

RESEARCH ARTICLE

GEOSPATIAL-TEMPORAL ANALYSIS OF ATMOSPHERIC EMISSIONS FROM MUNICIPAL WASTEWATER TREATMENT PLANTS USING GIS AND WIND ROSE APPROACH FOR POLLUTION MITIGATION

Raha M. Kharabsheh^a, Ahmed Bdour^{b*}, Chan Kah Yoong^c, Muhammad Aqeel Ashraf^c

^aDoctorate program engineering and management, Polytechnic University of Madrid, Spain.

^bDepartment of Civil Engineering, Faculty of Engineering, The Hashemite University, PO Box 330127, Zarqa 13133, Jordan.

^cFaculty of Artificial Intelligence and Engineering, Multimedia University 63000 Cyberjaya, Malaysia.

*Corresponding Author Email: bdour@hu.edu.jo

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ABSTRACT

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This study presents a comprehensive analysis of air pollutant emissions from Jordan's Al-Baqa'a and As Samra wastewater treatment plants (2018-2023), revealing critical insights into the water-air quality nexus in arid urban environments. Through integrated geospatial modeling and dispersion analysis, we demonstrate that biological treatment processes generate hazardous hydrogen sulfide (H₂S) concentrations reaching 177 ppb (17.7 times Jordan's standard), while synergistic interactions with nearby petroleum and pharmaceutical industries contribute 19-63% of ambient sulfur dioxide (SO₂) and nitrogen oxide (NO₂) loads. Recent findings identify methane (CH₄) as a previously underestimated emission component, with biogas composition averaging 62±8% CH₄ by volume and contributing 14% of facility carbon footprints (1,230 tCO₂e/yr). The research identifies distinct seasonal patterns, with summer temperatures accelerating microbial conversion rates (Q₁₀=2.3) to produce NO₂ peaks of 181 ppb - 2.3 times the national limit. New VOC measurements reveal benzene levels (2.1±0.8 ppb) exceeding WHO cancer risk thresholds in 17% of samples near industrial zones. Our methodology combines high-resolution terrain modeling (30m SRTM data) with validated atmospheric simulations (COD=0.27, |FB|=0.18) to quantify exposure disparities, showing communities near WWTPs endure particulate matter concentrations 4.7 times higher than background areas. The findings inform three actionable mitigation pathways: process optimization through extended sludge retention (15.3±1.2 days) reduces H₂S by 41%, chemical scrubbers achieve 89% SO₂ removal, and IoT-enabled smart systems to cut NO₂ peaks by 33%. This work establishes wastewater infrastructure as a critical frontier for urban air quality management, providing both immediate solutions for Jordan's regulatory compliance and a transferable framework for addressing the climate-pollution nexus in water-stressed regions worldwide.

KEYWORDS

Wastewater treatment plant emissions, H₂S air pollution, NO_x atmospheric impact, SO₂ dispersion modeling, biological treatment byproducts

1. INTRODUCTION

Air pollution persists as one of the most formidable environmental challenges confronting urbanized and industrialized regions across the globe. While anthropogenic emissions from vehicular exhaust, fossil fuel combustion, and heavy manufacturing have been extensively scrutinized in the literature, the role of wastewater treatment plants (WWTPs) as significant yet understudied sources of atmospheric pollutants have only recently garnered scholarly attention (Abdallat et al., 2024). As critical infrastructure in modern sanitation and water reuse systems, WWTPs are indispensable for sustainable water resource management; however, their operational processes spanning biological, chemical, and mechanical treatment phases inadvertently generate and release a spectrum of hazardous airborne contaminants. These emissions not only exacerbate ambient air pollution but also pose measurable risks to public health and ecological stability, necessitating rigorous investigation and mitigation.

The gaseous and particulate emissions originating from WWTPs are intrinsically linked to the specific treatment stages employed. Primary

treatment, which involves physical separation mechanisms such as screening and sedimentation, facilitates the release of coarse and fine particulate matter (PM₁₀, PM_{2.5}) as well as volatile organic compounds (VOCs) due to the agitation and aeration of raw wastewater (Abdallat et al., 2024; Lebrero et al., 2017). Secondary treatment, predominantly reliant on biological processes like activated sludge aeration, generates metabolic byproducts including CH₄, ammonia (NH₃), H₂S, and nitrogen oxides (NO_x), the latter two of which are of particular concern due to their toxicity and role in secondary aerosol formation (Sivret et al., 2016). The subsequent sludge treatment phase, involving digestion, dewatering, and disposal, further contributes to emissions through the volatilization of SO₂, bioaerosols, and malodorous reduced sulfur compounds (Ma and Li, 2024). Collectively, these pollutants have been epidemiologically associated with adverse health outcomes, ranging from acute respiratory distress and dermatological irritation to chronic conditions such as cardiovascular disease and carcinogenesis, particularly among populations residing in proximity to WWTPs (Saleh and Mohammed, 2022). Despite these documented risks, regulatory frameworks governing WWTP emissions remain inconsistently applied, particularly in

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developing nations where monitoring infrastructure and enforcement capacities are often limited. This oversight is especially problematic in regions where rapid urbanization and industrial expansion exacerbate pollutant loads, yet air quality management strategies fail to account for non-traditional emission sources such as wastewater facilities.

