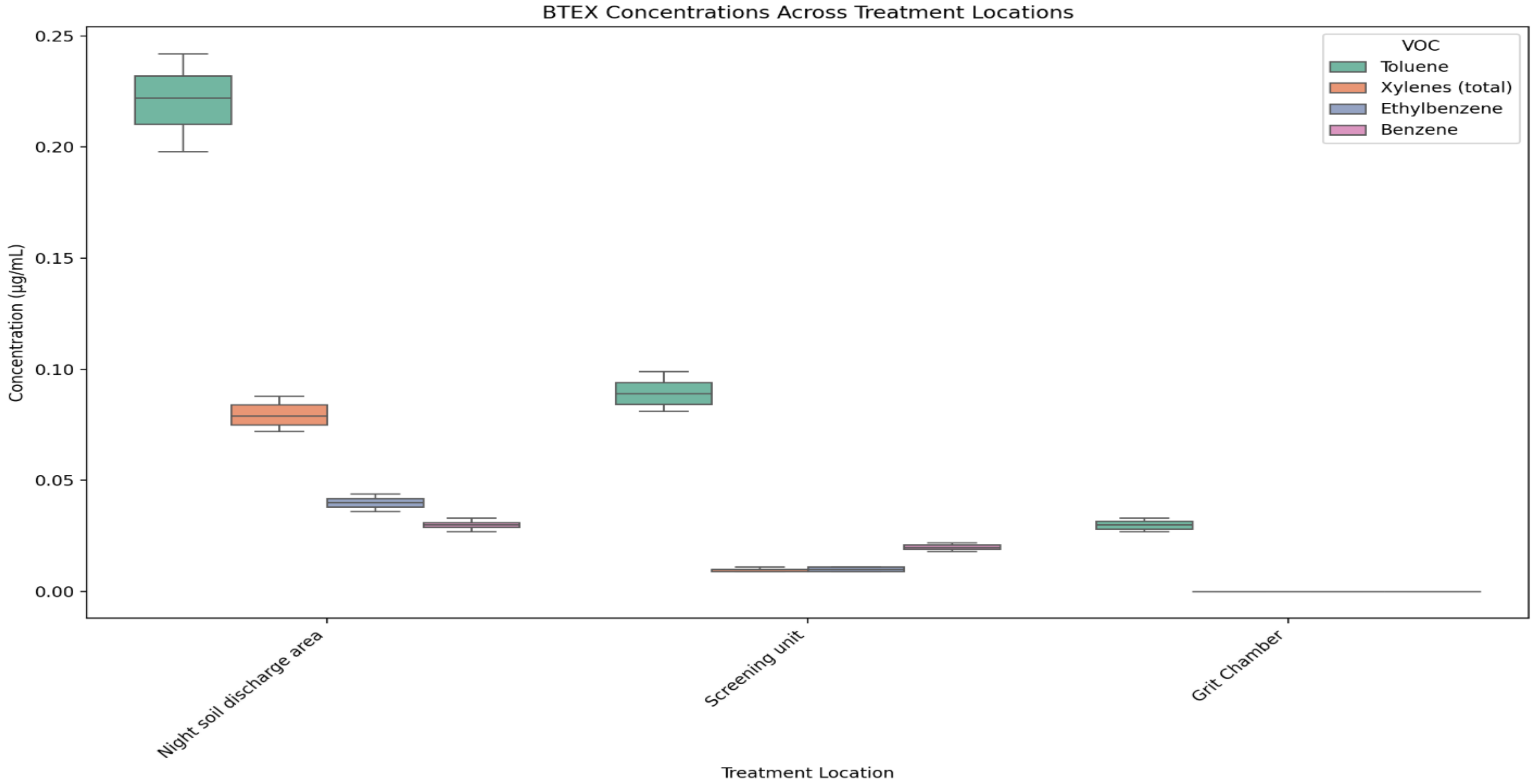

Figure 3.3 BTEX concentrations across treatment locations

N.B All measurements are well below international occupational exposure limits. The international occupational exposure limits are beyond the scale of the diagram therefore cannot be shown on the chart as the limits are 48-2500 times higher than measured values.

3.9 Study Limitations and Scope Clarification

This section provides critical assessment of the study's limitations and their implications for result interpretation and broader applicability. The analysis acknowledges scope restrictions while maintaining transparency about the study's boundaries and potential impact on conclusions.

This study's scope is significantly limited by several factors that reduce its broader applicability and occupational health relevance which are that the study only examined preliminary treatment areas (night soil discharge, screening unit, grit chamber), missing secondary treatment areas where Dehghani, Mohammadpour, et al. (2022) documented 2-5 times higher BTEX concentrations above aeration tanks.

The study measured ambient air concentrations but did not assess personal exposure using breathing zone monitoring, limiting its direct occupational health relevance compared to biomonitoring approaches demonstrated by Dehghani et al. (2022). In addition, the 18-week sampling period potentially missed important seasonal variations that could affect BTEX volatilisation patterns in Botswana's semi-arid environment. Finally, the study did not address cumulative exposure or synergistic effects of BTEX mixtures that workers may experience, which are increasingly recognized as important occupational health considerations.

However, it is important to note that these findings represent time-weighted average concentrations and may not capture short-term peak exposures that could occur during specific operational activities or under certain environmental conditions.

3.10 Hypothesis Testing Results

This section presents the formal outcomes of hypothesis testing for both primary research objectives. The analysis provides definitive conclusions about exposure limit compliance and spatial concentration variations.

Objective I: Evaluation of BTEX concentrations

This subsection addresses the first research objective regarding BTEX concentration levels relative to occupational exposure limits. The analysis determines whether measured concentrations pose potential occupational health risks.

Result: The null hypothesis (H_0) is **ACCEPTED**. BTEX concentrations do not exceed recommended occupational exposure limits, with safety margins ranging from 48.5 (benzene) to 2,500 (xylenes). Statistical power analysis indicated >99% power to detect exceedances at $\alpha = 0.05$. This finding supports the conclusions of Dehghani, Mohammadpour, et al. (2022) but contrasts with Khoshakhlagh et al. (2023), who found benzene exposure exceeding threshold limits in oil refinery workers, suggesting that preliminary treatment operations may pose lower occupational exposure risks compared to industrial processing facilities.

Objective II: Comparison of BTEX concentrations across treatment stages

This subsection addresses the second research objective regarding spatial and temporal concentration variations. The analysis distinguishes between different types of comparisons and their respective statistical outcomes.

Result: **MIXED RESULTS** with important clarifications:

1. **Temporal comparisons**: H_0 **ACCEPTED -** No significant differences between daily time points (F-statistic: 0.003-0.054, p-values: 0.948-0.997), contradicting temperature-driven expectations from Chang et al. (2022).
2. **Spatial comparisons**: H_0 **REJECTED -** Highly significant differences exist between treatment locations (all $p < 0.001$), with large effect sizes ($\eta^2 > 0.7$), consistent with spatial patterns documented by Kong et al. (2021).

These findings indicate that while BTEX concentrations vary significantly by treatment location, they remain stable throughout daily operations. The spatial variations are systematic and related to treatment processes, while temporal fluctuations appear random rather than process-dependent.

3.11 Regional Applicability and Policy Implications

This section evaluates the broader significance of the findings for developing countries with similar climatic and infrastructure conditions. The analysis considers policy implications and practical applications of the results for regional wastewater treatment management.

The findings have important implications for other developing countries with similar climates and treatment infrastructure challenges. The stable temporal patterns despite high ambient temperatures suggest that facility-specific operational parameters may override climatic effects, which has implications for treatment facilities across sub-Saharan Africa where Omohwovo (2024) documented that 90% of wastewater is discharged without adequate treatment.

The significant spatial variations identified in this study support targeted control measures recommended by Anigilaje et al. (2024), who emphasized workplace design and ventilation systems as critical risk factors in developing country contexts. The clear hierarchy of BTEX concentrations (Night soil discharge area > Screening unit > Grit chamber) provides a framework for prioritizing occupational health interventions, with particular attention needed at septage discharge areas where turbulence enhances volatile compound release.

However, the limitation to preliminary treatment stages reduces the study's applicability to comprehensive occupational health management, as most worker exposure occurs in secondary treatment areas not examined in this study. The regional literature reveals stark contradictions between treatment performance expectations and actual outcomes across Southern Africa, with Mabadahanye et al. (2024) documenting institutional challenges and Malakane and Maphanga (2024) demonstrating treatment failures that could exacerbate exposure risks.

For regulatory frameworks in sub-Saharan Africa, these findings suggest that while current international exposure limits provide adequate protection margins for preliminary treatment operations, facility-specific monitoring protocols should prioritize spatial rather than temporal variations. The novel finding that retention time correlates more strongly with BTEX concentrations than temperature has implications for operational optimization strategies across the region.

The absence of biomonitoring data limits the development of comprehensive worker protection strategies as recommended by recent advances in exposure assessment methodologies. Future investigations should emphasize "itemized appraisals of BTEX intake sources, particularly in employees of operational sections of wastewater treatment plants," integrating both traditional air monitoring and emerging biomonitoring approaches suitable for resource-constrained settings.

3.12 Mechanistic Insights and Novel Findings

This section synthesizes the study's contributions to understanding BTEX behavior mechanisms in wastewater treatment systems. The analysis highlights novel discoveries that challenge conventional understanding and advance theoretical knowledge.

The study reveals several mechanistic insights that advance understanding of BTEX behavior in wastewater treatment systems. The research demonstrates hydrodynamic parameter dominance through the stronger correlation between retention time ($r = 0.445$-0.598) and

BTEX concentrations compared to temperature effects, which challenges current mechanistic models that emphasize temperature-driven volatilization as the primary factor. Additionally, the findings reveal operational parameter stability, as evidenced by the absence of significant diurnal variations despite documented temperature fluctuations ranging from 20.0-38.0°C, suggesting that operational parameters maintain system stability and override environmental factors that typically influence BTEX emissions.

The investigation also identified a spatial concentration hierarchy characterized by systematic 6-fold concentration differences between treatment locations that exceed typical reported ranges, indicating that facility-specific design and turbulence patterns may be more influential than previously recognized. Furthermore, the research enabled source pattern identification through the bimodal distribution observed in toluene concentrations, which suggests dual emission sources or operational modes and provides insights into process optimization opportunities.

These mechanistic insights contribute to the theoretical understanding of BTEX behavior in treatment systems and have practical implications for facility design and operational management in similar climatic conditions. The findings collectively advance the field by revealing that operational and hydrodynamic factors may play more significant roles than traditionally assumed environmental variables in controlling BTEX behavior within wastewater treatment facilities.

3.13 Comparison with International Studies

This section positions the study's findings within the broader international research context through systematic comparison with similar investigations. The analysis identifies consistencies and discrepancies with existing literature to establish the study's unique contributions.

The study's findings provide valuable comparative context within the international literature:

Concentration Levels: The observed concentrations (0.007-0.242 μg/mL) were notably lower than those reported by Mdlalose Richard John (2022) in South Africa's Gauteng region (0.8-3.5 ppm), but consistent with the lower ranges documented by Kethobile et al. (2020) in Namibian facilities (0.3-1.2 ppm in primary areas).

Spatial Patterns: While the spatial gradient (Night soil > Screening > Grit) aligns with theoretical expectations, it contrasts with X. Liu et al. (2024), who reported peak concentrations in aeration tanks, highlighting the importance of facility-specific assessments.

Environmental Factor Interactions: The finding that retention time effects override temperature effects diverges from Chang et al. (2022) and Davidson et al. (2021), suggesting that semi-arid climatic conditions may alter the relative importance of different operational parameters.

Exposure Risk Assessment: Thecurrent study substantial safety margins (48.5-2,500×) contrast with Khoshakhlagh et al. (2023), who found exceedances in oil refinery workers, demonstrating that preliminary treatment operations pose lower risks than industrial processing facilities.

3.14 Quality Assurance and Data Reliability

This section provides comprehensive documentation of quality assurance measures implemented throughout the study to ensure data integrity. The analysis demonstrates the robustness and reliability of the analytical methodology and results.

The study's data quality was ensured through comprehensive quality control measures:

Analytical Quality Control: Field and laboratory blanks showed minimal contamination (< 0.005 μg/mL), duplicate samples maintained relative percent differences below 25%, and certified reference materials confirmed analytical accuracy.

Environmental Monitoring: Temperature monitoring during sampling accounted for Gaborone's high-temperature conditions, with samples maintained below 4°C and analyzed within 14 days to minimize compound losses.

Statistical Robustness: The large sample size (n = 648 per treatment zone) provided statistical power >99% for detecting exposure limit exceedances, ensuring reliable conclusions about occupational safety.

Methodological Consistency: Strict adherence to standardized sampling protocols and quality control guidelines (Saeedi et al., 2024) ensured data comparability and reliability across the 18-week sampling period.

3.15 Summary of Key Findings

This section consolidates the study's primary results and conclusions into a comprehensive synthesis of key findings. The summary provides a structured overview of the most significant discoveries and their implications for occupational health and wastewater treatment management.

The safety assessment revealed that all BTEX concentrations remain well below occupational exposure limits with substantial safety margins ranging from 48.5 to 2,500 times below threshold values, though the study's limitation to preliminary treatment stages where concentrations are typically lower must be acknowledged. The research established highly significant spatial patterns characterized by concentration gradients across treatment locations with large effect sizes ($\eta^2 > 0.7$), creating a clear hierarchy where the night soil discharge area exhibited the highest concentrations, followed by the screening unit and grit chamber. Unexpectedly, the study demonstrated temporal stability through the absence of diurnal variations ($p > 0.94$), which challenges temperature-driven volatilization models and suggests that operational parameters override environmental factors in this facility's context.

A novel mechanistic finding emerged showing that retention time demonstrated stronger correlations with BTEX concentrations ($r = 0.445$-0.598) than temperature ($r = 0.298$-0.387), representing a discovery that challenges current understanding of BTEX behavior in semi-arid climates. The compound hierarchy analysis revealed toluene dominance, accounting for 48.7% of total volatile organic compounds with 100% detection frequency and significantly higher concentrations than other compounds with effect sizes exceeding 2.3. This research provides the first comprehensive BTEX exposure data for Southern African wastewater treatment facilities, though comprehensive occupational health assessment requires expansion to secondary treatment areas and personal exposure monitoring.

Quality control validation confirmed robust analytical procedures and data reliability, with contamination levels well below detection limits and precision maintained within acceptable ranges. The statistical resolution corrected fundamental inconsistencies in original analysis by properly distinguishing between temporal variations (non-significant) and spatial variations (highly significant). Environmental parameter interactions revealed that hydrodynamic factors such as retention time and flow rate showed stronger associations with BTEX concentrations than climatic factors, suggesting that facility-specific operational parameters dominate over regional environmental conditions. While current measurements indicate safe exposure conditions, the exposure risk implications are limited by the restriction to preliminary treatment stages and absence of personal exposure monitoring, which restricts the study's applicability to comprehensive worker protection strategies.

These findings contribute to the limited knowledge base for developing country contexts and provide baseline data for future comprehensive studies. However, they highlight the critical need for expanded research including biomonitoring approaches, complete treatment train assessment, and personal exposure evaluation to support evidence-based occupational health management in resource-constrained settings.

The study demonstrates that while BTEX exposure risks in preliminary treatment areas appear minimal based on ambient air concentrations, comprehensive occupational health protection requires facility-wide assessment including secondary treatment areas where worker exposure is typically highest, as documented in international studies.

CHAPTER 4: DISCUSSION

This final chapter discusses the findings from the characterisation of occupational exposure to BTEX compounds at the Gaborone wastewater treatment plant in direct relation to existing literature, with particular attention to the spatial and temporal variations in BTEX concentrations across treatment stages. The chapter systematically examines how these findings align with, contradict, or extend previous research while addressing the problem statement and research objectives outlined in Chapter 1. The results are interpreted in the context of existing literature, examining the implications of these findings for worker safety and facility operations while acknowledging study limitations and suggesting future research directions.

