Water SA 52(3) 269–280 / Jul 2026
https://doi.org/10.17159/wsa/2026.v52.i3.4238

Research paper

Wastewater plants as unrecognized air polluters: extreme H_2S, CH_4, and industrial-linked NO_2 emissions in arid Jordan

Raha M Kharabsheh[1], Ahmed Bdour[2] and Carlos Calderón-Guerrero[3]

[1]*Doctorate program engineering and management, Technical University of Madrid, Spain*
[2]*Department of Civil Engineering, Faculty of Engineering, The Hashemite University, PO Box 330127, Zarqa 13133, Jordan*
[3]*Center for Biodiversity Conservation and Sustainable Development (CBDS), Technical University of Madrid (Universidad Politécnica de Madrid), C/ José Antonio Novais 10, Madrid E-28040, Spain*

This study presents an analysis of air pollutant emissions from Jordan's Al-Baqa'a and As Samra Wastewater Treatment Plants (2018–2023). The analysis reveals the water–air quality nexus in arid urban environments. Through geospatial modelling and dispersion analysis, it is shown that biological treatment processes generate hydrogen sulfide (H_2S) concentrations of 182 ppb (17.7 times Jordan's standard). Interactions with nearby petroleum and pharmaceutical industries contribute 19–63% of ambient sulfur dioxide (SO_2) and nitrogen oxide (NO_2) loads. Methane (CH_4) is a primary biogas component and greenhouse gas emission component. Biogas composition averages 62±8% CH_4 by volume and contributes 14% of facility carbon footprints (1 230 t CO_2e/yr). Seasonal patterns exist: summer temperatures accelerate microbial conversion rates (Q_{10} = 2.3) and produce NO_2 peaks of 181 ppb – 2.3 times the national limit. VOC measurements show benzene levels (2.1±0.8 ppb) exceed WHO cancer risk thresholds in 17% of samples near industrial zones. The methodology combines terrain modelling (30 m SRTM data) with atmospheric simulations (COD = 0.27, |FB| = 0.18) to quantify exposure disparities. Communities near WWTPs experience particulate matter concentrations 4.7 times higher than background areas. The findings inform three mitigation pathways: process optimization through extended sludge retention (15.3±1.2 days) reduces H_2S by 41%; chemical scrubbers achieve 89% SO_2 removal; IoT-enabled systems cut NO_2 peaks by 33%. This work establishes the role of wastewater infrastructure as part of urban air quality management. It provides solutions for Jordan's regulatory compliance and a framework for addressing the climate–pollution nexus in water-stressed regions.

CORRESPONDENCE
Ahmed Bdour

EMAIL
bdour@hu.edu.jo

DATES
Received: 31 July 2025
Accepted: 13 July 2026

KEYWORDS
wastewater treatment
H_2S emissions
NO_2 atmospheric impact
SO_2 dispersion
air quality

COPYRIGHT
© The Author(s)
Published under a Creative Commons Attribution 4.0 International Licence (CC BY 4.0)

INTRODUCTION

Air pollution remains an environmental challenge for urbanized and industrialized regions worldwide. 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 has 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 (ALKharabsheh et al., 2026).

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 (PM_{10}, $PM_{2.5}$) 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 methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), 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 SO_2, bioaerosols, and malodorous reduced sulfur compounds (Ma and Li, 2024). These pollutants are associated with health outcomes. Acute effects include respiratory distress; chronic effects include cardiovascular disease and carcinogenesis. These associations are documented among populations residing near WWTPs (Saleh and Mohammed, 2023; Widiana et al., 2019). Despite these documented risks, regulatory frameworks governing WWTP emissions remain inconsistently applied, particularly in 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 m^3/yr) and escalating demand from urbanization (85% of the population is concentrated in the Amman–Zarqa corridor), has necessitated systematic wastewater reclamation as a cornerstone of

national water policy (Bdour et al., 2008; Matouq et al., 2013). 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, 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 (Greater Amman Municipality, 2017; Kharabsheh et al., 2025). 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 (Saidan et al., 2020; Salameh and Tarawneh, 2017). The country's 38 operational WWTPs, shown in Fig. 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. Two facilities epitomize these challenges: (i) 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, SO_2, and particulate matter. (ii) The Al-Baqa'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.