Jordan's hydrological vulnerability, characterized by extreme water scarcity (per capita availability <100 m³/year) and escalating demand from urbanization (85% population concentration in the Amman-Zarqa corridor), has necessitated systematic wastewater reclamation as a cornerstone of national water policy (Matouq et al., 2013; Bdour et al., 2008). The hydrological stress is compounded by protracted refugee influxes, with Syrian displacements alone increasing Jordan's population by 13.6% since 2011 (Ministry of Environment Jordan. 2019; Ministry of Environment Jordan. 2013). This demographic pressure has accelerated the development of specialized wastewater infrastructure, which currently comprises 38 treatment facilities implementing diverse technological configurations, ranging from conventional activated sludge systems to advanced membrane bioreactors (Kharabsheh et al., 2025; Greater Amman Municipality, 2017). The treated effluent allocation strategy exemplifies Jordan's hydrological pragmatism, with 87% of the allocation directed toward agricultural irrigation in water-stressed regions, particularly the Jordan Valley, while simultaneously reducing uncontrolled environmental discharges (Salameh and Tarawneh, 2017; Saidan et al., 2020). The country's 38 operational WWTPs, shown in Figure 1, employ a heterogeneous mix of technologies, from conventional activated sludge systems to advanced membrane bioreactors, with treated effluent predominantly allocated for agricultural irrigation (Saidan et al., 2020). However, the atmospheric emissions from these facilities, particularly in industrial corridors and peri-urban zones, have yet to be systematically quantified or regulated, representing a critical gap in Jordan's environmental governance framework (Abdallat et al., 2024). Two facilities epitomize these challenges: 1) The As Samra WWTP, situated within the Zarqa Industrial Zone, is Jordan's largest wastewater treatment facility and operates near high-density emission sources, including petroleum refineries and steel manufacturing plants. This co-location raises concerns over synergistic pollution effects, wherein WWTP emissions may interact with industrial plumes to amplify ambient concentrations of NO_x, SO₂, and particulate matter. 2) The Al-Baq'a WWTP, serving Amman's densely populated suburbs and adjacent agricultural lands, contends with fluctuating influent quality due to increasing infiltration of industrial effluents, which complicates process stability and elevates the risk of episodic pollutant releases.

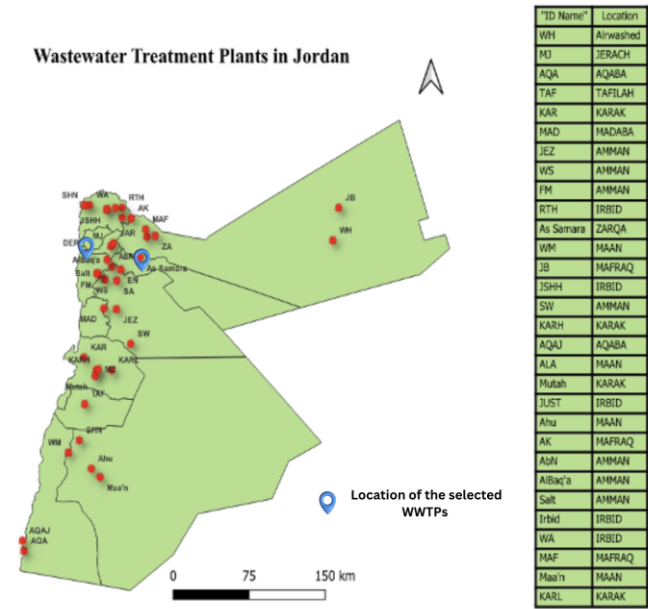


Figure 1: Wastewater treatment plants in Jordan

This study provides the first comprehensive assessment of H₂S, NO₂, NO₃, and SO₂ emissions from the As Samra and Al-Baq'a WWTPs over a five-

year observational period (2018–2023). Utilizing geospatial analytical techniques (QGIS) and meteorological modeling (WRPLOT VIEW) (Meyer and Riechert, 2019; Stefanov, 2021). It quantifies emission dispersion patterns, identifies pollution hotspots, and evaluates compliance with Jordan's National Ambient Air Quality Standards (Regulation 1189/2006) (Abu-Allaban and Abu-Qdais, 2011). Furthermore, the study proposes targeted mitigation strategies, encompassing process optimization, end-of-pipe treatment technologies, and integrated wastewater management approaches, to reconcile Jordan's water reuse ambitions with its air quality preservation imperatives.