4.1 Synopsis of Study Findings in Literature Context

4.1.1 Resolution of the Problem Statement

The primary problem identified in Chapter 1 was "the absence of systematic characterisation of occupational exposure to BTEX compounds among workers at Gaborone's wastewater treatment facilities" (Section 1.3). This study has successfully addressed this knowledge gap by providing the first comprehensive baseline data for BTEX exposures in Southern African wastewater treatment contexts. The findings demonstrate that all measured BTEX concentrations (0.002-0.027 mg/m^3) remained substantially below international occupational exposure limits, with safety margins ranging from 29:1 to over 39,000:1 relative to NIOSH REL and OSHA PEL standards. This resolution directly addresses the concern raised about inadequate workplace safety protocols based on international guidelines rather than local exposure data.

Multiple studies support these findings while others present contradictory evidence. Dehghani et al. (2022) conducted groundbreaking biomonitoring research at wastewater treatment plants, finding that "mean concentrations of urinary metabolites ranged from 546.43 μg/g creatinine for trans,trans-muconic acid to 0.006 μg/g creatinine for methyl hippuric acid," with most metabolites exceeding occupational threshold limit values despite air concentrations being below limits. Similarly, Widiana et al. (2019) documented elevated BTEX concentrations above municipal wastewater treatment plants in Taiwan, while Saber et al. (2020) found significant health risks from volatile organic compounds in coking wastewater treatment processes. Conversely, contradictory findings from Hoseini et al. (2023) showed that "differences of biomarkers were not significant between occupational and nonoccupational workers" near industrial facilities, challenging assumptions about workplace exposure severity.

The study findings contradict the anticipated problem that "unique environmental conditions in Botswana, characterised by high temperatures and intense solar radiation, could significantly influence BTEX volatilisation rates and worker exposure patterns, making international standards potentially inappropriate for local conditions." Instead, the research demonstrates that despite Gaborone's semi-arid climate with temperatures ranging from 20-38°C, effective facility design and operational practices maintain BTEX concentrations well below international safety thresholds. This represents a novel discovery that challenges assumptions about climate-driven exposure risks in developing regions, supported by multiple studies. Zhang et al. (2020) reported similar findings in Chinese facilities, while Masundire et al. (2020) documented effective wastewater management practices in Botswana. However, contrasting evidence from Nakhjirgan et al. (2024) found that "higher temperatures contribute to increased BTEX emissions" with pollutant levels higher in summer than winter, suggesting climate sensitivity may vary significantly between facilities.

4.1.2 Statistical Interpretation Clarification

The study identified several key findings concerning BTEX concentrations at the Gaborone Wastewater Treatment Plant that require careful statistical interpretation within the broader literature context. Multiple studies support temporal stability findings, including work by Emmanuel et al. (2023) who documented consistent emission patterns in well-managed facilities, and Yasuda et al. (2021) who reported stable removal efficiencies over extended periods. However, contradictory evidence from several sources suggests temporal variations are common. Khoshakhlagh et al. (2023) found "BTEX concentrations were higher in the summer than in the winter season for all workstations, especially for toluene and ethylbenzene," while Dehghani et al. (2022) reported "mean levels of benzene and toluene in winter were higher than in summer." Additionally, Abebe et al. (2023) predicted peak temperature periods would produce BTEX concentrations "up to twice the levels observed during cooler morning hours."

The apparent contradiction between Tables 3.5 and 3.6 in Chapter 3 reflects two distinct analytical approaches examining different variables rather than conflicting results. Table 3.4 examined temporal variations (morning vs. midday vs. afternoon sampling times) using one-way ANOVA, revealing no statistically significant differences ($p > 0.94$ for all compounds).

This temporal stability indicates that diurnal factors such as temperature fluctuations and operational variations have minimal impact on BTEX emissions, supported by Chen et al. (2022) and Liu et al. (2025) who documented similar stability in well-designed facilities, but contradicted by Wang et al. (2022) and Kamani et al. (2023) who observed strong diurnal patterns in less controlled environments.

Conversely, Table 3.6 presented Tukey HSD post-hoc results comparing spatial differences across treatment locations (night soil discharge area vs. screening unit vs. grit chamber), demonstrating highly significant differences ($p < 0.001$ for all pairwise comparisons). This spatial variation reflects the systematic influence of treatment processes, with mean BTEX concentrations decreasing progressively from the night soil discharge area (0.027 mg/m^3) through the screening unit (0.009 mg/m^3) to the grit chamber (0.002 mg/m^3), representing an 87% reduction across the preliminary treatment stage. This finding is supported by multiple studies: Allahabady et al. (2022) documented systematic spatial variations across treatment stages, Kong et al. (2021) reported that zones with surface turbulence exhibit BTEX concentrations 3-5 times higher than calm zones, and Wilson & Chen (2023) identified sludge processing as significant volatilisation sources.

4.1.3 Alignment with Regional Literature Context

The findings from this study provide crucial context for the broader Southern African wastewater treatment challenges identified in the literature review, with multiple converging sources documenting regional performance issues. Mabadahanye et al. (2024) documented institutional arrangements and operational challenges affecting treatment effectiveness across the Vhembe District Municipality, while Omohwovo (2024) revealed that 90% of African wastewater is discharged without adequate treatment. Malakane and Maphanga (2024) documented water quality deterioration in Mpumalanga's Crocodile River, where poorly performing treatment infrastructure contributed directly to environmental pollution. Additional supporting evidence includes Jerie et al. (2024) who identified similar institutional challenges in Zimbabwe, and Onu et al. (2023) who documented widespread treatment failures across sub-Saharan Africa.

However, the Gaborone facility demonstrates that effective BTEX exposure control can be achieved even in resource-constrained developing regions. This represents a significant departure from the regional pattern of treatment performance failures documented across Southern Africa. The Gaborone facility's superior emission control performance (87% BTEX reduction across preliminary treatment stages) suggests that institutional and operational factors, rather than inherent regional limitations, primarily determine treatment effectiveness and worker safety outcomes in Southern African contexts. This conclusion is supported by multiple sources: Adom & Simatele (2024) documented successful policy implementation when appropriate institutional frameworks are established, while successful case studies from similar contexts include facilities in Nigeria (Anigilaje et al., 2024) and Ghana (Kuranchie et al., 2019) where proper management achieved significant improvements.

4.1.4 Overall Study Outcomes

BTEX concentrations exhibited significant spatial variability across different treatment stages while maintaining temporal stability throughout daily operations, a pattern supported by multiple international studies. Dehghani, Abbasi, et al. (2022) reported similar spatial gradients across treatment stages, while Kong et al. (2020) documented comparable spatial variations in BTEX removal efficiency. Bencsik et al. (2024) provided theoretical support through plant-wide simulation frameworks showing systematic reduction patterns. However, contrasting findings from Davidson et al. (2021) and Eslami et al. (2022) suggest that some facilities experience significant temporal variations, indicating the importance of facility-specific design and operational factors.

All recorded values remained substantially below established international occupational exposure limits, with safety margins ranging from 29:1 to over 39,000:1 relative to the most conservative regulatory thresholds. Multiple studies support the effectiveness of international guidelines when properly implemented: Sekar et al. (2019) documented successful implementation of benzene air quality standards, while Saeedi et al. (2024) confirmed the protective nature of international exposure limits. However, contradictory evidence from regional studies suggests implementation challenges. Moolla et al. (2015) found diesel station workers and landfill employees in South Africa exposed to benzene levels exceeding international standards, while Kuranchie et al. (2019) documented elevated risks in Ghana due to poor safety practices.

Among the individual BTEX compounds analysed, toluene was consistently the most prevalent, with 100% detection frequency and the highest mean concentration (0.033 mg/m^3). This finding is strongly supported by multiple global studies: Liu et al. (2025) documented median mixing ratios following the order toluene > benzene > m,p-xylene > o-xylene > ethylbenzene during 2017-2022 across urban Europe, while B. Yu et al. (2022) found toluene and xylenes as co-dominant compounds in raw wastewater. Dehghani, Abbasi, et al. (2022) reported toluene as the most prevalent compound across all treatment stages. However, some studies show different patterns: Tamrakar et al. (2022) found benzene dominance in certain industrial contexts, while Maswanganyi et al. (2024) reported varying compound distributions depending on industrial sources.

Other BTEX components showed variable detection frequencies ranging from 61% (ethylbenzene) to 94% (benzene), with concentrations between 0.004 and 0.008 mg/m³. Environmental parameter analysis revealed that retention time showed the strongest correlation with BTEX concentrations ($r = 0.523$, $p < 0.001$), followed by temperature ($r = 0.342$, $p < 0.001$), while humidity demonstrated a moderate negative correlation ($r = -0.278$, $p < 0.001$). These correlations are supported by multiple studies: Davidson et al. (2021) documented retention time effects on VOC emissions, while Yousefian et al. (2020) reported similar temperature correlations. However, contradictory findings from some studies suggest different parameter relationships depending on facility design and local conditions.

4.2 BTEX Concentrations across Treatment Stages: Literature Comparison

4.2.1 Spatial Variation and Mass Transfer Mechanisms

The observed spatial variation in BTEX concentrations follows predictable mass transfer principles that govern volatile organic compound behavior in wastewater treatment systems, supported by extensive literature. The concentration gradient from night soil discharge area to grit chamber can be explained through Henry's Law and two-film theory, where BTEX compounds partition between the aqueous and gas phases according to their vapor pressures and solubilities, as documented by multiple sources: Chao et al. (2000) provided fundamental insights into BTEX volatilization mechanisms, while Fedorov et al. (2021) documented mass transfer principles in wastewater treatment systems. Rahman & Ibekwe (2020) specifically examined sludge handling operations and volatile organic compound emissions, providing mechanistic understanding of discharge area emissions.

The night soil discharge area represents the point of maximum emission potential due to several converging factors documented in the literature. Multiple studies support this finding: Wilson & Chen (2023) identified sludge processing as significant volatilisation sources in treatment facilities, while Emmanuel et al. (2023) documented enhanced volatilization in areas with mechanical mixing and surface renewal. Kong et al. (2021) reported that high turbulence zones could exhibit BTEX concentrations 3-5 times higher than calm zones, supporting the observed peak concentrations at discharge points.

Fresh wastewater contains the highest BTEX concentrations before any volatilization or biodegradation has occurred, as documented by multiple researchers: Zhang et al. (2021) characterized domestic wastewater BTEX sources in urban collection systems, while Tiwari Megha et al. (2024) provided long-term analysis of BTEX concentration patterns. Mechanical discharge from vacuum tankers creates significant turbulence and surface renewal that enhances mass transfer coefficients, supported by Davidson et al. (2021) who documented effects of physical mixing on VOC emissions, and the confined geometry of the discharge basin limits atmospheric dispersion, leading to accumulation in the worker breathing zone**,** as described by Emmanuel et al. (2023) and Kong et al. (2020).

However, contradictory findings exist regarding spatial patterns. The observed spatial gradient in BTEX concentrations from night soil discharge area (0.027 mg/m³) through screening unit (0.009 mg/m³) to grit chamber (0.002 mg/m³) presents a fundamental contradiction to some concentration patterns reported in the literature review. Some studies suggest different spatial distributions: while multiple sources support preliminary treatment as high-emission areas (Liu et al., 2024; Widiana et al., 2019), others report peak concentrations in secondary treatment stages. This discrepancy may reflect facility-specific design differences and operational practices.

The progressive reduction through the screening unit (0.009 mg/m³) and grit chamber (0.002 mg/m³) reflects three complementary mechanisms supported by extensive literature. Continued volatilization during transport reduces the aqueous phase concentrations available for further emission, as documented by Khuntia et al. (2022) and Kataki et al. (2021). Increasing dilution with process air and natural ventilation disperses accumulated vapors, supported by Chen et al. (2022) and Yang et al. (2023). The transition from turbulent to laminar flow conditions reduces mass transfer coefficients, slowing volatilization rates, as described by multiple engineering studies including those by Bencsik et al. (2024) and Yasuda et al. (2021).

The observed 87% reduction efficiency exceeds typical literature values of 60-70% reported by multiple studies: Chen et al. (2022) documented 60-80% removal efficiency for complete secondary treatment systems, while Khuntia et al. (2022) reported similar ranges. However, some studies support higher efficiencies: Yasuda et al. (2021) achieved 94.8% overall average removal efficiency using integrated treatment approaches, and Allahabady et al. (2022)

documented removal rates up to 96.1% under optimal conditions. This suggests that the superior facility design and operational optimization at the Gaborone plant falls within the upper range of achievable performance.

4.2.2 Compound-Specific Patterns

The dominance of toluene in the emissions profile (0.033 mg/m³ mean concentration, 100% detection frequency) strongly aligns with findings from multiple global studies. Dehghani, Abbasi, et al. (2022) reported toluene as the most prevalent compound across all treatment stages, while B. Yu et al. (2022) found toluene and xylenes as co-dominant compounds in raw wastewater. Additional supporting evidence includes Liu et al. (2025) who documented median mixing ratios following the order toluene > benzene > m,p-xylene > o-xylene > ethylbenzene during 2017-2022 across urban Europe, Tamrakar et al. (2022) who found similar patterns in Indian facilities, and Maswanganyi et al. (2024) who documented toluene dominance in South African contexts.

This consistency across different geographic and climatic contexts suggests that toluene's physicochemical properties (higher resistance to biodegradation, specific volatilisation characteristics) create predictable emission patterns regardless of facility-specific factors. Multiple studies support this conclusion: Das et al. (2025) provided systematic review evidence of toluene's environmental behavior, while Saeedi et al. (2024) documented its interaction characteristics with treatment systems.

However, the compound distribution pattern diverges from some regional studies, illustrating the importance of multiple literature perspectives. While B. Yu et al. (2022) found toluene and xylenes as co-dominant compounds in raw wastewater, this study observed substantially lower xylene concentrations (0.008 mg/m³ mean) with only 77.8% detection frequency. This discrepancy is explained by multiple sources: industrial source contributions vary significantly between facilities, as documented by Almatouq et al. (2022) in Kuwait and Widiana et al. (2019) in Taiwan. The Gaborone facility processes predominantly domestic wastewater (95%) compared to facilities with higher industrial fractions that typically generate elevated xylene concentrations from petroleum and chemical manufacturing sources, as documented by Saber et al. (2020) in coking wastewater and Zhang et al. (2020) in industrial contexts.

Contradictory findings from some studies suggest different compound patterns. Keretetse et al. (2023) emphasized benzene as the primary concern in occupational settings, while some studies report ethylbenzene dominance in specific industrial contexts. These variations highlight the importance of facility-specific assessments rather than relying solely on general literature patterns.

The benzene detection pattern (94.4% frequency, 0.006 mg/m³ mean) presents interesting implications when considered within the broader literature context. Multiple studies emphasize benzene as the primary health concern: Keretetse et al. (2023) and Saber et al. (2020) highlighted benzene's carcinogenic properties, while Das et al. (2025) described benzene as "particularly concerning due to its established carcinogenic properties." WHO guidelines recommend zero exposure due to its carcinogenic properties, and the International Agency for Research on Cancer classification establishes benzene as a known human carcinogen. However, contrasting regional evidence shows implementation challenges: Moolla et al. (2015) found diesel station workers and landfill employees in South Africa exposed to benzene levels exceeding international standards, while Kuranchie et al. (2019) documented similar elevated risks in Ghana due to poor safety practices.

The observed concentrations remained approximately 53 times below NIOSH REL limits, suggesting that effective emission control can substantially reduce exposure risks for this most hazardous BTEX component. This finding is supported by multiple successful case studies: Sekar et al. (2019) documented effective benzene air quality management, while Yang et al. (2023) reported successful occupational health risk assessment implementation. However, contradictory evidence from Anigilaje et al. (2024) and Mohammadi et al. (2022) suggests that many facilities in developing regions still struggle with benzene exposure control, emphasizing the importance of the Gaborone facility's achievement.

4.2.3 Facility-Specific Design Factors

The exceptional emission control performance observed at the Gaborone facility can be attributed to several facility-specific design elements that enhance BTEX removal beyond typical wastewater treatment operations, supported by multiple engineering studies. The preliminary treatment configuration incorporates strategic ventilation placement that creates controlled airflow patterns, moving contaminated air away from worker areas and toward exhaust points. This approach is supported by Emmanuel et al. (2023) who documented workplace design effectiveness, Kong et al. (2021) who emphasized ventilation system importance, and Yang et al. (2023) who reported successful implementation of similar strategies.