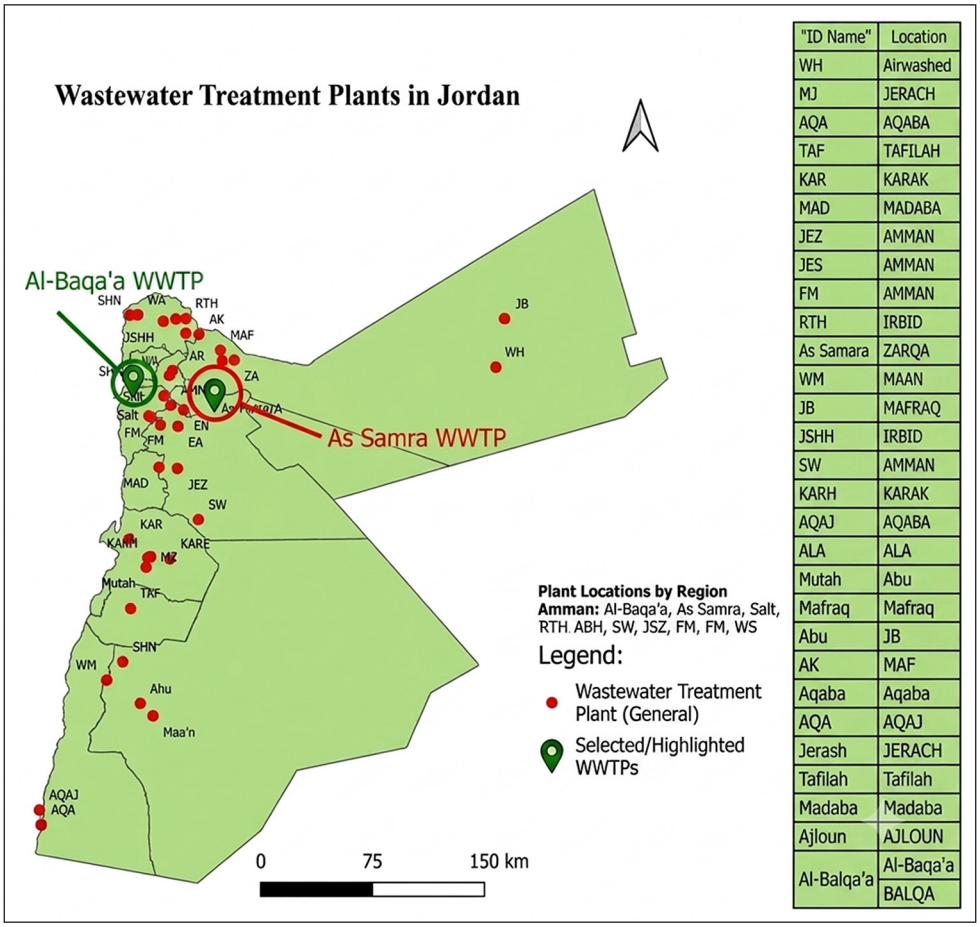
This study provides the first comprehensive assessment of H_2S, NO_2, NO_3, and SO_2 emissions from the As Samra and Al-Baqa'a WWTPs over a 5-year observational period (2018–2023). Utilizing geospatial analytical techniques (QGIS) and meteorological modelling (WRPLOT VIEW) (Meyer and Riechert, 2019; 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.

CASE STUDY SELECTION

The selection of As Samra and Al-Baqa'a WWTPs for this investigation was predicated on three operational and environmental criteria: (i) service scale (collectively processing >500 000 m^3/day), (ii) geographic proximity to sensitive receptors (urban settlements and irrigated agriculture), and (iii) 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. Table 1 gives comparative technical specifications for the As Samra and Al-Baqa'a WWTP case studies.