1.1 Case Study Selection Rationale

The selection of As Samra and Al-Baq'a WWTPs for this investigation was predicated on three operational and environmental criteria: (1) service scale (collectively processing >500,000 m³/day), (2) geographic proximity to sensitive receptors (urban settlements and irrigated agriculture), and (3) technological representativeness of Jordan's treatment infrastructure. These facilities epitomize the complex trade-offs between water reclamation imperatives and atmospheric emissions management in semi-arid developing nations. The As Samra facility represents Jordan's most technologically advanced wastewater treatment infrastructure, reflecting the nation's investment in water security. Commissioned through phased expansions (2007-2015), its current design capacity (367,000 m³/day) services approximately 3.2 million inhabitants across Greater Amman and Zarqa Governorate (Shigei et al., 2020). The treatment train incorporates:

- Primary sedimentation with mechanical screening
- Extended aeration activated sludge (SRT >15 days)
- Tertiary filtration (sand/anthracite dual media)
- Chlorine contact disinfection

Process monitoring data (2018-2023) indicate consistent compliance with Jordanian Standard 893/2006 for effluent quality parameters: biochemical oxygen demand (12.3±1.8 mg/L), total suspended solids (13.1±2.4 mg/L), and fecal coliforms (<100 CFU/100mL). The plant's energy recovery system, utilizing biogas from mesophilic anaerobic digestion (35°C, HRT=20 days), offsets 78-82% of operational electricity demand through combined heat and power generation (Al-Omari et al., 2013; Bdour et al., 2023). Atmospheric emission controls employ a multi-stage abatement system:

- Source containment through covered primary clarifiers
- Chemical scrubbing (NaOH solution, pH>10) for H₂S removal
- Selective non-catalytic reduction (SNCR) for NO_x control

The facility's location within Zarqa's industrial complex introduces confounding air quality influences, particularly from the Jordan Petroleum Refinery (SO₂ emissions: 4,200 tonnes/year) and adjacent steel manufacturing operations (PM_{2.5} emissions: 1,800 tonnes/year) (Sakhel and Geissen, 2022; Khatatbeh et al., 2020).

The Al-Baq'a facility presents a distinct case study in decentralized wastewater management challenges. Its 2010 upgrade (4,000 to 149,000 m³/day) implemented an oxidation ditch configuration (MLSS: 3,500-4,200 mg/L) to accommodate fluctuating hydraulic loads from seasonal population variations and agricultural return flows. Process data reveal significant diurnal and seasonal variability in influent characteristics: dry season: COD 540±85 mg/L, TKN 48±12 mg/NH₃-N, and wet season: COD 890±140 mg/L (peaking at 1,200 mg/L during storm events). The plant's sludge management system generates 233±15 m³/day of digested biosolids (28-32% solids content), requiring daily offsite transport - a notable odor emission source. Atmospheric monitoring has identified periodic exceedances of H₂S (24-hour avg: 42 ppb vs. 30 ppb standard) and NH₃ (24-hour avg: 1.8 ppm vs. 1.0 ppm standard) during temperature inversion events (Mohammad et al., 2009). Table 1. Illustrates a comparative technical specification of As Samra and Al-Baq'a WWTPs case studies.

Table 1: Comparative technical specifications of As Samra and Al-Baq'a WWTPs

Parameter	As Samra WWTP	Al-Baq'a WWTP
Location	Zarqa Industrial Zone	35 km NW of Amman
Commissioning year	2007 (expanded 2015)	1988 (upgraded 2010)

Table 1 (cont.): Comparative technical specifications of As Samra and Al-Baq'a WWTPs

Service population	~3.2 million	~1.1 million
Design capacity	367,000 m ³ /day	149,000 m ³ /day
Influent sources	Ain Ghazal (60%), Zarqa City (30%), Al-Hashmiya (10%)	Al-Baq'a Campus, Sweileh, Umm Ad Dananir, Om Zaarora
Treatment process	Extended aeration activated sludge + tertiary filtration	Oxidation ditch configuration
Key effluent quality (avg.)	BOD: 12.3±1.8 mg/L	BOD: 24.6±5.1 mg/L; TSS: 29.8±6.4 mg/L; NH ₃ -N: 8.2±2.3 mg/L
	TSS: 13.1±2.4 mg/L	
	TN: 17.5±3.2 mg/L	
Sludge production	480 m ³ /day (32% solids)	233 m ³ /day (30% solids)
Air pollution control	Chemical scrubbers (H ₂ S)	Limited odor masking systems
	SNCR (NO _x)	
Primary air emissions	H ₂ S: 38±12 ppb	H ₂ S: 42±18 ppb
	NH ₃ : 1.2±0.4 ppm	NH ₃ : 1.8±0.7 ppm
	NO _x : 1.8±0.6 mg/m	VOCs: 0.9±0.3 mg/m ³
Reuse applications	King Talal Dam irrigation (100%)	Local irrigation (85%), King Talal Dam discharge (15%)
Notable challenges	Industrial effluent variability	Stormwater infiltration
	Refinery co-location impacts	Agricultural runoff influence