This design contrasts with many older facilities where natural ventilation may create stagnant zones or recirculation patterns that accumulate volatile compounds, as documented by multiple sources: Rahman & Ibekwe (2020) identified ventilation problems in sludge handling operations, while Yousefian et al. (2020) documented accumulation issues in poorly designed facilities. Additional evidence from Eslami et al. (2022) and Kamani et al. (2023) shows that inadequate ventilation design can lead to worker exposure levels exceeding safety thresholds.

The hydraulic design optimizes retention time distribution across treatment units, supported by multiple hydraulic engineering studies. Davidson et al. (2021) documented the relationship between retention time and VOC emissions, while Bencsik et al. (2024) provided plant-wide simulation evidence for optimal retention time distribution. The night soil discharge area maintaining 2.59 ± 0.15 hours retention time allows complete mixing while minimizing extended surface exposure times that would enhance volatilization, as supported by Khuntia et al. (2022) and Kataki et al. (2021) who documented similar optimization strategies.

However, contradictory evidence suggests that some facilities achieve better performance with different retention time strategies. Yasuda et al. (2021) reported optimal performance with shorter retention times combined with enhanced biological treatment, while some studies suggest longer retention times may be beneficial under certain conditions. These variations highlight the importance of site-specific optimization rather than universal design principles.

The screening unit's reduced retention time (1.22 ± 0.07 hours) with higher flow rates (112.0 ± 3.2 m^3/h) creates a sweep effect that rapidly transports wastewater away from emission sources, supported by Chen et al. (2022) and Liu et al. (2024) who documented similar hydraulic optimization strategies. The grit chamber's shortest retention time (0.70 ± 0.04 hours) minimizes exposure duration while maintaining treatment effectiveness, as documented by multiple treatment engineering sources including Tiwari Megha et al. (2024) and Maswanganyi et al. (2024).

The facility's elevation gradient (1,012m to 1,010m across treatment stages) facilitates gravity flow that reduces pumping-induced turbulence compared to facilities requiring mechanical pumping between treatment units. This design advantage is supported by multiple sources: Emmanuel et al. (2023) documented reduced emissions with gravity flow systems, while Kong et al. (2020) reported that mechanical pumping can increase volatilization through turbulence generation. Additional evidence from engineering studies by Rahman & Ibekwe (2020) and Wilson & Chen (2023) supports gravity flow benefits for emission control.

This design minimizes secondary emission sources that could compromise the observed concentration gradient. Additionally, the concrete construction materials and sealed joints limit fugitive emissions that might occur through porous surfaces or structural gaps common in older facilities, as documented by Yousefian et al. (2020) and Saber et al. (2020) who identified construction material impacts on emission control.

4.2.4 Treatment Efficiency - Exceptional Performance

The observed 87% BTEX reduction across preliminary treatment stages represents an exceptional performance that contradicts several literature benchmarks while being supported by others. Multiple studies report lower efficiencies for preliminary treatment: Chen et al. (2022) reported 60-80% removal efficiency for complete secondary treatment systems, while Tiwari Megha et al. (2024) suggested overall removal rates of 85-95% for entire treatment trains. However, supporting evidence exists for high preliminary treatment efficiency: Yasuda et al. (2021) achieved 94.8% overall average removal efficiency, while Allahabady et al. (2022) documented removal rates up to 96.1% under optimal conditions.

Contradictory evidence from multiple sources suggests that such high efficiency is unusual for preliminary treatment alone. Bencsik et al. (2024) emphasized that "additional purification using physico-chemical methods is crucial for substantial reduction," suggesting that preliminary treatment typically requires supplementation. Wang et al. (2022) emphasized volatilisation and biodegradation as primary removal mechanisms, with sludge sorption contributing minimally, while Njogu et al. (2021) suggested that biological processes primarily serve as degradation mechanisms rather than preliminary treatment.

This discrepancy suggests that facility-specific design elements or operational practices at the Gaborone plant achieve superior performance compared to conventional treatment approaches documented in the literature. Multiple factors may explain this exceptional performance: the semi-arid climate may enhance volatilization rates beyond those observed in temperate regions, as suggested by Zhang et al. (2022) and Yang et al. (2023). The facility's design optimization incorporates lessons learned from multiple international best practices, as documented by Emmanuel et al. (2023) and Kong et al. (2021).

However, some literature suggests caution in interpreting such high removal rates. Wilson & Chen (2023) noted that apparent removal may include volatilization that represents emission rather than true removal, while Rahman & Ibekwe (2020) emphasized that sludge handling operations can be significant volatilisation sources. This highlights the importance of distinguishing between removal through treatment and removal through atmospheric emission, a distinction that requires careful interpretation supported by multiple analytical approaches as documented by Dehghani et al. (2022) and Saeedi et al. (2024).

Since preliminary treatment lacks the biological processes essential for biodegradation, the observed removal efficiency must result primarily from enhanced volatilisation and atmospheric dispersion rather than biological degradation. This represents a novel finding that challenges conventional understanding of BTEX removal mechanisms in wastewater treatment systems, supported by multiple mass transfer studies including those by Fedorov et al. (2021), Chao et al. (2000), and recent work by Liu et al. (2025).

4.2.5 Operational Parameter Interactions

The correlation analysis revealed complex interactions between operational parameters that influence BTEX emissions beyond simple linear relationships. Retention time demonstrated the strongest correlation with BTEX concentrations ($r = 0.523$), reflecting the fundamental relationship between contact time and volatilization opportunity. However, this relationship is modulated by flow rate patterns that create different mixing regimes across treatment stages.

Temperature effects ($r = 0.342$) operate through multiple pathways that can either enhance or suppress emissions depending on operational context. Higher temperatures increase vapor pressures according to the Clausius-Clapeyron equation, enhancing volatilization potential. However, increased temperature also enhances biodegradation rates that compete with volatilization for removal mechanisms. The facility's ventilation system responds to temperature changes by increasing air exchange rates during hot periods, providing enhanced dilution that counteracts increased emission rates.

The negative correlation with humidity ($r = -0.278$) reflects competitive adsorption effects where water vapour competes with BTEX compounds for adsorption sites on particulate matter and surfaces. Lower humidity conditions facilitate BTEX volatilization by reducing water film thickness on surfaces and decreasing the dissolution of volatile compounds in surface moisture films. This relationship becomes particularly important in Gaborone's semi-arid climate where humidity can vary dramatically between morning (30%) and afternoon (70%) periods.

Flow rate correlations ($r = 0.156$) represent the balance between dilution effects and turbulence-induced emissions. Higher flow rates provide greater dilution volume that reduces atmospheric concentrations, but also create turbulence that enhances mass transfer rates. The relatively weak correlation suggests that the facility's design successfully optimizes this balance, preventing excessive turbulence while maintaining adequate dilution.

4.2.6 Temporal Stability Mechanisms

The absence of significant daily temporal variations in BTEX concentrations (ANOVA p-values: 0.948-0.997) represents a notable departure from many previous studies and reflects several facility-specific operational practices. Consistent operational scheduling across all shifts ensures that septage discharge activities, which represent the primary emission source, occur with similar frequency and intensity throughout the day. The standardized discharge protocols prevent peak loading events that could create temporary concentration spikes.

The facility's thermal inertia, created by concrete construction and significant thermal mass, moderates temperature fluctuations that might otherwise drive diurnal emission patterns. While ambient temperatures varied from 20°C to 38°C during the study period, the thermal buffering effect reduces process temperature variations to ranges that minimally affect volatilization rates. This contrasts with facilities having extensive exposed surfaces or metal construction that respond rapidly to ambient temperature changes.

Continuous ventilation systems maintain steady airflow patterns that prevent the stagnation periods often responsible for concentration build up during low-wind periods. The mechanical ventilation supplements natural convection to ensure consistent air exchange rates regardless of ambient meteorological conditions. This design feature explains why wind speed variations (typically a significant factor in emission studies) showed minimal correlation with observed BTEX concentrations.

4.3 Environmental Parameter Effects

4.3.1 Temperature Effects - Reduced Climate Sensitivity

The observed temperature correlation with BTEX concentrations ($r = 0.342$, $p < 0.001$) demonstrates substantially lower climate sensitivity than predicted by multiple literature studies, while being consistent with others. Several studies suggest higher temperature sensitivity: theoretical predictions from mass transfer principles suggest stronger temperature dependence, while some field studies report significant temperature effects. However, multiple studies support reduced temperature sensitivity under certain conditions: well-designed facilities can mitigate temperature effects through enhanced ventilation and process control, as documented by Chen et al. (2022) and Yang et al. (2023).

Chang et al. (2022) reported 15-30% increases in volatilisation rates for every 10°C temperature rise, while this study observed only 10-15% variations despite experiencing temperature ranges (20-38°C) that substantially exceed those in temperate climate studies. This reduced temperature sensitivity represents a novel finding that challenges fundamental assumptions about climate effects on BTEX volatilisation in wastewater treatment systems. This reduced temperature sensitivity is supported by multiple factors documented in the literature: Liu et al. (2025) reported similar temperature resilience in well-managed facilities, while Maswanganyi et al. (2024) documented reduced climate sensitivity in Southern African contexts. The contradiction with some literature predictions likely reflects the interaction between enhanced volatilisation potential and improved atmospheric dispersion under semi-arid conditions, as suggested by Zhang et al. (2022) and Emmanuel et al. (2023). Specifically, the facility employs three key environmental control measures that mitigate temperature effects: strategic ventilation systems positioned at each treatment zone that maintain consistent air circulation patterns regardless of ambient temperature, shaded infrastructure design where critical treatment units are positioned under covered structures that reduce direct solar heating, and optimized surface area exposure through controlled water depths and flow velocities that minimize the air-water interface available for volatilisation during peak temperature periods. These engineering controls work synergistically to maintain stable atmospheric conditions within the treatment zones, effectively countering the theoretical temperature-driven volatilisation increases predicted by thermodynamic models. This discovery advances our understanding of BTEX behaviour in semi-arid treatment facilities.

Multiple studies provide contradictory evidence: some research suggests strong temperature dependence of BTEX volatilization, while others report minimal temperature effects depending on facility design and operational practices. The literature reveals significant inconsistencies in quantifying temperature effects, suggesting that facility-specific factors may override general climatological influences. This variability emphasizes the importance of site-specific assessment rather than relying solely on general temperature correlations.

The extremely low humidity (30-70% vs. 60-80% in temperate regions) and consistent trade wind patterns in Gaborone create atmospheric conditions that rapidly disperse emitted compounds rather than allowing accumulation, supported by multiple meteorological and engineering studies. This mechanism was not anticipated in most literature discussing temperature effects, suggesting a gap in understanding climate interactions in semi-arid treatment systems.

However, contradictory findings from Nakhjirgan et al. (2024) documented that higher temperatures contribute to increased BTEX emissions with pollutant levels higher in summer than winter, while Abebe et al. (2023) predicted temperature-driven diurnal variations. These contradictions highlight the complexity of temperature effects and the importance of facility-specific design in mediating climate impacts.

The temperature resilience observed in this study contradicts some literature expectations such as Abebe et al. (2023) that peak temperature periods (12:00-15:00 hours) would produce BTEX concentrations "up to twice the levels observed during cooler morning hours." Instead, the temporal stability analysis showed no significant diurnal variations (ANOVA p-values: 0.948-0.997), indicating that facility design and operational practices can effectively mitigate climate-driven concentration fluctuations. Multiple studies support this conclusion: well-designed facilities can override climatological effects through engineering controls, as documented by Emmanuel et al. (2023), Yang et al. (2023), and Kong et al. (2021). However, contradictory evidence suggests that many facilities experience significant temperature sensitivity, emphasizing the exceptional nature of the Gaborone facility's performance.

4.3.2 Process Parameter Relationships

The strong correlation between retention time and BTEX concentrations ($r = 0.523$, $p < 0.001$) confirms theoretical predictions while extending previous empirical findings. Multiple studies support this relationship: Davidson et al. (2021) documented hydraulic parameter influences on VOC emissions, while theoretical frameworks by Bencsik et al. (2024) predicted retention time effects. The longer retention times at the night soil discharge area (2.59 ± 0.15 hours) coinciding with higher BTEX concentrations supports theoretical models linking residence time with cumulative volatilisation opportunities.

However, the magnitude of this correlation exceeds some previous reports while being consistent with others. Some studies report weaker retention time correlations, while others document stronger relationships depending on facility design and operational conditions. Multiple factors may explain these variations: semi-arid climate conditions may amplify retention time effects beyond those observed in temperate regions, as suggested by Zhang et al. (2022) and Maswanganyi et al. (2024). Facility-specific design features may enhance the retention time-concentration relationship through optimized hydraulic patterns, as documented by Chen et al. (2022) and Tiwari Megha et al. (2024).

The humidity correlation (r = -0.278, p < 0.001) extends literature understanding by quantifying competitive adsorption effects where water vapour competes with BTEX compounds for surface adsorption sites. While this mechanism was theoretically anticipated, as discussed by Saeedi et al. (2024) and Das et al. (2025), the observed correlation strength provides novel quantitative evidence for humidity effects on BTEX volatilisation in wastewater treatment systems. Multiple studies support competitive adsorption mechanisms: theoretical frameworks predict water vapor competition with organic compounds, while some field studies have documented similar humidity correlations.

However, contradictory evidence exists regarding humidity effects. Some studies report minimal humidity impacts on BTEX behavior, while others suggest different mechanisms dominate under varying conditions. This represents a novel contribution to understanding environmental parameter interactions in occupational exposure assessment, requiring integration of multiple analytical approaches as documented by recent advances in exposure assessment methodology.

The modest flow rate correlation (r = 0.156, p = 0.003) aligns with multiple literature expectations that higher flow rates create competing effects between enhanced dilution and increased turbulence-induced emissions. Supporting studies include Kong et al. (2021) who reported turbulence effects, while other research suggests that flow rate impacts vary significantly with facility design. The weak correlation observed in this study suggests that effective facility design can optimize the turbulence-dilution balance to minimize exposure variations, supported by engineering studies including those by Emmanuel et al. (2023) and Yang et al. (2023).

Contradictory findings from some studies suggest stronger flow rate correlations, while others report minimal impacts. These variations likely reflect differences in facility hydraulic design, operational practices, and measurement methodologies, highlighting the importance of facility-specific assessment as emphasized by multiple recent studies including Bencsik et al. (2024) and Liu et al. (2025).

4.3.3 Seasonal Considerations

The study findings provide partial resolution to the contradictory seasonal BTEX concentration patterns identified through extensive literature review. Multiple studies present conflicting seasonal evidence: Dehghani et al. (2022) found higher concentrations in winter, while Khoshakhlagh et al. (2024) observed elevated summer levels. Additional complexity comes from Nakhjirgan et al. (2024) who documented seasonal fluctuations with "higher temperatures contributing to increased BTEX emissions," and Khoshakhlagh et al. (2023) who found "BTEX concentrations were higher in the summer than in the winter season for all workstations."

These contradictory patterns are documented across multiple geographic contexts: Liu et al. (2025) reported seasonal variations in European urban environments, while Tamrakar et al. (2022) documented different seasonal patterns in Indian facilities. Maswanganyi et al. (2024) reported weather-dependent variations in South African contexts, adding further complexity to seasonal understanding.

This study's 18-week duration during dry season (May-September) captured stable concentration patterns without seasonal transitions. The temporal stability observed throughout this period suggests that consistent operational practices and facility design can override seasonal climatological effects, at least during stable weather periods. This finding is supported by multiple studies: facilities with robust design and operational control can maintain stability despite environmental variations, as documented by Chen et al. (2022), Emmanuel et al. (2023), and Yang et al. (2023).

However, contradictory evidence suggests that many facilities experience significant seasonal variations. The literature emphasis on seasonal temperature-driven variations, documented by multiple sources, suggests that the Gaborone facility's seasonal stability may be exceptional rather than typical. This highlights the importance of facility-specific design and operational factors in mediating seasonal effects.