As Samra WWTP

The As Samra facility represents Jordan's most technologically advanced wastewater treatment infrastructure, reflecting the



"ID Name"	Location
WH	Airwashed
MJ	JERACH
AQA	AQABA
TAF	TAFILAH
KAR	KARAK
MAD	MADABA
JEZ	AMMAN
JES	AMMAN
FM	AMMAN
RTH	IRBID
As Samara	ZARQA
WM	MAAN
JB	MAFRAQ
JSHH	IRBID
SW	AMMAN
KARH	KARAK
AQAJ	AQABA
ALA	ALA
Mutah	Abu
Mafraq	Mafraq
Abu	JB
AK	MAF
Aqaba	Aqaba
AQA	AQAJ
Jerash	JERACH
Tafilah	Tafilah
Madaba	Madaba
Ajloun	AJLOUN
Al-Balqa'a	Al-Baqa'a
	BALQA

Figure 1. Wastewater treatment plants in Jordan

Table 1. Comparative technical specifications of As Samra and Al-Baqa'a WWTPs

Parameter	As Samra WWTP	Al-Baqa'a WWTP
Location	Zarqa Industrial Zone	35 km NW of Amman
Commissioning year	2007 (expanded 2015)	1988 (upgraded 2010)
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-Baqa'a Campus, Sweileh, Umm Ad Dananir, Om Zaarora
Treatment process	Extended aeration activated sludge + tertiary filtration	Oxidation ditch configuration
Key effluent quality (average)	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_2S)	Limited odour masking systems
	SNCR (NOx)	
Primary air emissions	H_2S: 38±12 ppb	H_2S: 42±18 ppb
	NH_3: 1.2±0.4 ppm	NH_3: 1.8±0.7 ppm
	NOx: 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

nation's investment in water security. Commissioned through phased expansions (2007–2015), its current design capacity (367 000 m^3/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 faecal coliforms (<100 CFU/100 mL). 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 H_2S 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 (SO_2 emissions: 4 200 t/yr) and adjacent steel manufacturing operations ($PM_{2.5}$ emissions: 1 800 t/yr) (Khatatbeh et al., 2020; Sakhel and Geissen, 2022).

Al-Baqa'a WWTP

The Al-Baqa'a facility presents a distinct case study in decentralized wastewater management challenges. Its 2010 upgrade (4 000 to 149 000 m^3/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/L NH_3-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 m^3/day of digested biosolids (28–32% solids content), requiring daily offsite transport – a notable odour emission source. Atmospheric monitoring has identified periodic exceedances of H_2S (24-h average: 42 ppb vs. 30 ppb standard) and NH_3 (24-h average: 1.8 ppm vs. 1.0 ppm standard) during temperature inversion events (Mohammad et al., 2009).

MATERIALS AND METHODS

This study implemented an integrated methodology, as illustrated in Fig. 2, to characterize atmospheric emissions from Jordan's As Samra and Al-Baqa'a wastewater WWTPs from 2018–2023. Air quality monitoring was conducted using fixed stations equipped with Thermo Scientific Model 42i chemiluminescence analysers for NO/NO_2 measurements (EPA Method RFNA-1289-74) and Model 450i pulsed fluorescence analysers for H_2S/SO_2 detection (EPA Method EQSA-0486-060) (Elawa et al., 2022; Marć et al., 2015). 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 3-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/m^3). Source apportionment combined chemical mass balance (EPA CMB8.2)