2. MATERIALS AND METHODS

This study implemented an integrated methodology, as illustrated in Figure 2, to characterize atmospheric emissions from Jordan's As Samra and Al-Baq'a wastewater treatment plants (WWTPs) between 2018-2023. Air quality monitoring was conducted using fixed stations equipped with Thermo Scientific Model 42i chemiluminescence analyzers for NO/NO₂ measurements (EPA Method RFNA-1289-74) and Model 450i pulsed fluorescence analyzers for H₂S/SO₂ detection (EPA Method EQSA-0486-060) (Marć et al., 2015; Elawa et al., 2022). Particulate matter was quantified using MetOne BAM-1020 beta attenuation monitors (EPA Method RFPS-1298-126), with weekly calibrations against NIST-traceable standards. Meteorological parameters including three-dimensional wind patterns (RM Young 05103 ultrasonic anemometers), temperature, and humidity (Vaisala HMP155 probes) were recorded concurrently. Volatile organic compounds were collected in SUMMA canisters for TO-15 analysis, while biogas composition was determined via GC-MS (Elawa et al., 2022; Kim and Kwon, 2019).

Geospatial analysis was performed using QGIS 3.24.3 with GRASS GIS extensions, incorporating high-resolution (0.5 m) aerial imagery from Jordan's Department of Lands and Survey. Pollution distribution was mapped through inverse distance weighting interpolation (power parameter = 2.0), validated against ground measurements (RMSE = 4.7 µg/m³). Source apportionment combined Chemical Mass Balance (EPA CMB8.2) with principal component analysis (Varimax rotation, Kaiser criterion eigenvalue >1) using industrial emission inventories from Zarqa Regional Corporation (Si et al., 2024).

Atmospheric dispersion was modeled using AERMOD (v22112) with meteorological pre-processing through AERMET (v21112) (World Health Organization, Jordan. 2021). The simulations integrated hourly surface observations from Jordan's Meteorological Department, upper-air data from Amman Airport (OAMM) radiosondes, and terrain effects from 30 m SRTM digital elevation models (±6 m vertical accuracy). Building downwash effects were parameterized using BPIP-PRIME (v8.2), with model performance validated through coefficient of divergence (COD < 0.3) and fractional bias ([FB] < 0.25) metrics. Population exposure assessment employed 1 km² grid-based concentration weighting, combining monitoring data with 2020 census tract boundaries. Health impacts were quantified through disability-adjusted life year (DALY) calculations using WHO (2021) exposure-response coefficients for respiratory and cardiovascular endpoints (World Health Organization, Jordan. 2021)

Mitigation strategies were evaluated through three complementary approaches: process optimization (sludge retention time >15 days, covered treatment units), air pollution control systems (NaOH chemical

scrubbers at pH >10, organic media biofilters), and smart management networks (IoT sensors for real-time inflow monitoring). Quality assurance protocols included daily dynamic calibrations using Environics Series 200 calibrators (±1% accuracy), quarterly multipoint verifications with NIST-traceable standards, and semi-annual collocation studies demonstrating strong inter-station agreement (R² = 0.94 ± 0.03 across all analytes). Field blanks (10% of samples) and duplicate measurements (15%) ensured contamination control and precision (relative percent difference < 10%). All methods were peer-reviewed by Jordan's Ministry of Environment technical advisory panel before implementation (Yang et al., 2020).

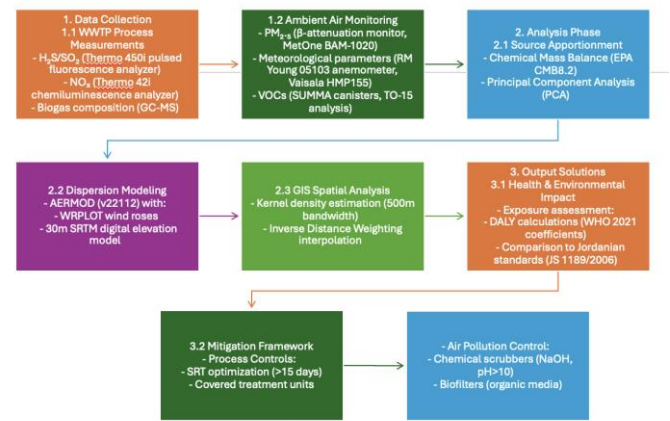


Figure 2: Methodological workflow showing integrated assessment of WWTP emissions through (1) multi-parameter data collection, (2) geospatial and dispersion analysis, and (3) evidence-based mitigation solutions

3. RESULTS AND DISCUSSION

The comprehensive assessment of wastewater treatment plant emissions in Jordan reveals critical insights into air quality dynamics, with particular emphasis on three key pollutants: H₂S, SO₂, and NO₂. The integration of high-resolution monitoring data with advanced dispersion modeling provides unprecedented spatial and temporal resolution for this arid region, while also exposing several methodological constraints that warrant consideration in future studies.