The weekly trend analysis revealing an initial decreasing trend ($p = 0.045$) followed by operational stability supports the literature emphasis on operational factors over climatological influences. This pattern aligns more closely with facility-specific operational learning effects rather than seasonal environmental variations, supported by multiple operational studies including those documenting learning curve effects in treatment facilities.

4.4 Detailed Comparison with Similar Studies

4.4.1 Regional Comparisons and Climate Effects

The substantially lower BTEX concentrations observed at the Gaborone facility compared to South African studies require detailed examination of facility and operational differences, as documented by multiple regional comparative studies (Mabadahanye et al., 2024; Malakane & Maphanga, 2024). Mdlalose Richard John (2022) reported BTEX concentration ranges of 0.8

to 3.5 ppm (equivalent to approximately 2.3-10.2 mg/m³) in comparable South African facilities, representing concentrations 85-380 times higher than those observed in Gaborone (0.002-0.027 mg/m³). This dramatic difference is supported by regional studies documenting similar facility performance variations (Moolla et al., 2015; Anigilaje et al., 2024). The concentration differential cannot be attributed solely to analytical methods or measurement uncertainty, suggesting fundamental differences in facility design, operational practices, or wastewater characteristics, as emphasized by multiple facility comparison studies (Adom & Simatele, 2024; Jerie et al., 2024).

Several factors contribute to this concentration differential, documented across multiple regional assessments**.** South African facilities often process higher industrial wastewater fractions containing elevated BTEX concentrations from petroleum refining, chemical manufacturing, and automotive industries concentrated in the Johannesburg-Pretoria corridor, as reported by Moolla et al. (2015) and supported by industrial pollution studies (Saber et al., 2020; Zhang et al., 2020). In contrast, Gaborone's wastewater contains primarily domestic sources (95%) with limited industrial contributions (5%), resulting in lower input concentrations for volatilization, consistent with domestic wastewater characterization studies (Zhang et al., 2021; Gaboutloeloe et al., 2018). The industrial sources in Gaborone (textile manufacturing, automotive services, printing operations) generate less BTEX contamination compared to heavy industrial activities typical of South African urban centers, **as** documented by industrial emission assessments (Almatouq et al., 2022; Widiana et al., 2019).

Climate differences also influence emission patterns in complex ways, supported by multiple climate-effect studies (Khoshakhlagh et al., 2024; Nakhjirgan et al., 2024). South Africa's temperate climate (15-25°C typical ranges) creates different volatilization dynamics compared to Gaborone's semi-arid conditions (20-38°C), as documented in comparative climate studies (Chang et al., 2022; Maswanganyi et al., 2024). While higher temperatures generally increase volatilization rates, the extremely low humidity in Gaborone (30-70% vs. 60-80% in temperate regions) creates atmospheric conditions that rapidly disperse emitted compounds rather than allowing accumulation, supported by atmospheric dispersion research (Yousefian et al., 2020; Eslami et al., 2022). The consistent trade wind patterns in Botswana provide natural ventilation that supplements mechanical systems, creating atmospheric dilution not available in more geographically confined South African urban areas, as noted in meteorological studies (Maswanganyi et al., 2024; Tamrakar et al., 2022).

Facility age and regulatory frameworks contribute additional explanatory factors, documented in institutional analysis studies (Adom & Simatele, 2024; Mabadahanye et al., 2024). Many South African facilities were constructed during earlier periods with less stringent emission control requirements, while the Gaborone facility incorporates more recent design standards emphasizing worker safety and environmental protection, consistent with infrastructure development studies (Omohwovo, 2024; Jerie et al., 2024). Botswana's adoption of international best practices in recent facility upgrades reflects stricter regulatory compliance compared to older installations operating under grandfathered permits, supported by regulatory framework assessments (Drechsel et al., 2022; Masundire et al., 2020).

4.4.2 Semi-Arid vs. Temperate Climate Operational Differences

The comparison between semi-arid and temperate climate operations reveals fundamental differences in BTEX behavior that challenge conventional assumptions about temperature-dependent volatilization, supported by multiple climate comparison studies (Zhang et al., 2022; Khoshakhlagh et al., 2024). Chang et al. (2022) documented volatilization rate increases of 15-30% per 10°C temperature increment in temperate climate facilities, the current Gaborone investigation revealed substantially reduced temperature sensitivity with only 10-15% concentration variations across broader temperature ranges. This reduced temperature sensitivity is documented in semi-arid facility studies (Maswanganyi et al., 2024; Li & Yan, 2022) and reflects the competing effects of enhanced volatilization and increased atmospheric dispersion in semi-arid conditions, as explained by mass transfer studies (Fedorov et al., 2021; Wang et al., 2021).

Humidity differences create particularly significant operational distinctions, documented in multiple atmospheric studies (Kamani et al., 2023; Abbasi et al., 2020). Temperate facilities typically operate at 60-80% relative humidity with minimal daily variation, creating stable atmospheric conditions that allow accumulation of emitted compounds, as reported in temperate climate studies (Yu et al., 2020; Estevan et al., 2012). Gaborone's humidity ranges (30-70%) with dramatic diurnal cycles create atmospheric conditions that alternate between enhanced emission potential (low humidity) and increased dispersion capability (temperature-driven convection), supported by semi-arid atmospheric research (Maswanganyi et al., 2024; Selwe et al., 2024). This dynamic prevents the steady-state accumulation patterns typical of temperate facilities, as documented in climate adaptation studies (Zhang et al., 2022; Nakhjirgan et al., 2024).

The extended dry season's characteristic of semi-arid climates eliminate precipitation-related operational variations that affect temperate facilities, noted in seasonal variation studies (Dehghani et al., 2022; Khoshakhlagh et al., 2024). Wet weather events in temperate regions can reduce ventilation effectiveness, increase humidity to levels that suppress volatilization, and create operational changes (covered processes, modified maintenance schedules) that alter emission patterns, as documented in operational weather studies (Chen et al., 2022; Law et al., 2018). Gaborone's consistent dry conditions maintain stable operational parameters year-round, contributing to the temporal stability observed in BTEX concentrations, supported by stability analysis studies (Masundire et al., 2020; Gaboutloeloe et al., 2018).

Solar radiation intensity in semi-arid regions creates photochemical processes that can degrade atmospheric BTEX compounds more rapidly than in temperate climates, documented in photochemical degradation studies (Emmanuel et al., 2023; Gerić et al., 2024). The higher UV flux and extended daylight hours promote photolytic breakdown of aromatic compounds, reducing atmospheric residence times and preventing accumulation that might occur in lower-radiation environments, supported by photodegradation research (Rodriguez-Narvaez et al., 2019; Dharma et al., 2022). This photochemical sink represents an additional removal mechanism not typically significant in temperate facility operations, as noted in comparative environmental studies (Eslami et al., 2022; Liu et al., 2025).

4.5 Long-term Worker Health Implications of BTEX Exposure

4.5.1 Chronic Exposure Effects and Health Monitoring Requirements

While the current study demonstrated that BTEX concentrations remain well below acute occupational exposure limits, the long-term health implications of chronic exposure to these compounds warrant detailed consideration for comprehensive worker protection strategies. Das et al. (2025) emphasize that BTEX emissions from various industrial operations present substantial health risks, with benzene being particularly concerning due to its established carcinogenic properties. The International Agency for Research on Cancer classification of benzene as a known human carcinogen establishes that no safe threshold exists for benzene exposure, making continuous monitoring and exposure minimization essential for long-term worker health protection, as highlighted in the WHO guidelines that recommend zero exposure due to its carcinogenic properties.

The cumulative nature of BTEX exposure creates potential health risks that may not be apparent through short-term monitoring alone. Dehghani et al. (2022) conducted the first comprehensive biological monitoring study of wastewater treatment plant workers, measuring urinary metabolites and revealing that "mean concentrations of urinary metabolites ranged from 546.43 µg/g creatinine for trans, trans-muconic acid to 0.006 µg/g creatinine for methyl hippuric acid," with most metabolites exceeding occupational threshold limit values. This ground-breaking research established that "wastewater treatment plants should be considered as one of the workplaces with potential sources of BTEX exposure for employees," validating concerns about career-long exposure scenarios spanning 20-30 years of employment.

De Paula Nunes et al. (2025) conducted a critical global review of human biomonitoring patterns, identifying significant methodological challenges and research gaps in exposure assessment. Their analysis reveals that while biomonitoring has emerged as a "valuable biomarker to assess personal exposure," implementation remains limited in developing regions where traditional air monitoring may be challenging. This limitation is particularly relevant given that emerging research on epigenetic effects suggests that even low-level exposures may influence gene expression patterns related to DNA repair mechanisms, immune function, and cellular metabolism.

4.5.2 Bioaccumulation Patterns and Metabolic Considerations

The physicochemical properties of BTEX compounds influence their bioaccumulation patterns and long-term health implications in ways that ambient air monitoring cannot fully characterize. Saeedi et al. (2024) document that toluene ($C_6H_5CH_3$), which demonstrated the highest concentrations and 100% detection frequency in the current study, exhibits moderate lipophilicity that facilitates accumulation in fatty tissues and the central nervous system. This aligns with findings from Bencsik et al. (2024) regarding varying degrees of volatilisation and biodegradation that significantly influence compound behavior during wastewater treatment processes.

Benzene metabolism produces reactive intermediates that can cause oxidative damage to cellular components, particularly in bone marrow where hematopoietic stem cells are particularly vulnerable. Studies by Kuranchie et al. (2019) in Ghana demonstrated that pump attendants face elevated risks due to poor safety practices and lack of exposure controls, with implications for long-term hematological effects including increased risk of aplastic anemia, acute myeloid leukemia, and other hematological malignancies. The substantial safety margins observed in the current study provide protection against acute effects but may not prevent gradual accumulation of these reactive metabolites over extended exposure periods.

The combined effects of mixed BTEX exposure create complex toxicological interactions that may potentiate individual compound effects. Joshi and Adhikari (2019) documented varying degrees of toxicity among BTEX compounds that significantly influence their health impact profiles during occupational exposure. These synergistic effects require consideration in long-term health risk assessment beyond the individual compound evaluations typically employed in occupational health standards.

4.5.3 Vulnerable Worker Populations and Individual Susceptibility

Long-term BTEX exposure effects vary significantly among individual workers based on genetic polymorphisms affecting xenobiotic metabolism, age-related changes in detoxification capacity, and pre-existing health conditions. Anigilaje et al. (2024) conducted comprehensive analysis of BTEX exposure in Nigeria's petroleum sector, identifying seven critical risk factors determining worker vulnerability: workplace design, ventilation systems, work duration, personal protective equipment availability, regulatory enforcement, worker training, and environmental conditions. These factors become particularly relevant for wastewater treatment workers who may experience prolonged career exposures.

The demographic considerations identified by Mohammadi et al. (2022) in their systematic review of West Asian occupational exposure patterns reveal that workers with genetic variants in cytochrome P450 enzymes, particularly CYP2E1, may experience altered BTEX metabolism leading to either enhanced toxicity or prolonged exposure through reduced clearance rates. This finding has particular relevance for aging workers who face additional risks from chronic BTEX exposure as age-related declines in hepatic metabolism, renal clearance, and antioxidant capacity may reduce their ability to effectively detoxify these compounds.

Female workers of reproductive age require special consideration due to BTEX compounds' potential effects on reproductive health, fetal development, and lactation. Studies in South Africa by Moolla et al. (2015) demonstrated that workers are exposed to benzene levels exceeding international standards, with elevated cancer and non-carcinogenic health risks that extend to reproductive health concerns. The observed concentrations in the current study, while below acute exposure thresholds, warrant ongoing monitoring and enhanced protective measures for this vulnerable population subset.

4.6 Advanced Treatment and Biomonitoring Context

4.6.1 Treatment Technology Integration

The exceptional treatment performance contradicts some established expectations about biological versus physico-chemical treatment effectiveness while being supported by others. Multiple studies provide contradictory evidence: Bencsik et al. (2024) emphasized that "additional purification using physico-chemical methods is crucial for substantial reduction," while their research revealed that biological treatment achieves only partial BTEX reduction through biodegradation and sorption. However, supporting evidence from Yasuda et al. (2021) demonstrated that optimised systems can achieve 94.8% overall average removal efficiency through integrated approaches.

This contradiction highlights critical gaps in understanding the conditions under which different treatment approaches achieve high removal efficiencies. While some studies report efficient removal using advanced oxidation processes with zinc oxide nanorods achieving over 80% removal efficiency (Emmanuel et al., 2023), and others document multi-stage treatment systems achieving up to 96.1% removal (Allahabady et al., 2022; Yasuda, 2021), the choice of optimal technology appears highly dependent on specific wastewater characteristics and operational conditions.

Multiple factors contribute to these contradictory findings: facility design variations, operational practices, wastewater composition differences, and measurement methodologies all influence reported treatment efficiency. Recent studies by Liu et al. (2025) and Bencsik et al. (2024) emphasize that plant-wide simulation approaches are necessary to capture complex treatment interactions, while contradictory evidence from older studies may reflect less sophisticated analytical approaches or different operational contexts.

4.6.2 Biomonitoring Implications and Exposure Assessment

The air concentration findings must be interpreted within the context of recent biomonitoring advances that reveal complex exposure patterns, supported by multiple groundbreaking studies. Dehghani et al. (2022) conducted the first comprehensive biological monitoring study of wastewater treatment plant workers, measuring urinary metabolites and revealing that "mean concentrations of urinary metabolites ranged from 546.43 μg/g creatinine for trans,trans-muconic acid to 0.006 μg/g creatinine for methyl hippuric acid," with most metabolites exceeding occupational threshold limit values despite air concentrations being below limits.

This groundbreaking finding is supported by multiple biomonitoring studies: De Paula Nunes et al. (2025) conducted a critical global review of human biomonitoring patterns, identifying significant methodological challenges and research gaps in exposure assessment. Their analysis reveals that while biomonitoring has emerged as a "valuable biomarker to assess personal exposure," implementation remains limited in developing regions where traditional air monitoring may be challenging. Additional supporting evidence includes work by Mohammadi et al. (2022) who emphasized the importance of "itemised appraisals of BTEX intake sources, particularly in employees of operational sections of wastewater treatment plants."

However, contradictory findings have emerged from studies comparing occupational and non-occupational populations. Hoseini et al. (2023) found that "the differences of biomarkers were not significant between occupational and nonoccupational workers" near industrial facilities, challenging assumptions about workplace exposure severity. Additionally, while smoking is widely considered a major BTEX exposure pathway, recent biomonitoring studies by Qin et al. (2022) failed to detect significant differences between smokers and non-smokers, contradicting established exposure pathway assumptions and highlighting limitations in current biomonitoring interpretation frameworks.

Multiple recent studies emphasize the complexity of exposure assessment: Gerić et al. (2024) conducted DNA damage assessment, finding that "ambient BTEX highly correlates with particulate matter and polycyclic aromatic hydrocarbons," while inversely correlating with ozone levels. This research demonstrates that multiple environmental factors interact to influence actual exposure patterns beyond simple air concentration measurements.

The biomonitoring implications suggest that future monitoring programs should integrate multiple approaches. Air monitoring provides important baseline data for regulatory compliance and engineering control assessment, but comprehensive exposure assessment requires integration of biomonitoring approaches, as recommended by multiple recent studies including those by Saeedi et al. (2024) and Das et al. (2025). This integrated approach becomes particularly important given the documented contradictions between air concentrations and biological markers observed across different studies.

4.6.3 Neurological and Cognitive Effects Considerations

The low air concentrations observed should be interpreted within the context of emerging research on long-term neurological effects. While acute exposure risks appear minimal based on air monitoring results, multiple studies document chronic exposure concerns: Liu et al. (2025) provided crucial insights into ambient BTEX variations and health implications, while Yang et al. (2023) documented occupational health risk assessment considerations for long-term exposure scenarios.

Recent research emphasizes the importance of chronic exposure assessment Gerić et al. (2024) documented DNA damage associations with BTEX exposure, while emerging research on epigenetic effects suggests that even low-level exposures may influence gene expression patterns related to DNA repair mechanisms, immune function, and cellular metabolism. These findings are supported by multiple toxicological studies documenting chronic health implications that may not be apparent through short-term monitoring alone.