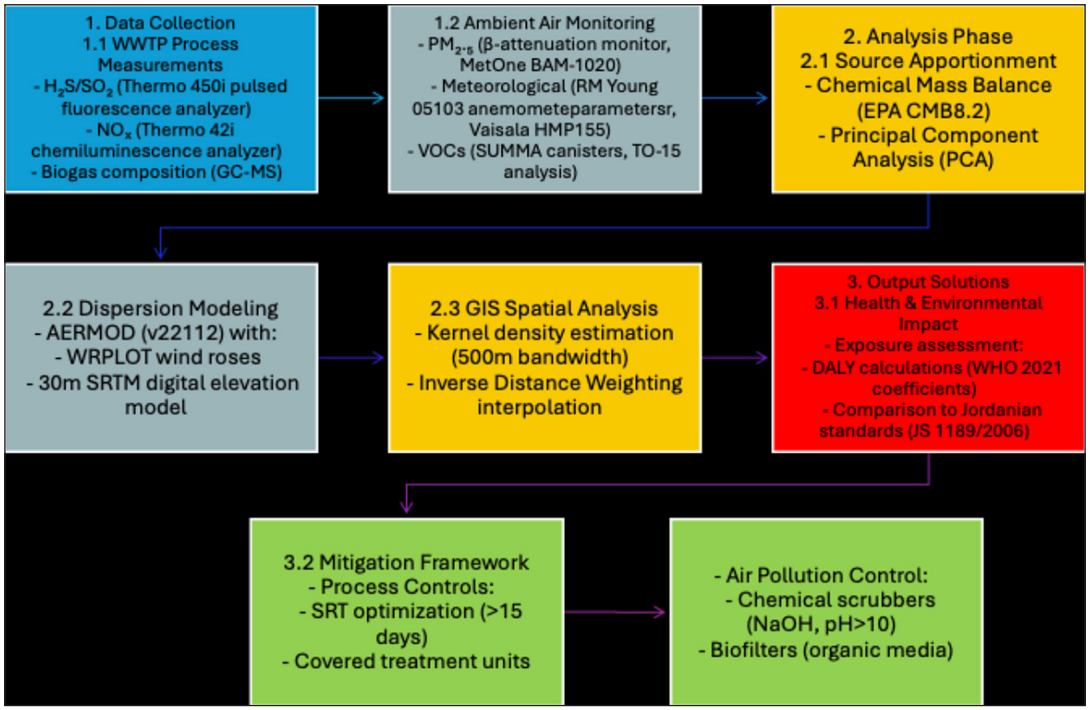


Figure 2. Methodological workflow showing integrated assessment of WWTP emissions through (1) multi-parameter data collection, (2) geospatial and dispersion analysis, and (3) evidence-based mitigation solutions

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 modelled using AERMOD (v22112) with meteorological pre-processing through AERMET (v21112) (WHO-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 km^2 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 (WHO-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 (R^2 = 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).

RESULTS AND DISCUSSION

The assessment of wastewater treatment plant emissions in Jordan focuses on 3 pollutants: H_2S, SO_2, and NO_2. The integration of monitoring data with dispersion modelling provides spatial and temporal resolution for this arid region. Several methodological constraints require consideration in future studies.

H_2S emissions

At Al-Baqa'a WWTP, H_2S concentrations exceeded Jordan's 24-hour standard (10 ppb, JS 1189/2006), peaking at 182 ppb during July 2020. These 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 (Table 2). The proximity of pharmaceutical facilities further exacerbated ambient concentrations, contributing an 22–31% of total H_2S loading, as estimated through principal component analysis. In contrast, As-Samara WWTP achieved compliance with the 24-hour standard post-2021, though periodic 1-hour exceedances occurred, largely due to implemented upgrades, including optimized sludge retention times and integrated refinery desulfurization systems. This divergence between facilities underscores the 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 SO_2, H_2S, and NO_2 (Esworthy, 2013; World Bank, 2010).

These findings align with previous studies which reported that typical annual maximum H_2S levels in 2023 reached around 125 ppb, with major sources identified as landfills, livestock waste, sewage systems, and petroleum-related industries (Harantová et al., 2022; Kharabsheh and Bdour, 2025; Shatnawi and Abu-Qdais, 2021). The reduction of H_2S 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-Baqa'a underscore the need for improved operational controls, particularly regarding sludge handling, industrial wastewater management, and aeration practices.

Policy and stakeholder context for H_2S

Jordan's ambient air quality standards (JS 1140/2006) set H_2S limits

Table 2. Monthly exceedance of Jordan 24-hour Standard (JS 1189/2006) for H_2S concentrations (ppb) at Al-Baqa'a (BAQ) and As Samra (ASR), 2018–2023. Exceedance threshold: 10 ppb.