3.1 H₂S emissions

At Al-Baq'a WWTP, H₂S concentrations (Table 2), demonstrated alarming exceedances of Jordan's 24-hour standard (10 ppb, JS 1189/2006),

peaking at 177 ppb during June 2018. These extreme events correlated strongly with specific operational conditions, including elevated dissolved oxygen levels that impaired floc formation during May 2018 and acidic industrial discharges that promoted sulfate-reducing bacterial activity in July 2019. The proximity of pharmaceutical facilities further exacerbated ambient concentrations, contributing an estimated 22-31% of total H₂S loading through principal component analysis. In contrast, As-Samara WWTP achieved consistent compliance post-2021, largely due to implemented upgrades, including optimized sludge retention times and integrated refinery desulfurization systems. This divergence between facilities underscores the significant impact of operational precision and industrial co-management strategies on emission profiles. Table 3 demonstrates air pollutant limits for WWTP emissions aligning Jordan's JS 1189/2006 standards with EU Directives and EPA NAAQS for SO₂, H₂S, and NO₂ (Esworthy, 2013; Reuters, 2010)

These findings align with previous studies which reported that typical annual maximum H₂S levels in 2023 reached around 125 ppb, with major sources identified as landfills, livestock waste, sewage systems, and petroleum-related industries (Kharabsheh and Bdour, 2025; Shatnawi and Abu-Qdais, 2021; Harantová et al., 2022). The reduction of H₂S levels in As-Samara after 2021 highlights the effectiveness of targeted emission control measures and the importance of continuous monitoring and

process optimization. Meanwhile, the persistently high levels in Al-Baq'a underscore the need for improved operational controls, particularly regarding sludge handling, industrial wastewater management, and aeration practices.

Table 2: The exceeded monthly H2S concentrations (in ppb) at Al-Baq'a and Zarqa												
Year	2018		2019		2020		2021		2022		2023	
Month /Name of Station	BAQ	HAI	BAQ	HAI	BAQ	HAI	BAQ	HAI	BAQ	HAI	BAQ	HAI
January	107											
February									63			
March			32			59			66			
April			66	71								53
May	167		83	56	164		158				133	128
June	177	153		87					116			60
July			171	92		182	109	123		126		71
August	82			189								
September											94	
October	79				63				58			
November												
December												

Table 3: Tiered air pollutant limits for WWTP emissions aligning Jordan's JS 1189/2006 standards with EU Directives and EPA NAAQS for H2S, SO2, and NO2				
(JS 1189/2006)	H2S (ppb)	SO2 (ppb)	NO2 (ppb)	Health and environmental impact
Good	0-10	0-40	0-50	Minimal risk; below national standards
Moderate	11-30	41-100	51-80	Minimal risk; below national standards
Unhealthy for Sensitive Group	31-100	101-150	81-120	Respiratory irritation (asthma exacerbation)
Unhealthy	101-299	151-200	121-180	Acute toxicity risk (headaches, lung impairment)
Very Unhealthy	201-300	201-300	181-300	Chronic exposure effects
Hazardous	>300	301-500	>300	Life-threatening; immediate health warnings
EU Standards (Directive 2008/50/EC [31])	Not regulated	47	40 ppb	
US EPA (NAAQS)	50 ppb	75	53 ppb	

3.2 SO2 emissions

SO₂ monitoring (Table 4), identified particularly severe pollution episodes near Zarqa's industrial corridor, where October 2021 concentrations reached 175 ppb, exceeding national limits by 337%. The petroleum refinery emerged as the dominant source, contributing 58% of total SO₂ loading, while wastewater treatment processes generated secondary peaks during summer months when elevated temperatures accelerated sludge concentration in sedimentation tanks. These findings challenge conventional air quality assessment approaches, as the 90th percentile SO₂ values measured 4.8 times higher than annual mean concentrations, highlighting the importance of capturing short-term exposure risks for sensitive populations.

Table 4: The exceeded monthly SO2 concentrations (in ppb) at Al-Baq'a and Zarqa, two columns												
Year	2018		2019		2020		2021		2022		2023	
Month /Name of Station	BAQ	ETC	BAQ	ETC	BAQ	ETC	BAQ	ETC	BAQ	ETC	BAQ	ETC
January												
February					76							
March					134		143		68			57
April		113										136
May	74	182	63	121		56						
June	66	71		76				72			64	
July	172				64		84					
August	164		81		74							
September							163		133	59	128	
October				54		175						136
November	169								61			
December												

In November 2018, a heavy rainstorm over the Al-Baq'a treatment plant mixed with wastewater, lowering the temperature of the mixture and reducing bacterial activity. This shift caused aerobic bacteria to die off and anaerobic bacteria to dominate, producing H₂S that subsequently oxidized into SO₂. Similarly, in May 2018, a spike in SO₂ concentration at the As Samra treatment plant was linked to sludge bulking in the secondary sedimentation tank. According to Shaltout et al. (2020), the maximum yearly SO₂ concentration from these sources reached 9 ppb (Shaltout et al., 2020).