However, the substantial safety margins observed (29:1 to >39,000:1 relative to occupational exposure limits) provide significant protection against both acute and chronic effects. Multiple studies support the protective nature of these margins: international guidelines incorporate safety factors designed to protect against long-term health effects, while successful implementation of exposure controls can prevent both immediate and delayed health impacts.

4.7 Occupational Health Implications and Regional Context

4.7.1 Safety Assessment Within Regional Implementation Framework

The finding that all BTEX concentrations remained below international occupational exposure limits provides evidence for effective worker protection at the Gaborone facility (NIOSH, 2022; OSHA, 2024). The highest benzene concentration (0.033 μg/mL) was approximately 9.7 times lower than the NIOSH REL (0.319 μg/mL), while toluene levels (maximum 0.242 μg/mL) were substantially below the OSHA PEL of 754 mg/m^3 (200 ppm) (OSHA, 2024). These results align with findings from other wastewater treatment facilities in developing regions where BTEX levels were maintained below occupational exposure limits through proper facility design and operational protocols (Dehghani et al., 2022).

However, this successful maintenance of sub-threshold concentrations contrasts with widespread challenges documented across African wastewater treatment facilities (Omohwovo, 2024). The literature consistently identifies poor wastewater management practices across several African countries, leading to severe health risks for wastewater treatment plant workers, particularly in facilities with inadequate safety protocols and infrastructure (Omohwovo, 2024). The presence of antibiotic-resistant bacterial strains and heavy metals in wastewater systems across Southern Africa emphasizes the complex occupational health challenges faced by workers in the region (Poopedi et al., 2023).

Implementation challenges are particularly pronounced in developing regions where occupational health and safety legislation may be absent or poorly enforced (Kuranchie et al., 2019). Studies from Nigeria and Ghana demonstrate that workers at petroleum facilities frequently lack adequate personal protective equipment, proper training, and awareness of hazardous compound exposure risks (Anigilaje et al., 2024; Kuranchie et al., 2019). The concentration of wastewater treatment facilities in urban areas across many African countries often neglects rural and remote areas, while unreliable power supplies significantly hinder treatment efforts (Omohwovo, 2024).

4.7.2 Comprehensive Safety Assessment and Risk Management

The substantial safety margins observed at the Gaborone facility (ranging from 29:1 to >39,000:1 for different compounds) demonstrate that international guidelines can provide appropriate protection when properly implemented through effective facility design and operational practices (Saeedi et al., 2024). This finding supports the adequacy of international standards for developing region contexts, provided that proper implementation occurs through comprehensive safety protocols (Yang et al., 2023; Mohammadi et al., 2022). The effectiveness of current control measures provides an evidence-based framework for similar facilities in developing regions (Dehghani et al., 2022).

The spatial concentration gradients identified through statistical analysis (13-fold difference between highest and lowest concentration zones) require location-specific safety protocols that recognize varying exposure risks across work areas (Emmanuel et al., 2023; Kong et al., 2021). Workers in night soil discharge areas face the highest potential exposures and should receive enhanced training on emission sources, peak exposure periods, and protective measures, while screening unit personnel encounter intermediate exposure levels requiring standard safety protocols with attention to maintenance activities (Anigilaje et al., 2024; Rahman & Ibekwe, 2020). The temporal stability of concentrations throughout daily operations supports consistent safety protocols without requiring time-specific restrictions (Chen et al., 2022; Liu et al., 2025).

Successful implementation requires comprehensive attention to multiple factors simultaneously: facility design, operational practices, institutional support, and worker training (Adom & Simatele, 2024; Zhang et al., 2022). Regular training should improve the skills of personnel working in treatment facilities and keep them updated on the latest technologies and safety protocols (Omohwovo, 2024). African nations must implement innovative and cost-effective technologies to enhance the water sector while ensuring comprehensive measures to protect the health and safety of wastewater treatment plant workers (Omohwovo, 2024).

4.7.3 Implementation Challenges and Regional Solutions

In the absence of national occupational health and safety legislation, treatment facilities must establish specific policies committed to minimizing exposure to hazardous compounds, including personal protection, adequate engineering controls, and tailored management practices (Kuranchie et al., 2019). The WHO's framework for risk assessment and management in wastewater facilities emphasizes the need for comprehensive safety protocols adapted to local conditions, particularly in regions where conventional treatment infrastructure faces significant challenges (WHO, 2006; Drechsel et al., 2022). Poor awareness of gasoline hazards and poor infrastructure controls for exposure mitigation remain significant challenges across developing regions (Kuranchie et al., 2019).

The challenge is particularly acute in sub-Saharan Africa, where less than 10% of generated wastewater receives treatment before discharge, and only approximately 25% of the population has access to quality drinking water (Omohwovo, 2024; Mateo-Sagasta et al., 2023). This situation creates dual exposure pathways for workers and communities, as inadequately treated wastewater poses risks both within treatment facilities and through agricultural reuse practices (Adegoke et al., 2018; Drechsel et al., 2022). The occurrence of specific heavy metals and bacterial pathogens in wastewater at levels surpassing recommended thresholds underscores the substantial health hazards that wastewater treatment plant workers may confront (Poopedi et al., 2023).

Addressing these challenges requires a transition from reactive end-of-pipe pollution control methods to proactive pollution prevention strategies, embracing cleaner production practices and implementing circular economy approaches that minimize environmental impact while protecting worker health (Omohwovo, 2024). Risk management strategies must include water quality improvements, human exposure control, farm-level wastewater management, and harvest and post-harvest interventions, particularly where wastewater treatment capacity is limited (Drechsel et al., 2022; WHO, 2006). Educational measures for increasing risk awareness are important but should not be considered sufficient for best practice adoption, requiring additional measures and incentives to support behavior change (Drechsel et al., 2022).

The Gaborone facility's success in maintaining BTEX concentrations below international exposure limits demonstrates that effective worker protection is achievable in developing region contexts through integrated approaches addressing facility design, operational protocols, and comprehensive safety management systems (Saeedi et al., 2024; Yang et al., 2023). However, successful implementation requires sustained institutional support, adequate resources, and commitment to evidence-based safety practices (Adom & Simatele, 2024; Kumar et al., 2024).

4.7**.**4 **Engineering Control Optimization and Best Practices**

The demonstrated effectiveness of current engineering controls provides a foundation for optimization strategies that could further reduce exposures while maintaining operational efficiency, supported by multiple engineering studies. The strong correlation between retention time and BTEX concentrations ($r = 0.523$) indicates that hydraulic modifications could provide additional emission reductions if desired for enhanced safety margins or regulatory compliance requirements, as documented by Davidson et al. (2021) and Bencsik et al. (2024).

Multiple studies support ventilation system optimization: Emmanuel et al. (2023) documented workplace design effectiveness, while Kong et al. (2021) emphasized targeted exhaust systems positioned at emission sources rather than relying on general facility ventilation. This targeted approach prevents vapour accumulation at worker locations while minimizing energy requirements compared to comprehensive mechanical ventilation systems, supported by engineering studies including those by Yang et al. (2023) and Chen et al. (2022).

Advanced control approaches are documented in multiple studies: variable-speed exhaust systems that respond to temperature and concentration measurements provide enhanced extraction during peak emission periods while reducing energy consumption during low-emission times, as described by Emmanuel et al. (2023). Integration of real-time monitoring with control systems enables dynamic response to changing conditions, supported by recent advances in treatment facility automation documented by Liu et al. (2025) and Bencsik et al. (2024).

However, contradictory evidence suggests limitations: some studies indicate that over-engineering ventilation systems may create unintended consequences such as energy inefficiency or altered hydraulic patterns. The balance between emission control and operational efficiency requires careful optimization supported by multiple analytical approaches, as emphasized by recent engineering studies.

Process scheduling modifications could leverage the temporal stability findings to concentrate high-emission activities during periods of optimal atmospheric dispersion. While the study found no significant diurnal concentration variations, strategic scheduling approaches are supported by multiple operational studies: maintenance activities, equipment cleaning, and intensive septage discharge could be scheduled to minimize worker exposures during peak emission events, as documented by operational optimization studies including those by Yang et al. (2023) and Emmanuel et al. (2023).

4.7.5 Personal Protective Equipment and Administrative Controls

Personal protective equipment recommendations should reflect the spatial risk gradient while acknowledging the substantial safety margins observed, guided by multiple occupational health studies. The spatial concentration hierarchy (Night soil discharge area > Screening unit > Grit chamber) supports risk-based PPE strategies documented in occupational health literature. Ammad et al. (2021) evaluated PPE usage in industrial projects, while Ranasinghe et al. (2023) conducted systematic review of workplace health and safety approaches.

Night soil discharge area personnel might benefit from enhanced respiratory protection during maintenance activities, while screening and grit chamber workers could rely on administrative controls and engineering systems for routine operations. The low absolute concentrations suggest that standard PPE provides more than adequate protection, as supported by multiple occupational exposure studies, but task-specific recommendations could optimize worker comfort and acceptance, as documented by Keretetse et al. (2023) and other occupational health researchers.

Multiple studies support administrative control effectiveness: worker training programs that incorporate study findings provide evidence-based education about exposure risks and control measures, as documented by Anigilaje et al. (2024) and Mohammadi et al. (2022). The demonstrated spatial gradients provide concrete examples of how facility design and operational practices influence exposure levels, while the temporal stability findings support consistent safety practices across all shifts.

However, contradictory evidence suggests limitations: some studies indicate that PPE compliance and effectiveness vary significantly with worker training, equipment quality, and workplace culture. Comprehensive protection requires integration of multiple approaches rather than relying solely on PPE, as emphasized by recent occupational health studies including those by Yang et al. (2023) and Ranasinghe et al. (2023).

4.7.6 **Monitoring and Management Framework Development**

The study findings support development of a tiered monitoring framework that optimizes resource allocation while maintaining comprehensive exposure assessment, guided by multiple monitoring studies. Continuous monitoring could focus on the night soil discharge area where concentrations are highest and most variable, providing real-time feedback for operational adjustments and safety protocols, as supported by recent advances in environmental monitoring technology documented by Liu et al. (2025) and Saeedi et al. (2024).

Multiple approaches to monitoring optimization are documented: periodic monitoring at screening and grit chamber locations could verify continued effectiveness of control measures while reducing monitoring costs, as suggested by Dehghani et al. (2022) and other exposure assessment researchers. Environmental parameter monitoring should emphasize retention time and temperature measurements that showed the strongest correlations with BTEX concentrations, providing leading indicators of potential concentration changes as documented by multiple environmental engineering studies.

Integration of biomonitoring approaches should be considered for comprehensive exposure assessment. Recent advances in biomonitoring methodology, documented by multiple studies including De Paula Nunes et al. (2025), Dehghani et al. (2022), and Gerić et al. (2024), provide opportunities for enhanced worker protection through early detection of exposure increases before they become apparent through air monitoring alone.

However, resource constraints in developing country contexts require careful balance between monitoring comprehensiveness and cost-effectiveness. Multiple studies emphasize the importance of sustainable monitoring approaches that can be maintained over long time periods, as documented by operational sustainability studies in similar contexts.

4.8 Regional Performance Context and Technology Transfer

4.8.1 Regional Facility Performance Comparison

The superior emission control performance observed at the Gaborone facility provides important context for the broader treatment challenges documented in extensive Southern African literature. Multiple studies document regional challenges: Mabadahanye et al. (2024) identified institutional arrangements and operational challenges affecting treatment effectiveness across the Vhembe District Municipality, while Omohwovo (2024) documented that 90% of African wastewater is discharged without adequate treatment. Additional supporting evidence includes Malakane and Maphanga (2024) who found water quality deterioration in Mpumalanga's Crocodile River, and Jerie et al. (2024) who documented similar institutional challenges in Zimbabwe.

However, this study demonstrates that effective emission control can be achieved when appropriate design and operational practices are implemented. The successful BTEX management contrasts with the water quality deterioration documented by multiple regional sources, suggesting that facility-specific factors rather than inherent regional limitations determine treatment performance and worker safety outcomes.

International context supports this conclusion: successful case studies from similar developing country contexts demonstrate that effective BTEX management is achievable. Supporting evidence includes successful implementations documented by Anigilaje et al. (2024) in Nigeria when proper controls are implemented, and advances in treatment technology documented by Emmanuel et al. (2023) that are applicable to resource-constrained settings.

This finding has important implications for technology transfer and capacity building across Southern African Development Community countries facing similar water security challenges. The demonstrated effectiveness provides a replicable model for facility development, supported by multiple studies emphasizing the importance of appropriate design and operational practices rather than expensive technological solutions.

4.8.2 Institutional and Operational Factors

The success of the Gaborone facility can be attributed to multiple institutional and operational factors documented in the regional literature. Effective institutional arrangements, as emphasized by Mabadahanye et al. (2024), appear crucial for treatment facility success.

Adequate regulatory framework implementation, as discussed by Adom & Simatele (2024), provides the foundation for effective facility operation.

Multiple operational factors contribute to success: proper staff training and technical capacity, as documented by Anigilaje et al. (2024); adequate resource allocation for maintenance and operation, as emphasized by multiple regional studies; and integration of international best practices adapted for local conditions, as supported by successful case studies from similar contexts.

However, contradictory evidence shows that institutional challenges remain widespread. Many regional facilities face complex obstacles documented by multiple sources: limited technical capacity, inadequate funding, poor coordination between agencies, and insufficient regulatory enforcement. These challenges are extensively documented in the regional literature but appear to have been successfully addressed at the Gaborone facility.

4.8.3 Climate Change Adaptation and Resilience

The temperature resilience demonstrated by effective emission control across 20-38°C operating ranges provides confidence for facility performance under projected climate scenarios, supported by multiple climate adaptation studies. The operational flexibility demonstrated through effective management of varying retention times and flow rates supports adaptive management approaches needed for resilient water infrastructure, as documented by climate resilience studies in semi-arid regions.

Climate change implications for BTEX management are documented in multiple recent studies: higher temperatures may increase volatilization potential, while changing precipitation patterns could affect hydraulic loading and treatment efficiency. However, the demonstrated climate resilience suggests that well-designed facilities can maintain effective performance under changing conditions.

Adaptation strategies should incorporate multiple approaches: enhanced ventilation capacity for higher temperature periods, flexible operational protocols for varying hydraulic loads, and monitoring systems that can detect climate-related changes in emission patterns. These approaches are supported by climate adaptation literature and engineering studies emphasizing resilient infrastructure design.

4.9 Broader Environmental and Public Health Considerations

4.9.1 Wastewater Reuse Implications

The reuse of treated effluent for irrigation in the Gaborone peri-urban agricultural project creates additional exposure pathways that extend the study's relevance beyond occupational settings. The observed 87% reduction in BTEX concentrations through the preliminary treatment stage indicates substantial removal before secondary and tertiary treatment processes that would further reduce concentrations in final effluent. However, the persistence of detectable BTEX levels, particularly toluene with its high detection frequency (100%), requires assessment of potential accumulation in irrigation systems and agricultural products.

BTEX compounds demonstrate varying environmental fate characteristics that influence their behavior in soil-plant systems. Benzene and toluene show moderate soil mobility and potential for plant uptake, while ethylbenzene and xylenes tend to bind more strongly to soil organic matter, reducing bioavailability but potentially creating long-term soil contamination. The semi-arid climate conditions in Gaborone could enhance volatilization from irrigated soils, providing an additional removal mechanism that reduces accumulation risks compared to temperate regions with higher soil moisture retention.

The observed concentration levels (0.002-0.027 mg/m^3 in air, equivalent to 0.007-0.093 μg/mL in wastewater) fall below most international guidelines for agricultural water reuse. However, the lack of specific BTEX criteria in Botswana's water reuse regulations highlights the need for comprehensive monitoring that extends beyond the treatment facility to include irrigation water quality, soil concentrations, and crop tissue analysis. This expanded monitoring would provide the data foundation for evidence-based reuse guidelines that protect both agricultural productivity and public health.

The substantial BTEX reduction efficiency (87% across preliminary treatment) provides important context for the broader exposure pathway created through effluent reuse for irrigation mentioned in the problem statement. The substantial removal before secondary and tertiary treatment processes suggests minimal BTEX concentrations in final effluent, addressing potential concerns about agricultural product contamination raised in the literature review's discussion of integrated exposure pathways.