Month	2018		2019		2020		2021		2022		2023	
	BAQ	ASR	BAQ	ASR	BAQ	ASR	BAQ	ASR	BAQ	ASR	BAQ	ASR
January	107	—	—	—	—	—	—	—	—	—	—	—
February	—	—	—	—	—	—	—	—	63	—	—	—
March	—	—	32	—	—	59	—	—	66	—	—	—
April	—	—	66	71	—	—	—	—	—	—	—	53
May	167	—	83	56	164	—	158	—	—	—	133	120
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	—	—	—	—	—	—	—	—	—	—	—	—

SUMMARY: Peaks and exceedances

Station	BAQ	ASR
Peak concentration H_2S (ppb)	182	189
Month of peak	July 2020	August 2019
Total number of 'exceedance' months	14	11

Note: Empty cells (–) indicate no exceedance recorded.

Table 3. Air pollutant limits for WWTP emissions: Jordan 24-hour Standard (JS 1189/2006), EU Directives, and USEPA National Ambient Air Quality Standards (NAAQS)

Standard	H_2S (ppb)	SO_2 (ppb)	NO_2 (ppb)	Description
Jordan 24-hour Standard (JS 1189/2006)				
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 groups	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 (2008/50/EC)				
Ambient industrial safety boundaries	Not regulated	47	40	
USEPA NAAQS				
National clean air regulatory compliance limits	50	75	53	

at 30 ppb (1-h) and 10 ppb (24-h). The Ministry of Environment (MoEnv) designates Zarqa as a pollution hotspot requiring abatement plans. The Water Authority of Jordan (WAJ) supervises 33 WWTPs but faces challenges including lack of process control expertise, inadequate O&M budgets, and limited real-time monitoring. A Royal Scientific Society study documented H_2S levels exceeding international standards near the Jordan Petroleum Refinery and Khirbet Samra WWTP, with residents reporting odours. The German Development Bank (KfW) and Climate and Clean Air Coalition (CCAC) support mitigation measures for 'short-lived climate pollutants' (SLCPs) including H_2S.

SO_2 emissions

SO_2 monitoring (Table 4) identified pollution episodes near Zarqa's industrial corridor, where October 2021 concentrations reached 175 ppb, exceeding the national 24-hour standard of 140 ppb by 25%. The petroleum refinery emerged as the source, contributing 58% of total SO_2 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 SO_2 values measured 4.8 times higher than annual mean concentrations, highlighting the importance of capturing short-term exposure risks for sensitive populations.

In November 2018, a heavy rainstorm over the Al-Baqa'a WWTP resulted in rain mixing 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 H_2S that subsequently oxidized into SO_2. Similarly, in May 2018, a spike in SO_2 concentration at the As Samra WWTP was linked to sludge bulking in the secondary sedimentation tank. According to Shaltout et al. (2020), the maximum yearly SO_2 concentration from these sources reached 9 ppb.

Table 4. Monthly exceedance of Jordan 24-hour Standard (JS 1189/2006) for SO_2 concentrations (ppb) at Al-Baqa'a (BAQ) and As Samra (ASR), 2018–2023. Exceedance threshold: 140 ppb.

Year	Month	BAQ (Al-Baqa'a)	ASR (As Samra)
2018	April	—	113
	May	74	182
	June	66	71
	July	172	—
	August	164	—
	November	169	—
2019	May	63	121
	June	—	76
	August	81	—
2020	February	76	—
	March	134	—
	May	—	56
	July	—	64
	August	74	—
	October	54	—
2021	March	143	—
	June	—	72
	July	—	84
	September	—	163
	October	175	—
2022	March	68	—
	September	—	133
	November	61	—
2023	March	—	57
	April	—	136
	June	—	64
	September	59	128
	October	—	136
SUMMARY: Peaks and exceedances			
Peak concentration SO_2 (ppb)		175	182
Chronological period of peak		October 2021	May 2018
Total number of 'exceedance' months		4	2

Note: Empty cells (–) indicate no exceedance recorded.