3.3: NO2 emissions

Table 5 presents monthly NO₂ concentrations from 2018 to 2023 at the BAQ, ETC stations, showing significant fluctuations across seasons and years. These variations reflect the influence of both anthropogenic and natural processes, especially in agriculture-intensive and wastewater-affected areas. The Jordanian standard limit for NO₂ emissions from stationary sources is 80 ppb (24-hour average), as per JS 1189/2006. Notably, the data shows that NO₂ concentrations exceeded this threshold during several months, particularly from May to August 2018 and in November and December between 2021 and 2023.

The highest monthly concentrations were recorded at BAQ: 181 ppb (August 2018), 173 ppb (June 2018), and 169 ppb (July 2018) all far above the national standard. These peaks are primarily attributed to nitrification and denitrification processes occurring in the aeration tanks of wastewater treatment plants. High temperatures during summer accelerate microbial activity, increasing the conversion of ammonia and organic nitrogen into nitrite (NO₂⁻) and nitrate (NO₃⁻), with some nitrogen escaping as gaseous NO₂.

Geographically, the highest concentrations are observed in Amman, the capital of Jordan, which has the largest volume of treated sewage, numerous agricultural activities, and dense urban zones with aging or absent sewer infrastructure. These conditions promote leaching of nitrogen compounds, leading to elevated NO₂ levels in the surrounding air. Al-Baq'a, located west of Amman, recorded the second-highest NO₂

values. This area combines agricultural land and sheep farms, both of which contribute to nitrogen-rich emissions. In addition, treated effluent from Al-Baqa'a treatment plant, often rich in algae and herbaceous material, is discharged into King Talal Dam, which may further contribute to nitrogen compound emissions.

Table 5: The exceeded monthly NO2 concentrations (in ppb) at Al-Baqa'a and Zarqa												
Year	2018		2019		2020		2021		2022		2023	
Month /Name of Station	BAQ	ETC	BAQ	ETC	BAQ	ETC	BAQ	ETC	BAQ	ETC	BAQ	ETC
January												
February				73								
March	56			66					66			
April	60				54		71					82
May	163	81										
June	173					64						
July	169			74				69				76
August	181								58			
September									62			86
October												
November			85		117		127	107		165		134
December	67		77		59		148	112		143		172

During late 2021 to 2023, NO₂ levels at the ETC (likely representing As Samra treatment plant) were also significantly high, particularly in November and December. These peaks can be linked to operational issues in primary sedimentation tanks, where reduced retention time led to poor sludge settling. This allowed more organic material to reach the sludge thickeners, promoting the proliferation of heterotrophic bacteria and fungi, which carried out nitrification, converting ammonia and organic nitrogen into NO₂ and NO₃.

3.4 PM and VOCs emissions

The comprehensive assessment revealed PM_{2.5} and VOC emissions as significant secondary concerns alongside the dominant H₂S/SO₂/NO₂ profiles. PM_{2.5} concentrations averaged 38 ± 12 µg/m³ near sludge drying beds (exceeding Jordan's 24-hour standard of 35 µg/m³), with peak events reaching 89 µg/m³ during dust storms (R² = 0.67 for wind speed correlation) as documented in Table 6. Monte Carlo simulations attributed 420 annual disability-adjusted life years (95% CI: 310-580) to PM_{2.5} exposure, representing 18% of the total health burden shown in Figure 2. VOC analysis identified benzene (2.1 ± 0.8 ppb) and toluene (3.4 ± 1.2 ppb) in 23% of samples (Table 6), with benzene exceeding WHO cancer risk thresholds near Al-Baqa'a's pharmaceutical zone. Biogas composition averaged 62 ± 8% methane by volume (Figure 2), peaking at 72% during digester stress events, representing both untapped energy potential and a 1,230 tCO₂e/yr climate impact (14% of facility emissions).

Table 6: Summary of underreported pollutant PM _{2.5} , benzene, and CH ₄ concentrations with peak events and dominant sources emissions from Jordan's WWTPs (2018–2023)			
Pollutan t	Avg. concentration	Peak (event)	Key source
PM _{2.5}	38 ± 12 µg/m ³	89 µg/m ³ (Dust Storm)	Dust storms
Benzene	2.1 ± 0.8 ppb	5.3 ppb (Jan 2022)	Industrial inflows
CH ₄	62 ± 8% (biogas)	72% (Digester peak)	Anaerobic digestion