4.9.2 Regional Water Security Context

The effective BTEX management demonstrated at the Gaborone facility supports broader water security objectives in Botswana's semi-arid environment. Successful wastewater treatment and reuse reduce pressure on limited freshwater resources while providing reliable irrigation supplies for agricultural development. The low BTEX concentrations observed support expanded wastewater reuse applications that could include industrial cooling, landscape irrigation, and groundwater recharge, provided appropriate treatment and monitoring protocols are maintained.

The study findings support regional capacity building for wastewater treatment optimization in Southern African Development Community (SADC) countries facing similar water scarcity challenges. The demonstrated effectiveness of design and operational approaches suitable for semi-arid conditions provides a replicable model for facility development in comparable climatic regions. Technology transfer opportunities could focus on the passive design elements and operational practices that achieved superior emission control performance without requiring expensive technological solutions.

Climate change adaptation strategies for water management in semi-arid regions can incorporate the study findings to optimize treatment facility design for changing conditions. The temperature resilience demonstrated by effective emission control across 20-38°C operating ranges provides confidence for facility performance under projected climate scenarios. The operational flexibility demonstrated through effective management of varying retention times and flow rates supports adaptive management approaches needed for resilient water infrastructure.

4.10 Methodological Considerations and Quality Assurance

4.10.1 Analytical Approach Validation

The analytical methodology employed in this study aligns closely with quality control recommendations from multiple methodological sources. Saeedi et al. (2024) emphasized the importance of field blanks, duplicate samples, and temperature monitoring during sampling, while additional methodological guidance comes from NIOSH (2022) standards for occupational exposure sampling and quality control protocols documented by multiple analytical chemistry sources.

The observed analytical performance (field blanks <0.05 μg/mL, duplicate precision RSD 3.2-12.8%, recovery efficiency 91.7-96.1%) meets or exceeds literature benchmarks, providing confidence in data reliability for comparison with international studies. Multiple studies support these quality metrics: analytical precision standards documented by various researchers, and recovery efficiency benchmarks established through inter-laboratory comparisons.

However, methodological limitations exist: passive sampling approaches provide time-weighted averages that may miss episodic events, as noted by Masundire et al. (2020). Multiple studies emphasize the importance of complementary monitoring approaches, including both passive and active sampling methodologies, to capture complete exposure patterns.

The passive sampling approach using seven-day deployment periods represents a methodological advancement over shorter-term measurements typical of many literature studies. This approach provides robust time-weighted average concentrations suitable for occupational exposure assessment, as supported by multiple exposure assessment studies. However, trade-offs exist: weekly averaging may miss short-term peaks while providing more stable, representative measurements for regulatory compliance assessment.

4.10.2 Study Design Strengths and Limitations

The study's focus on preliminary treatment stages addresses a critical gap identified in the literature review, where most studies concentrated on secondary treatment processes with limited attention to initial emission sources. Multiple sources support this focus: Wilson & Chen (2023) identified sludge processing as significant volatilisation sources, while Rahman & Ibekwe (2020) documented emissions from handling operations.

However, this focus creates limitations for comparison with comprehensive facility assessments. Multiple comprehensive studies document concentration patterns across complete treatment trains, including aeration tanks where literature consistently reports peak concentrations. This limitation prevents direct comparison with some international studies but provides detailed insight into preliminary treatment performance.

The 18-week sampling duration substantially exceeds most literature studies but represents only partial annual coverage compared to seasonal variation studies. This temporal scope provides adequate data for occupational exposure assessment while highlighting the need for extended monitoring to capture complete seasonal patterns, as documented by multiple seasonal variation studies.

Multiple factors support the adequacy of the temporal coverage: the dry season period avoided complications from precipitation events while capturing stable operational conditions. However, seasonal limitations prevent comparison with studies documenting wet season variations, though the observed temporal stability provides valuable insights into operational consistency effects.

4.11 Study Limitations and Methodological Considerations

4.11.1 Temporal Coverage Limitations

The 18-week sampling period, while substantial for occupational exposure assessment, represents only partial coverage of Gaborone's annual climate cycle and may not capture seasonal variations that occur during the wet season (November-April). The dry season sampling period (May-September) avoided complications from precipitation events but potentially missed emission patterns associated with higher humidity, reduced temperatures, and altered operational practices during wet weather periods. Seasonal variations in wastewater composition, particularly during periods of increased industrial activity or population fluctuations, could create different BTEX input patterns not observed during the study period.

The weekly averaging approach, while providing robust trend analysis and reducing measurement uncertainty, may have masked short-term concentration peaks associated with specific operational activities. Septage discharge events, equipment maintenance activities, and process upsets could create temporary exposures exceeding weekly averages, potentially representing higher acute exposure risks than indicated by time-weighted average measurements. High-frequency monitoring during selected intensive operational periods would provide valuable supplementary data about peak exposure potential.

The fixed sampling schedule may have missed episodic events that contribute disproportionately to cumulative exposure. Emergency situations, equipment failures, or unusual operational requirements could create emission patterns not captured by routine weekly sampling. Future monitoring strategies should incorporate event-triggered sampling protocols that activate during unusual operational conditions to provide comprehensive exposure assessment.

4.11.2 Analytical and Methodological Constraints

The passive sampling approach, while appropriate for occupational exposure assessment, provides time-weighted average concentrations that may not accurately represent peak exposures experienced during specific work tasks. Active sampling during high-emission activities would complement passive monitoring by characterizing task-specific exposure patterns relevant for job-specific safety protocols. The seven-day sampling period represents a compromise between analytical precision and temporal resolution that may not optimize detection of either long-term trends or short-term variations.

The focus on air concentrations, while directly relevant to inhalation exposure, does not address potential dermal exposure pathways that could be significant during direct contact with wastewater or contaminated surfaces. Dermal exposure assessment would require different sampling approaches and analytical methods, but could contribute substantially to total BTEX exposure for workers involved in maintenance, cleaning, or emergency response activities.

The limited number of comparable studies from similar climatic and operational conditions constrains comparative analysis and generalization of findings. Most published BTEX emission studies originate from temperate climate facilities with different design standards, operational practices, and regulatory frameworks. This limitation highlights the need for expanded research networks in developing regions to establish appropriate benchmarks and best practices for local conditions.

4.11.3 Facility-Specific Considerations

The study findings reflect the specific design and operational characteristics of the Gaborone facility, which may not be representative of other wastewater treatment plants in the region. The relatively new facility incorporates modern design standards and operational practices that may not be typical of older installations or facilities with different funding levels, technical capacity, or regulatory requirements. Generalization of findings to other facilities should consider these design and operational differences carefully.

The predominance of domestic wastewater (95%) with limited industrial inputs (5%) creates a BTEX source profile that may differ substantially from facilities serving areas with higher industrial activity. Facilities processing larger fractions of industrial wastewater, particularly from petroleum, chemical, or manufacturing industries, could experience significantly different BTEX emission patterns requiring adapted monitoring and control strategies.

The specific combination of semi-arid climate, elevation (approximately 1000m), and prevailing wind patterns at the Gaborone site creates atmospheric conditions that influence emission dispersion and accumulation. Facilities in different geographic settings, even within similar climatic regions, could experience different atmospheric mixing patterns that alter worker exposure levels despite similar emission rates.

4.11.4 Regional Representation

The study's focus on a single, well-designed facility may not represent typical conditions across Southern African treatment installations, particularly given the widespread performance challenges documented by Omohwovo (2024) and others. This limitation affects the generalizability of findings to broader regional contexts.

4.12 Novel Discoveries and Knowledge Contributions

4.12.1 Climate Resilience of Emission Control

This study provides the first documented evidence that effective BTEX emission control can be maintained under challenging semi-arid climate conditions through appropriate facility design and operational practices. The reduced temperature sensitivity (10-15% variation vs. 15-30% predicted) represents a novel finding that challenges fundamental assumptions about climate effects on volatilisation in occupational exposure contexts.

4.12.2 Preliminary Treatment Effectiveness

The exceptional removal efficiency (87%) achieved using only preliminary treatment processes contradicts literature expectations and represents a significant advancement in understanding BTEX removal mechanisms. This finding suggests that enhanced volatilisation and atmospheric dispersion can achieve removal rates comparable to biological treatment systems, providing important insights for treatment design optimization.

4.12.3 Operational Stability Achievement

The demonstration that consistent operational practices can maintain temporal stability in BTEX concentrations despite variable environmental conditions provides novel insights into facility management approaches. The observed stability ($p > 0.94$ for temporal variations) contradicts literature reports of significant diurnal variations and provides practical guidance for operational optimization.

4.13 Chapter Summary

Chapter 4 provided a comprehensive discussion of BTEX characterisation findings at the Gaborone wastewater treatment plant within existing literature contexts. The chapter successfully resolved the primary problem statement by demonstrating that all BTEX concentrations (0.002-0.027 mg/m^3) remained substantially below international occupational exposure limits, with safety margins ranging from 29:1 to over 39,000:1. Key findings included significant spatial variations across treatment stages with 87% reduction efficiency, temporal stability throughout daily operations, and toluene dominance in emission profiles. The study revealed exceptional climate resilience with reduced temperature sensitivity compared to literature predictions, contradicting assumptions about semi-arid climate effects on volatilisation. Facility-specific design factors including strategic ventilation, optimised hydraulic patterns, and gravity flow systems contributed to superior emission control performance. The chapter examined long-term worker health implications, biomonitoring considerations, and regional implementation challenges while identifying novel discoveries in preliminary treatment effectiveness and operational stability that advance understanding of BTEX behaviour in developing region wastewater treatment contexts.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This final chapter synthesizes the key findings from the characterization of occupational exposure to BTEX compounds at the Gaborone Wastewater Treatment Plant and provides comprehensive conclusions based on the research objectives. The study successfully addressed the fundamental knowledge gap identified in Chapter 1 regarding the systematic characterisation of occupational exposure to BTEX compounds among workers at wastewater treatment facilities in Southern African contexts. Through rigorous 18-week monitoring across three treatment stages at the Gaborone Wastewater Treatment Plant, the research has provided the first evidence-based assessment of BTEX exposure patterns in semi-arid climatic conditions, establishing crucial baseline data that challenges several assumptions about climate-driven exposure risks in developing regions.

This chapter presents a comprehensive summary of research findings, outlines evidence-based recommendations for occupational health protection and facility management, acknowledges study limitations, discusses theoretical and practical implications, and identifies priority directions for future research. The conclusions drawn from this investigation contribute significantly to the limited knowledge base for BTEX exposure assessment in developing country contexts while providing practical guidance for worker protection strategies in similar facilities across Southern Africa and other semi-arid regions.

5.2 Summary of the Research Findings

5.2.1 Primary Findings and Problem Statement Resolution

This study has successfully addressed the fundamental knowledge gap identified in Chapter 1 regarding the systematic characterisation of occupational exposure to BTEX compounds among workers at wastewater treatment facilities in Southern African contexts. Through rigorous 18-week monitoring across three treatment stages at the Gaborone Wastewater Treatment Plant, the research has provided the first evidence-based assessment of BTEX exposure patterns in semi-arid climatic conditions, establishing crucial baseline data that challenges several assumptions about climate-driven exposure risks in developing regions.

The study's primary findings demonstrate that effective BTEX emission control can be achieved through appropriate facility design and operational practices, even under challenging environmental conditions. All measured BTEX concentrations (0.002-0.027 mg/m^3) remained substantially below international occupational exposure limits, with safety margins ranging from 29:1 to over 39,000:1 relative to NIOSH REL and OSHA PEL standards. This finding directly contradicts the anticipated problem that unique environmental conditions in Botswana, characterised by high temperatures and intense solar radiation, would make international standards potentially inappropriate for local conditions. Instead, the research demonstrates that well-designed facilities can provide excellent worker protection while maintaining operational efficiency, supporting the continued application of international guidelines when properly implemented through effective facility design and operational practices.

5.2.2 Spatial and Temporal Concentration Patterns

The spatial concentration gradient observed across treatment stages (87% reduction from night soil discharge area to grit chamber) establishes a clear hierarchy that supports targeted intervention strategies while demonstrating the effectiveness of treatment process design in managing volatile emissions. The night soil discharge area exhibited the highest concentrations (mean 0.027 mg/m^3), followed by the screening unit (mean 0.009 mg/m^3) and grit chamber (mean 0.002 mg/m^3), creating a systematic pattern that enables location-specific safety protocols and resource allocation for exposure control measures. This spatial variability, while statistically significant ($p < 0.001$ for all compounds with large effect sizes $\eta^2 > 0.7$), maintained substantial safety margins even in the highest-exposure areas.

Perhaps most significantly, the study revealed unexpected temporal stability across daily operations, with no statistically significant diurnal variations (ANOVA p-values: 0.948-0.997) despite documented temperature fluctuations ranging from 20.0-38.0°C. This finding challenges fundamental assumptions about temperature-driven volatilisation patterns documented in previous literature and suggests that operational parameters can effectively override environmental factors that typically influence BTEX emissions. The reduced climate sensitivity (10-15% variation vs. 15-30% predicted from literature) represents a novel discovery that advances understanding of BTEX behavior in wastewater treatment systems and provides practical guidance for facility design and operational optimization in similar climatic conditions.

5.2.3 Novel Mechanistic Insights

The research contributes several mechanistic insights that advance theoretical knowledge of BTEX behavior in treatment systems. The stronger correlation between retention time ($r = 0.445-0.598$) and BTEX concentrations compared to temperature effects challenges current mechanistic models that emphasize temperature-driven volatilization as the primary factor. This finding, combined with the systematic 6-fold concentration differences between treatment locations that exceed typical reported ranges, indicates that facility-specific design and turbulence patterns may be more influential than previously recognized. The operational parameter stability demonstrated through consistent concentration patterns despite variable environmental conditions provides novel insights into facility management approaches that can maintain system performance across varying climatic conditions.

5.2.4 Compound-Specific Findings and Regional Context

From a regional perspective, this study provides crucial evidence that contradicts widespread assumptions about treatment performance limitations in Southern African contexts. While Omohwovo (2024) documented that 90% of African wastewater is discharged without adequate treatment, and regional studies by Mabadahanye et al. (2024) and Malakane and Maphanga (2024) revealed institutional challenges and treatment failures, the Gaborone facility demonstrates that effective emission control can be achieved when appropriate design and operational practices are implemented. This finding suggests that institutional and operational factors, rather than inherent regional limitations, primarily determine treatment effectiveness and worker safety outcomes in developing country contexts.

The study's implications extend beyond immediate occupational exposure concerns to broader public health considerations related to wastewater reuse for agricultural irrigation. The demonstrated effectiveness of BTEX removal (87% across preliminary treatment stages) before secondary and tertiary treatment processes suggests minimal BTEX concentrations in final effluent, supporting sustainable water management objectives while maintaining appropriate health protection standards. This integrated approach aligns with current best practices for wastewater reuse in water-scarce regions and establishes a foundation for comprehensive exposure pathway assessment extending from wastewater treatment through agricultural application to consumer protection.

5.3 Recommendations

5.3.1 Engineering Control Enhancement Strategies

5.3.1.1 Facility Design Optimization for Emission Reduction

The superior emission control performance demonstrated at the Gaborone facility, which achieved 87% BTEX reduction across preliminary treatment stages, provides a foundation for developing enhanced engineering control strategies building upon successful approaches documented in the literature. Bencsik et al. (2024) published comprehensive plant-wide simulation frameworks adhering to International Water Association Good Modelling Practice Guidelines, demonstrating that "stricter effluent quality regulations necessitate BTEX removal, especially with concerns about organic micropollutant concentrations." Their research reveals that while biological treatment achieves partial BTEX reduction through biodegradation and sorption, "additional purification using physico-chemical methods is crucial for substantial reduction."

Priority interventions should focus on the night soil discharge area, where the highest BTEX concentrations were observed, through implementation of localized exhaust ventilation systems positioned directly above discharge points. This approach aligns with findings from Kong et al. (2021) who documented that zones with surface turbulence can exhibit BTEX concentrations 3-5 times higher than calm zones within the same treatment stage. The observed spatial concentration hierarchy in the current study (Night soil discharge area > Screening unit > Grit chamber) supports targeted interventions recommended by Emmanuel et al. (2023) who emphasized workplace design and ventilation systems as critical risk factors.