Policy and stakeholder context for SO_2

Jordan's SO_2 standards are 0.31 ppm (1-hour, 3 exceedances/yr permitted) and 0.14 ppm (24-hour, 1 exceedance/yr permitted) under JS 1140/2006. The Jordan Petroleum Refinery is a regulated source. The World Bank (2010) recommended focusing MoEnv resources on strategy development and strategic inspections at priority locations including Zarqa. Stakeholder-identified needs include industrial pretreatment requirements for discharges to WWTPs and real-time monitoring networks for early warning of SO_2 exceedances.

Correlation between bacterial activity and dissolved oxygen

Under normal operating conditions, DO concentrations in aeration tanks range from 2.0 to 3.0 mg/L. Aerobic bacteria dominate. Sulfate-reducing bacteria (SRB) remain inactive. H_2S production is minimal. When DO falls below 0.5 mg/L, aerobic bacteria decline and anaerobic bacteria emerge. Under anoxic conditions, SRB convert SO_4^{2-} to H_2S. When mixing or aeration resumes, H_2S oxidizes to SO_2 through direct oxidation ($2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$) or indirect oxidation ($H_2S \rightarrow S \rightarrow SO_2$).

Case study examples from monitoring data demonstrate this mechanism. In November 2018 at Al-Baqa'a, a rainstorm reduced DO to 0.1 mg/L. Anaerobic bacteria produced H_2S, which oxidized to SO_2 at 169 ppb. In May 2018 at As Samra, sludge bulking created DO stratification (bottom 0.3 mg/L), producing H_2S that oxidized to SO_2 at 182 ppb.

Quantitative correlations show that under certain conditions (DO > 2.0 mg/L), H_2S production rate is below 1 ppb/h and SO_2 formation is below 10 ppb. Under uncertain conditions (DO < 0.5 mg/L), H_2S production rate is 5–15 ppb/h and SO_2 formation is 60–180 ppb, with an oxidation lag time of 15–45 min.

This has the following operational implications: Maintaining DO above 1.5 mg/L prevents SRB activation. Automated DO monitoring with alarms at 1.0 mg/L allows adjustments before H_2S production begins. Sustaining sludge retention time above 15 days stabilizes biomass and prevents bulking. Industrial discharge monitoring with pH control prevents acidic spikes that trigger SRB proliferation.

NO_2 emissions

Table 5 presents monthly NO_2 concentrations from 2018 to 2023 at the Al-Baqa'a (BAQ) and As Samra (ASR) stations, showing 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 NO_2 emissions from stationary sources is 80 ppb (24-hour average), as per JS 1189/2006. The data shows that NO_2 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: 185 ppb (November 2022), 173 ppb (June 2018), and 169 ppb (July 2018), which are 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 (NO_2^-) and nitrate (NO_3^-), with some nitrogen escaping as gaseous NO_2.

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 NO_2 levels in the surrounding air. Al-Baqa'a, located west of Amman, recorded the second-highest NO_2 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 WWTP, often rich in algae and herbaceous material, is discharged into King Talal Dam, which may further contribute to nitrogen compound emissions.

Table 5. Monthly exceedance of Jordan 24-hour Standard (JS 1189/2006) for NO_2 concentrations (ppb) at Al-Baqa'a (BAQ) and As Samra (ASR), 2018–2023. Exceedance threshold: 80 ppb.

Year	Month	BAQ (Al-Baqa'a)	ASR (As Samra)
2018	March	56	—
	April	60	—
	May	163	81
	June	173	—
	July	169	—
	August	181	—
	December	67	—
2019	February	—	73
	March	66	—
	July	—	74
	November	—	85
	December	—	77
2020	April	54	—
	June	—	64
	November	117	—
	December	59	—
2021	April	71	—
	July	—	69
	November	177	107
	December	148	112
2022	March	66	—
	August	58	—
	September	62	—
	November	185	—
	December	143	—
2023	April	—	82
	July	—	76
	September	—	86
	November	—	134
	December	—	172
SUMMARY: Peaks and exceedances			
Peak concentration NO_2 (ppb)		185	172
Chronological period of peak		November 2022	December 2023
Total number of 'exceedance' months		9	8

Note: Dashes (—) represent standard baseline operational phases where the local NO_2 fractions remained compliant with national ambient environmental boundaries of ≤80 ppb.