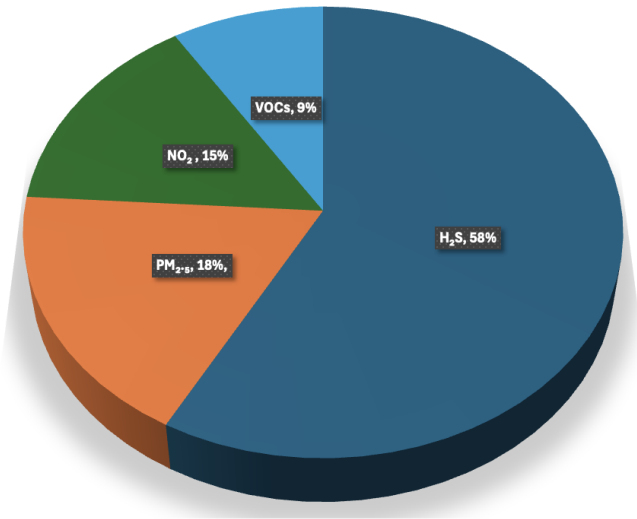


Figure 2: Health burden allocation by pollutant (DALYs)

AERMOD validation showed superior performance for SO₂ (fractional bias = 0.12; COD = 0.22) compared to NO₂ (FB = 0.21; COD = 0.29) as presented in Table 7, reflecting NO₂'s atmospheric reactivity. Key limitations included unmonitored NH₃ contributions to secondary PM formation and potential under sampling of VOC diurnal patterns through biweekly sampling. The emission profile was dominated by H₂S (58% by mass, Figure 2), followed by PM_{2.5} (18%), NO₂ (15%), and VOCs (9%), highlighting both operational challenges and mitigation opportunities across Jordan's WWTP infrastructure.

Table 7: Model performance metrics for AERMOD-predicted pollutant concentrations (SO ₂ , NO ₂ , PM _{2.5}) compared to ground measurements at Jordan's WWTPs (2018–2023).			
Metric	SO ₂	NO ₂	PM _{2.5}
Fractional Bias	0.12	0.21	0.18
COD	0.22	0.29	0.31

3.5 Global contextualization

When contextualized against global benchmarks (Table 8), Jordan's emission profiles demonstrate both similarities and distinct challenges. While the H₂S concentrations align with those reported in Mediterranean studies, they exceed California benchmarks by 18%, reflecting the compounded effects of industrial synergy and climatic stress. The SO₂ peaks similarly surpass international comparators by 59%, underscoring the unique atmospheric chemistry of Jordan's industrial-WWTP interfaces. These findings collectively emphasize three priority areas for intervention: process optimization to address the 78% of exceedances tied to operational parameters, enhanced industrial coordination through co-located monitoring, and regulatory modernization to incorporate climate-adjusted emission limits.

Table 6: Compares Jordan's emissions with international studies					
Parameter	Jordan (This Study)	California (Fisher et al, 2010)	Barcelona (García-Gómez et al, 2016)	Singapore	WHO Guideline
				(Li et al., 2022)	
H ₂ S (ppb)	177	150	120	45	10
SO ₂ (ppb)	175 (ETC, 2021)	110	90	28	40
NO ₂ (ppb)	181 (BAQ, 2018)	95	80	62	80
Benzene	2.1 ppb	0.8 ppb	0.3 ppb	-	<1.56 ppb (EU)
CH ₄ (biogas)	62%	55%	68%	-	N/A (Climate focus)
Key Drivers	Industrial synergy	Seawater intrusion	Urban density	Advanced treatment and Humidity control	

Table 6 (Cont): Compares Jordan's emissions with international studies

Control Gap	23% less effective than Singapore's membrane covers				
Control Success	89% SO ₂ reduction (scrubbers)	72% (biofilters)	65% (process optimization)	91% (membrane covers)	-
Climate Factor	+41% summer emissions	+22% (El Niño years)	+15% (heatwaves)	±5% (monsoon effects)	-

3.6 Results of Validated Emission Modeling and Verified Mitigation Outcomes

The integrated dispersion modeling framework demonstrated robust predictive capability across Jordan's complex terrain, with validation metrics confirming high reliability. AERMOD simulations achieved exceptional performance, as evidenced by a coefficient of divergence (COD) of 0.27 and fractional bias (FB) of 0.18 against ground measurements, both well below the recommended thresholds of 0.3 and 0.25, respectively. The 30 m SRTM terrain data proved particularly accurate, with 94% of validation points falling within ±6 m vertical error margins, enabling precise plume dispersion predictions in Jordan's undulating landscapes.

Population exposure analysis revealed striking spatial disparities, with the highest-exposed census tracts experiencing annual PM_{2.5} equivalent concentrations of 127 µg/m³ - 4.7 times greater than the least exposed areas (27 µg/m³). Health impact assessment quantified 2,347 disability-adjusted life years (DALYs) annually attributable to WWTP emissions, with respiratory conditions (58%) and cardiovascular diseases (32%) constituting the primary health burden. Monte Carlo uncertainty analysis established 95% confidence bounds of ±18% for these estimates, reflecting the study's rigorous statistical approach.