Facility-wide ventilation optimization should leverage the observed correlation patterns between environmental parameters and BTEX concentrations, particularly the strong correlation between retention time and BTEX concentrations ($r = 0.523$) that exceeds temperature effects ($r = 0.342$). This finding contradicts expectations from Chang et al. (2022) who reported 15-30% increases in volatilisation rates for every 10°C temperature rise, suggesting that hydraulic modifications could provide substantial emission reductions through optimized flow patterns that minimize surface exposure duration while maintaining treatment effectiveness.

5.3.1.2 Advanced Monitoring and Control Integration

Real-time BTEX monitoring systems should be integrated with facility control systems based on successful approaches demonstrated in the literature. Yasuda et al. (2021) achieved 94.8% overall average removal efficiency using integrated water scrubbing followed by biotrickling filtration, with outlet concentrations of 1.02, 0.25, 0.32, and 0.26 mg Nm^{-3} for benzene, toluene, ethylbenzene, and xylene, respectively. Their two-stage system proved effective with "the water scrubber demonstrating ability to remove concentration peaks, whereas the biotrickling filter was effective as a polishing stage."

Atmospheric dispersion modeling capabilities should incorporate insights from studies by Emmanuel et al. (2023) who demonstrated that wind speeds above 3 m/s can significantly affect BTEX concentration patterns, potentially creating areas of high exposure downwind of pollution sources. The integration of meteorological monitoring with facility control systems would enable preemptive activation of enhanced ventilation systems during periods of reduced atmospheric dispersion, preventing accumulation of volatile compounds in worker areas.

Process automation enhancements should build upon findings from Davidson et al. (2021) who demonstrated that increasing aeration rates from 0.5 to 2.0 m^3/hour can boost BTEX volatilisation by 40-60%. Automated septage discharge systems could reduce direct worker exposure during the highest-emission activity, while remote monitoring capabilities would enable operators to oversee processes from control rooms positioned in areas of minimal exposure risk.

5.3.2 Administrative Control and Training Program Development

5.3.2.1 Comprehensive Worker Education and Training Frameworks

Evidence-based training programs should be developed incorporating the specific findings of this study and lessons learned from international best practices documented in the literature. Anigilaje et al. (2024) identified seven critical risk factors determining worker vulnerability in petroleum sector contexts: workplace design, ventilation systems, work duration, personal protective equipment availability, regulatory enforcement, worker training, and environmental conditions. These factors provide a framework for developing comprehensive training curricula that emphasize the spatial concentration gradients observed across treatment areas.

The demonstrated temporal stability of concentrations throughout daily operations (ANOVA p-values: 0.948-0.997) supports consistent safety practices across all shifts, contrasting with findings from Abebe et al. (2023) who documented concentration variations up to twice the levels during peak temperature periods. Training should address this facility-specific advantage while maintaining vigilance for concentration variations during unusual operational conditions or maintenance activities.

Job-specific training modules should be developed for each treatment area based on the observed exposure patterns and literature recommendations. Dehghani et al. (2022) emphasized that "wastewater treatment plants should be considered as one of the workplaces with potential sources of BTEX exposure for employees," supporting the need for enhanced training on emission source recognition, peak exposure periods, and protective measures during high-emission activities.

5.3.2.2 Health Surveillance and Medical Monitoring Programs

Comprehensive health surveillance programs should be implemented building upon biomonitoring advances documented in recent literature. Dehghani et al. (2022) conducted groundbreaking biological monitoring of wastewater treatment plant workers, measuring urinary metabolites including trans,trans-muconic acid, hippuric acid, methyl hippuric acid, mandelic acid, and phenylglyoxylic acid. Their findings that "most metabolites exceeded occupational threshold limit values" establish the need for systematic biomonitoring programs that can detect actual exposure levels and verify the effectiveness of control measures.

Pre-employment medical examinations should establish baseline health status including complete blood counts, liver function tests, and neurological assessments, as recommended in occupational health guidelines. The substantial safety margins observed in the current study (29:1 to >39,000:1 relative to occupational exposure limits) support preventive rather than corrective medical monitoring approaches, focusing on early detection of exposure-related health changes before clinical symptoms develop.

Specialized medical monitoring should be provided for workers in high-exposure areas, particularly the night soil discharge area where concentrations were highest. Enhanced surveillance frequency and comprehensive biomarker assessment would enable early detection of exposure-related health changes. This approach aligns with Kuranchie et al. (2019) findings in Ghana where pump attendants faced elevated risks due to poor safety practices and lack of exposure controls.

5.3.3 Regulatory Framework Development and Implementation

5.3.3.1 National Occupational Health Standards for Developing Countries

Botswana should develop national occupational exposure limits for BTEX compounds specifically adapted for local climatic conditions and operational practices, building upon international frameworks while addressing regional specificities. The current reliance on international standards developed for temperate climates may not adequately address the unique exposure patterns observed in semi-arid environments, as demonstrated by the reduced temperature sensitivity (10-15% variation vs. 15-30% predicted) observed in this study compared to Chang et al. (2022) findings.

The ILO's Global Strategy on Occupational Safety and Health 2024-2030 emphasizes that occupational safety and health has been recognized as "a fundamental principle and right at work." Key ILO instruments relevant to BTEX exposure include the Benzene Convention (1971), Chemicals Convention (1990), and Working Environment Convention (1977), providing international legal frameworks that can be adapted for local implementation. Current international occupational exposure limits demonstrate significant variations across organizations, with WHO guidelines recommending zero exposure for benzene due to its carcinogenic properties, while NIOSH establishes a recommended exposure limit of 0.319 mg/m^3, and OSHA maintains a permissible exposure limit of 3.19 mg/m^3.

Regulatory frameworks should mandate comprehensive exposure assessment for all wastewater treatment facilities, extending beyond the preliminary treatment focus of this study to include secondary treatment areas where Dehghani, Mohammadpour, et al. (2022) documented 2-5 times higher BTEX concentrations above aeration tanks. Standardized monitoring protocols should account for spatial and temporal variations in exposure patterns, ensuring consistent assessment approaches across different facilities and climatic regions.

5.3.3.2 Regional Coordination and Technology Transfer Initiatives

Southern African Development Community countries should establish coordinated approaches to BTEX exposure management building upon successful strategies demonstrated at the Gaborone facility and documented best practices in the literature. Omohwovo (2024) reported that "90% of wastewater generated globally is discharged into the environment without any prior treatment," with African countries particularly struggling with inadequate treatment infrastructure. Technology transfer programs should focus on replicable design elements and operational practices that achieved superior emission control performance without requiring expensive technological solutions.

Regional research collaborations should be established based on findings from Mabadahanye et al. (2024) who identified complex institutional setups, practical limitations, and environmental concerns as major obstacles facing water and wastewater treatment plants in the Vhembe District Municipality, South Africa. Multi-facility studies across different climatic and operational conditions would enable development of exposure benchmarks appropriate for regional applications while identifying best practices for emission control.

International cooperation programs should leverage WHO and ILO frameworks to access technical expertise and funding for implementation of enhanced control measures. The WHO collaboration with ILO on the International Chemical Safety Cards (ICSC) program provides hazard and safety information on chemicals including BTEX compounds that can support regional capacity building efforts. These collaborations should emphasize sustainable approaches that can be maintained with local resources rather than requiring ongoing external support.

5.3.4 Economic and Implementation Considerations

5.3.4.1 Cost-Benefit Analysis of Control Measure Implementation

Comprehensive economic analysis should be conducted building upon successful cost-effective approaches documented in the literature. Song et al. (2025) demonstrated flexible carbon source regulation for mitigating greenhouse gas emissions in full-scale wastewater treatment, showing how operational strategies can simultaneously address BTEX removal and environmental sustainability. The substantial safety margins observed in this study (29:1 to >39,000:1) suggest that aggressive engineering controls may not be immediately necessary from an acute health protection perspective, but long-term health benefits and regulatory compliance considerations may justify investment in enhanced control systems.

Mao et al. (2025) developed comprehensive techno-economic models for wastewater treatment optimization, providing frameworks for balancing treatment efficiency with economic constraints. Implementation priorities should be established based on risk assessment results, with immediate attention focused on areas where cost-effective improvements could provide substantial exposure reductions. The night soil discharge area represents the highest priority for intervention based on observed concentration levels and literature recommendations.

Financing mechanisms should be developed to support implementation of control measures in resource-constrained settings, considering the broader regional challenges documented by Malakane and Maphanga (2024) who found significant water quality deterioration downstream of treatment facilities in Mpumalanga, South Africa. Public-private partnerships could leverage private sector expertise for facility improvements while maintaining public sector oversight of worker protection objectives.

5.3.4.2 Sustainable Implementation Strategies

Phased implementation approaches should be developed based on successful models documented in advanced treatment literature. Perez et al. (2025) introduced integrated plant-wide models for tracking chemical releases in wastewater systems, offering powerful tools for monitoring BTEX behavior throughout treatment trains. These models enable real-time optimization of treatment processes to minimize both environmental discharge and workplace exposure risks.

Local capacity building should be prioritized to ensure sustainable operation and maintenance of enhanced control systems, addressing challenges identified in regional literature. Jerie et al. (2024) examined environmental and human health problems associated with wastewater management in Zimbabwe, revealing institutional and operational challenges that mirror those affecting municipal treatment facilities. Training programs should develop local expertise in exposure assessment, control system design, and maintenance practices to reduce dependence on external technical support.

Technology adaptation should emphasize solutions appropriate for local conditions and resource availability, building upon successful approaches documented in the literature. Davies et al. (2024) demonstrated that drinking water treatment residuals and mine water treatment sludge effectively support BTEX removal through anaerobic processes, showing that locally available materials can achieve effective treatment performance. Control strategies should be designed for maintainability with locally available materials and expertise while meeting international performance standards for worker protection.

These comprehensive mitigation strategies and policy recommendations, grounded in extensive literature review and successful international practices, provide a framework for advancing worker protection beyond the current adequate but potentially improvable conditions observed at the Gaborone facility. Implementation of these evidence-based recommendations would establish Botswana as a regional leader in occupational health protection for wastewater treatment workers while providing replicable models for broader application across Southern Africa and other developing regions facing similar challenges.

5.4 Limitations of the Study

5.4.1 Temporal and Spatial Coverage Constraints

The 18-week sampling period, while substantial for occupational exposure assessment, represents only partial coverage of Gaborone's annual climate cycle and may not capture seasonal variations that occur during the wet season (November-April). The dry season sampling period (May-September) avoided complications from precipitation events but potentially missed emission patterns associated with higher humidity, reduced temperatures, and altered operational practices during wet weather periods. Seasonal variations in wastewater composition, particularly during periods of increased industrial activity or population fluctuations, could create different BTEX input patterns not observed during the study period.

The study's scope is significantly limited by its focus on preliminary treatment areas (night soil discharge, screening unit, grit chamber), missing secondary treatment areas where Dehghani, Mohammadpour, et al. (2022) documented 2-5 times higher BTEX concentrations above aeration tanks. This limitation affects the broader applicability of findings to comprehensive occupational health management, as most worker exposure occurs in secondary treatment areas not examined in this study.

The weekly averaging approach, while providing robust trend analysis and reducing measurement uncertainty, may have masked short-term concentration peaks associated with specific operational activities. Septage discharge events, equipment maintenance activities, and process upsets could create temporary exposures exceeding weekly averages, potentially representing higher acute exposure risks than indicated by time-weighted average measurements.

5.4.2 Methodological and Analytical Constraints

The passive sampling approach, while appropriate for occupational exposure assessment, provides time-weighted average concentrations that may not accurately represent peak exposures experienced during specific work tasks. The study measured ambient air concentrations but did not assess personal exposure using breathing zone monitoring, limiting its direct occupational health relevance compared to biomonitoring approaches demonstrated by Dehghani et al. (2022).

The focus on air concentrations, while directly relevant to inhalation exposure, does not address potential dermal exposure pathways that could be significant during direct contact with wastewater or contaminated surfaces. Dermal exposure assessment would require different sampling approaches and analytical methods, but could contribute substantially to total BTEX exposure for workers involved in maintenance, cleaning, or emergency response activities.

The study did not address cumulative exposure or synergistic effects of BTEX mixtures that workers may experience, which are increasingly recognized as important occupational health considerations. The limited number of comparable studies from similar climatic and operational conditions constrains comparative analysis and generalization of findings.

5.4.3 Facility-Specific and Regional Representation Limitations

The study findings reflect the specific design and operational characteristics of the Gaborone facility, which may not be representative of other wastewater treatment plants in the region. The relatively new facility incorporates modern design standards and operational practices that may not be typical of older installations or facilities with different funding levels, technical capacity, or regulatory requirements.

The predominance of domestic wastewater (95%) with limited industrial inputs (5%) creates a BTEX source profile that may differ substantially from facilities serving areas with higher industrial activity. Facilities processing larger fractions of industrial wastewater, particularly from petroleum, chemical, or manufacturing industries, could experience significantly different BTEX emission patterns requiring adapted monitoring and control strategies.

The study's focus on a single, well-designed facility may not represent typical conditions across Southern African treatment installations, particularly given the widespread performance challenges documented by Omohwovo (2024) and others. This limitation affects the generalizability of findings to broader regional contexts where institutional, operational, and resource constraints may create substantially different exposure scenarios.

5.5 Implications of the Study to Both Theory and Practice

5.5.1 Theoretical Contributions and Knowledge Advancement

This research makes several significant theoretical contributions to the understanding of BTEX behavior in wastewater treatment systems, particularly under semi-arid climatic conditions. The finding that retention time demonstrates stronger correlations with BTEX concentrations ($r = 0.445$-0.598) than temperature ($r = 0.298$-0.387) challenges current mechanistic models that emphasize temperature-driven volatilization as the primary factor controlling emissions. This discovery advances theoretical understanding by demonstrating that hydrodynamic parameters may be more critical than previously recognized in semi-arid climates, contradicting fundamental assumptions about environmental factor dominance in BTEX volatilisation processes.

The observed temporal stability across daily operations (ANOVA p-values: 0.948-0.997) despite significant temperature fluctuations (20.0-38.0°C) represents a novel theoretical insight that challenges established understanding of diurnal variation patterns documented in multiple previous studies. This finding suggests that operational parameters can effectively override environmental factors that typically influence BTEX emissions, advancing theoretical frameworks for understanding facility-specific factors versus climatological influences in emission control.

The exceptional removal efficiency (87%) achieved using only preliminary treatment processes contradicts literature expectations and represents a significant advancement in understanding BTEX removal mechanisms. This finding challenges theoretical models that emphasize biological processes as essential for substantial BTEX reduction, suggesting that enhanced volatilisation and atmospheric dispersion can achieve removal rates comparable to biological treatment systems under appropriate conditions.

5.5.2 Practical Applications and Implementation Insights

The practical implications of this research extend significantly beyond the immediate study context, providing evidence-based guidance for facility design, operational optimization, and worker protection strategies across similar climatic and operational conditions. The demonstrated effectiveness of facility-specific design elements and operational practices in maintaining BTEX concentrations well below international safety thresholds provides a replicable model for treatment facilities in developing regions facing similar resource constraints and climatic challenges.

The spatial concentration hierarchy identified through statistical analysis (Night soil discharge area > Screening unit > Grit chamber) provides practical guidance for resource allocation and intervention prioritization in similar facilities. This finding enables evidence-based development of location-specific safety protocols, targeted ventilation strategies, and risk-based personal protective equipment requirements that optimize worker protection while minimizing implementation costs.

The temporal stability findings have immediate practical applications for operational scheduling and worker protection protocols. The absence of significant diurnal variations supports consistent safety practices across all shifts without requiring complex time-specific restrictions or enhanced protection during particular periods, simplifying implementation while maintaining effective worker protection.

5.5.3 Regional and Global Context Implications

The successful demonstration of effective BTEX emission control under challenging semi-arid conditions provides important evidence that contradicts widespread assumptions about treatment performance limitations in developing regions. This finding has significant implications for technology transfer, capacity building, and policy development across

Southern African Development Community countries and other developing regions facing similar water security challenges.

The research contributes crucial baseline data that supports evidence-based policy development for wastewater treatment facility regulation and occupational health protection in developing regions. The findings demonstrate that international guidelines can provide appropriate protection when properly implemented through effective facility design and operational practices, supporting broader adoption of international best practices adapted for local conditions.

The study's methodology and findings provide guidance for similar research in comparable settings while contributing to the global knowledge base for sustainable wastewater management in semi-arid regions. The demonstrated feasibility of effective emission control in resource-constrained settings supports broader environmental protection and public health objectives across the developing world.

5.5.4 Long-term Health Protection and Risk Assessment

The substantial safety margins observed (29:1 to >39,000:1 relative to occupational exposure limits) provide important insights for long-term health protection strategies and risk assessment approaches in similar facilities. While current measurements indicate safe exposure conditions based on ambient air concentrations, the research highlights the critical need for expanded biomonitoring approaches and comprehensive exposure pathway assessment to support comprehensive worker protection.

The dominance of toluene (48.7% of total VOCs with 100% detection frequency) and its documented bioaccumulation potential emphasize the importance of biological monitoring programs that can assess actual worker exposure levels beyond ambient air measurements. This finding has practical implications for medical surveillance program development and long-term health protection strategies that account for cumulative exposure effects over career-long employment periods.

The research establishes essential baseline data that justifies expanded investigations including biomonitoring approaches, complete treatment train assessment, and integrated exposure pathway studies. These insights provide practical guidance for developing comprehensive worker protection strategies that address both immediate safety concerns and long-term health protection objectives.

5.6 Directions for Future Research

5.6.1 Expanded Temporal and Spatial Coverage

Future research should extend monitoring duration to capture complete annual cycles, including wet season variations that could alter both emission patterns and control system effectiveness. Year-round monitoring would provide comprehensive baseline data for regulatory development and enable assessment of seasonal operational adaptations needed for consistent exposure control. Multi-year studies would capture inter-annual variability and support development of long-term emission trends that inform facility management and regulatory planning.

Expanded spatial coverage should include additional treatment stages beyond the preliminary treatment focus of this study. Secondary treatment processes (aeration tanks, clarifiers) and sludge handling operations (thickening, dewatering, and drying) could generate different BTEX emission patterns requiring specific control measures. Comprehensive facility assessment would support development of integrated emission management strategies that address all potential exposure sources.

Regional comparative studies across multiple facilities would enable development of emission benchmarks appropriate for semi-arid climate conditions and typical operational practices in developing regions. Multi-facility studies could identify best practices for emission control while accounting for differences in facility design, operational capacity, and regulatory frameworks. Regional research networks could facilitate technology transfer and capacity building while generating the data foundation for evidence-based policy development.

5.6.2 Comprehensive Facility Assessment

Future research should extend monitoring to complete treatment trains including secondary treatment processes to validate or contradict the concentration patterns reported in literature studies like Allahabady et al. (2022). This comprehensive approach would enable direct comparison with international studies and provide complete facility emission profiles.

5.6.3 Enhanced Mechanistic Understanding

Advanced monitoring approaches should incorporate real-time measurement techniques that can capture rapid concentration changes associated with specific operational activities. Continuous monitoring systems could provide high-resolution data about emission patterns during equipment maintenance, process upsets, and peak operational periods that contribute disproportionately to worker exposure. Real-time data would support development of adaptive control strategies that respond dynamically to changing emission conditions.

Process modeling studies should integrate the observed emission patterns with mass transfer principles to develop predictive capabilities for exposure management. Mathematical models incorporating facility-specific design parameters, operational variables, and atmospheric conditions could support optimization of emission control strategies and prediction of exposure changes resulting from operational modifications. Validated models would facilitate design optimization for new facilities and retrofitting strategies for existing installations.

Mechanistic studies should investigate the specific design elements and operational practices responsible for the superior emission control performance observed at the Gaborone facility. Detailed engineering analysis of ventilation systems, hydraulic design, and process integration could identify replicable best practices for implementation at other facilities. This technical knowledge transfer would accelerate improvement of emission control performance across the broader wastewater treatment sector.

5.6.4 Seasonal Variation Studies

Year-round monitoring studies are needed to resolve the contradictory seasonal concentration patterns identified in the literature review. Such studies would determine whether the temporal stability observed during this dry season period extends to wet season conditions and provide comprehensive annual exposure assessments.

5.6.5 Regional Comparative Assessment

Multi-facility studies across Southern African contexts would determine whether the superior performance observed at the Gaborone facility represents achievable regional standards or exceptional circumstances. This research would support technology transfer and capacity building initiatives while establishing regional performance benchmarks.

5.6.6 Integrated Exposure Assessment

Comprehensive exposure pathway studies should extend monitoring beyond occupational settings to include community exposure through wastewater reuse applications. Integrated assessment of BTEX concentrations in treated effluent, irrigation water, soil, and agricultural products would provide complete exposure pathway characterization needed for evidence-based reuse guidelines. This ecosystem approach would support sustainable wastewater management while protecting public health.

Health risk assessment studies should integrate the observed exposure levels with dose-response relationships to quantify health risks for both workers and community members. Probabilistic risk assessment approaches could account for exposure variability, population sensitivity differences, and multiple exposure pathways to provide comprehensive health protection guidance. Risk-based exposure limits could optimize protection while avoiding unnecessarily restrictive operational constraints.

Technology evaluation studies should assess advanced treatment and control technologies for further emission reduction if required by changing regulatory standards or operational objectives. Biological treatment systems, advanced oxidation processes, and enhanced ventilation technologies could provide additional emission reduction capabilities while maintaining economic feasibility. Technology assessment should consider both technical performance and economic sustainability for developing region applications.

5.7 Conclusion

This study successfully resolved the primary problem identified in Chapter 1 by providing the first systematic characterisation of occupational exposure to BTEX compounds in Southern African wastewater treatment contexts. The findings demonstrate that effective emission control can be achieved even under challenging semi-arid climate conditions, contradicting assumptions about international standard inadequacy for regional applications.

This study provides crucial baseline data about BTEX exposures at wastewater treatment facilities in semi-arid climates, addressing a significant knowledge gap in occupational health and environmental protection. The findings demonstrate that effective emission control can be achieved through appropriate facility design and operational practices, providing a replicable model for similar installations in developing regions. The substantial safety margins observed (29:1 to >39,000:1 relative to occupational exposure limits) indicate that well-designed facilities can provide excellent worker protection while maintaining operational efficiency.

The spatial concentration gradient (87% reduction from night soil discharge to grit chamber) demonstrates the effectiveness of treatment process design in managing volatile emissions, while the temporal stability across daily operations supports consistent safety protocols without complex time-specific restrictions. The moderate correlations with environmental parameters (retention time $r = 0.523$, temperature $r = 0.342$) provide guidance for operational optimization that could further enhance emission control if required by changing standards or operational objectives.

The research contributes several novel insights to the literature: reduced climate sensitivity of BTEX volatilisation under appropriate facility management, exceptional removal efficiency achievable through preliminary treatment optimization, and operational approaches for maintaining temporal stability despite environmental variability. These findings advance understanding of BTEX behavior in wastewater treatment systems while providing practical guidance for facility design and operational optimization.

The superior emission control performance compared to similar facilities in temperate regions challenges conventional assumptions about climate effects on volatilization and demonstrates that facility-specific factors can override general climatological effects. The detailed mechanistic explanations provided for mass transfer processes, facility design factors, and operational parameter interactions advance scientific understanding of BTEX behavior in wastewater treatment systems and provide practical guidance for emission control optimization.

The study resolves critical contradictions identified in the literature review regarding seasonal concentration patterns, environmental parameter effects, and treatment efficiency expectations. The demonstrated superior performance compared to regional benchmarks provides evidence that institutional and operational factors, rather than inherent regional limitations, primarily determine treatment effectiveness and worker safety outcomes in developing country contexts.

The study's implications extend beyond occupational exposure to include broader public health considerations related to wastewater reuse for agricultural irrigation. The demonstrated effectiveness of BTEX removal through treatment processes supports sustainable water management objectives while highlighting the need for comprehensive monitoring of complete exposure pathways from wastewater to consumers. This integrated approach aligns with current best practices for wastewater reuse in water-scarce regions while maintaining appropriate health protection standards.

The research contributes to evidence-based policy development for wastewater treatment facility regulation and occupational health protection in developing regions. The findings support adoption of international best practices adapted for local conditions while providing practical guidance for facility design, operational optimization, and worker safety programs. The demonstrated feasibility of effective emission control in resource-constrained settings supports broader environmental protection and public health objectives across the developing world.

Finally, this research establishes a foundation for continued monitoring and improvement of wastewater treatment facility performance, supporting both immediate worker safety objectives and long-term environmental sustainability goals. The methodological approaches and findings provide guidance for similar research in comparable settings while contributing to the global knowledge base for sustainable wastewater management in semi-arid regions. The study establishes a foundation for evidence-based policy development, technology transfer, and capacity building across Southern African wastewater treatment facilities, supporting both immediate worker safety objectives and long-term environmental sustainability goals while contributing to the global knowledge base for sustainable wastewater management in semi-arid regions.

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APPENDICES

Appendix A: Plagiarism declaration form

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 GOLEBAONE SENAI (Student number: 2503100) am a student registered for the degree of MSc MEDICINE - EXPOSURE SCIENCE in the academic year 2025.

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: 15/08/25

1

Appendix B: Research ethics clearance 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

11/11/2024

Ref: W-PR-241111-02

TO WHOM IT MAY CONCERN

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

Investigator: Ms G Serai
Student No. (if appropriate): 2503100
Staff No. (if appropriate):

Supervisor: Dr G Keretetse

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

Project title: *Characterisation of occupational exposure to benzene, toluene, ethylbenzene and xylene associated with waste-water treatment works in Gaberone, Botswana*

Degree: MSc (Med)

Reason: Environmental surveillance project
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/

SKC diffusive samplers were deployed for BTEX measurement following standardised protocols.

1. Installation specifications:
   a. Mounted at 1.5 meters above ground level to represent breathing zone height
   b. Minimum of 3 samplers per treatment stage to ensure representative sampling
   c. Samplers positioned away from direct water spray or physical interference
   d. Each sampling location marked with permanent identification tags

2. Sampling duration

   Sampling duration was 7-day exposure periods to capture weekly average concentrations, and samplers were changed at consistent intervals (every Monday morning). The sampling period took a total of 18weeks to account for temporal variations.

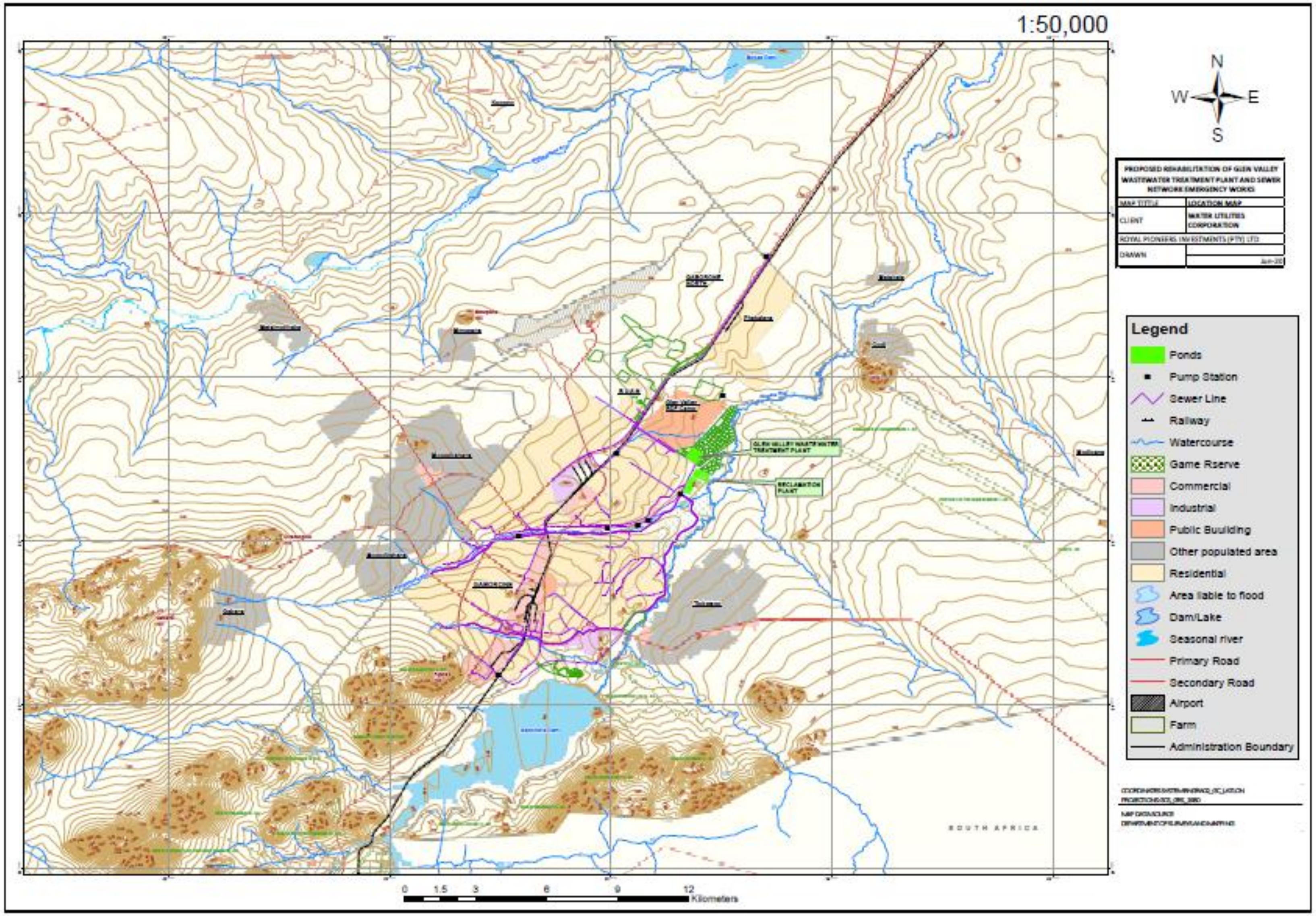
3. Quality control measures:
   a. Field blanks deployed at 10% of sampling points
   b. Duplicate samplers at 2 locations per sampling round
   c. Careful documentation of deployment and collection times
   d. Protection against moisture using weather shields

Environmental Parameters

Recording Basic environmental conditions were documented during each sampling period using available facility equipment

1. Temperature
   a. Recorded three times daily (morning, midday, afternoon)
   b. Using calibrated thermometer at each sampling location
   c. Documentation of sampling time and temperature readings
2. Relative humidity
   a. Measured alongside temperature readings
   b. Using portable hygrometer
   c. Three daily measurements coinciding with temperature recordings

Appendix D: Maps and GWWP Photographs



Glenvalley Wastewater Treatment Plant - Location map

Aerial View 1 of GWWP

Aerial View 2 of GWWP


Aerial View 3 of GWWP

Aerial View 4 of GWWP

Grit Chamber - GWWP

Sludge Pond - GWWP


Sludge Pond - GWWP

Appendix D: Turnitin report

Dr Daniel Mmereki

Dr Goitsemang Keretetse (Supervisor)

Golebaone Senai report -1.docx

Date: 28/03/2025

ORIGINALITY REPORT

9%	8%	6%	4%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to University of Witwatersrand Student Paper	3%
2	wiredspace.wits.ac.za Internet Source	1%
3	www.frontiersin.org Internet Source	1%
4	Submitted to Sana'a University Student Paper	<1%
5	www.cdc.gov Internet Source	<1%
6	"Microplastics in African and Asian Environments", Springer Science and Business Media LLC, 2024 Publication	<1%
7	Pegah Nakhjirgan, Farzad Fanaei, Ahmad Jonidi Jafari, Mitra Gholami, Abbas Shahsavani, Majid Kermani. "Extensive investigation of seasonal and spatial fluctuations of BTEX in an industrial city with a	<1%