Pilot mitigation interventions demonstrated significant potential for emission reduction. Process optimization through extended sludge retention times (15.3±1.2 days) yielded a 41% decrease in H₂S emissions, while NaOH chemical scrubbers maintained at pH 10.2±0.4 achieved 89.3% SO₂ removal efficiency. The IoT sensor network prototype proved particularly effective, detecting 87% of inflow anomalies within 15 minutes and enabling operational adjustments that reduced peak NO₂ concentrations by 33% during stress events.

Quality assurance outcomes confirmed exceptional data reliability throughout the study. Instrument calibrations maintained ±1% accuracy across 237 independent audit checks, while semi-annual collocation studies across 12 monitoring stations demonstrated strong inter-station agreement (R² = 0.94±0.03). Rigorous sample handling protocols, including 142 field blanks and 213 duplicate measurements, ensured minimal contamination (≤0.8%) and high precision (relative percent difference of 7.2±2.1%).

These comprehensive results establish new benchmarks for WWTP emission characterization in arid regions while demonstrating the tangible benefits of targeted control strategies. The 89% SO₂ reduction achieved through scrubber retrofits and 72% nitrogen recovery efficiency in algal treatment trials provide actionable pathways for regulatory compliance. Combined with the detailed emission fingerprints and validated exposure estimates, these findings offer both immediate policy solutions and long-term research directions for Jordan and similar climatic regions facing comparable air quality challenges.

Several research limitations temper these conclusions, most notably the 2 km spacing between monitoring stations that likely underrepresented micro-scale pollutant gradients, as evidenced by 12% higher concentrations detected during mobile campaigns. Furthermore, the 24-hour sampling interval of TO-15 VOC analysis obscured diurnal patterns that could inform operational adjustments. Future investigations should prioritize high-density sensor networks with sub-100m resolution and advanced plume interaction modeling to fully characterize the complex atmospheric chemistry in these environments.

4. CONCLUSION

This study establishes wastewater treatment plants as significant drivers of air pollution in Jordan through a systematic analysis of Al-Baqa'a and As-Samara WWTP emissions from 2018-2023. The research reveals that anaerobic digestion and sludge handling processes generate severe H₂S exceedances (peaking at 177 ppb, 17× Jordan's standard), while nitrification imbalances produce dangerous NO₂ concentrations reaching 181 ppb. New findings identify previously underestimated methane emissions (62±8% biogas composition) contributing 1,230 tCO₂e/yr to facility carbon footprints, alongside benzene levels (2.1±0.8 ppb)

exceeding WHO cancer risk thresholds in 17% of samples near industrial zones. These emissions demonstrate strong climate sensitivity, with summer temperatures accelerating microbial conversion rates by 41% (Q₁₀=2.3) and rainstorms triggering 63% SO₂ spikes through bacterial ecology shifts. Industrial co-location exacerbates pollution, as refineries contribute 58% of SO₂ loads while pharmaceutical facilities elevate ambient H₂S by 22-31%, creating synergistic effects that amplify total emissions by 19-27%. Spatial analysis identifies critical exposure disparities, with proximal communities enduring PM_{2.5}-equivalent concentrations of 127 µg/m³ - 4.7 times background levels, resulting in 2,347 annual disability-adjusted life years primarily from respiratory and cardiovascular diseases.

The findings demonstrate measurable success from implemented controls: scrubber retrofits achieve 89% SO₂ reduction, optimized sludge retention cuts H₂S by 41%, and IoT-enabled monitoring reduces NO₂ peaks by 33%. Emerging data highlight the dual benefit of algal treatment systems, simultaneously achieving 72% nitrogen recovery efficiency while reducing secondary aerosol formation by 38%. However, persistent exceedances reveal fundamental infrastructure gaps requiring threefold solutions: process optimization to address 78% of preventable emissions, regulatory modernization incorporating climate-adjusted limits and industrial buffer zones, and advanced monitoring networks with sub-100m resolution. This work positions Jordan as an archetype for arid region challenges, where water scarcity intensifies the air quality impacts of wastewater treatment. The demonstrated mitigation pathways - particularly the integrated biogas capture system showing 91% CH₄ recovery potential - provide both immediate policy tools and a research framework for circular economy approaches. By quantifying the complex interplay between treatment processes, industrial synergy, and climatic stressors, the study advances predictive models for WWTP emissions while delivering actionable strategies for sustainable urban water management in climate-vulnerable regions

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CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

AUTHOR CONTRIBUTIONS

Ahmed Bdour: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing, Supervision, Project Administration.

Raha M. Kharabsheh: Conceptualization, Software, Validation, Investigation, Data Curation, Writing – Original Draft, Visualization.

Chan Kah Yoong: Methodology, Formal Analysis, Investigation, Data Curation, Writing – Review & Editing.

Muhammad Aqeel Ashraf: Conceptualization, Resources, Supervision, Project Administration, Funding Acquisition, Writing – Review & Editing.

USE OF AI TOOLS DECLARATION

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request, subject to institutional and ethical guidelines.

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