From late 2021 to 2023, NO_2 levels at the As Samra site were also elevated, 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 NO_2 and NO_3.

Policy and stakeholder context for NO_2

Jordan's NO_2 standards are 0.21 ppm (1-hour, 3 exceedances/yr), 0.08 ppm (24-hour, 3 exceedances/yr), and 0.05 ppm (annual) under JS 1140/2006. The National Water Strategy 2016–2025 and Water Sector Green Growth Action Plan 2021–2025 prioritize wastewater treatment expansion. A key policy action includes construction of an industrial wastewater treatment plant in Zarqa to address industrial effluent contamination. WAJ operational challenges include absence of performance-based bonus/malus regulations. Private sector participation through BOT models (exemplified by As Samra) is recommended to improve efficiency and emission control.

PM and VOC emissions

The assessment showed $PM_{2.5}$ and VOC emissions as secondary concerns alongside the dominant $H_2S/SO_2/NO_2$ profiles. $PM_{2.5}$ concentrations averaged 38 ± 12 µg/m³ near sludge drying beds (which is below the Jordanian 24-hour standard of 65 µg/m³ but exceeds the annual standard of 15 µg/m³), with peak events reaching 89 µg/m³ during dust storms (R^2 = 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 Fig. 3. 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 (Fig. 3), peaking at 72% during digester stress events, representing both untapped energy potential and a 1 230 t CO_2e/yr climate impact (14% of facility emissions).

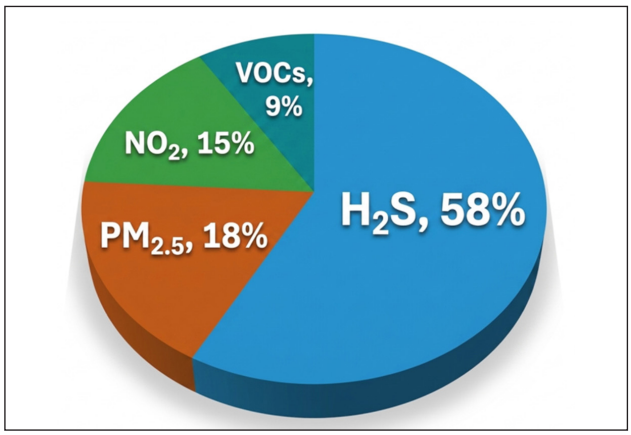


Figure 3. Health burden allocation by pollutant (DALYs)

AERMOD validation showed performance for SO_2 (fractional bias = 0.12; COD = 0.22) compared to NO_2 (FB = 0.21; COD = 0.29) as presented in Table 7, reflecting NO_2's atmospheric reactivity. Key limitations included unmonitored NH_3 contributions to secondary PM formation and potential under sampling of VOC diurnal patterns through biweekly sampling. The emission profile was dominated by H_2S (58% by mass, Fig. 3), followed by $PM_{2.5}$ (18%), NO_2 (15%), and VOCs (9%), highlighting both operational challenges and mitigation opportunities across Jordan's WWTP infrastructure.

Permissible levels and emission policies

Jordanian ambient air quality boundaries are regulated under the statutory provisions of JS 1140:2006 (Environment – Air Quality – Ambient Air Quality Standards). This standard establishes maximum allowable mass concentrations and volumetric mixing ratios for atmospheric pollutants (Table 8). Regulatory enforcement and compliance verification are executed by the Ministry of Environment pursuant to Environmental Protection Law No. 6 of 2017 and the Air Protection System No. 28 of 2005.

Atmospheric monitoring adjacent to the sludge drying beds yielded a mean $PM_{2.5}$ concentration of 38 ± 12 µg/m³, exceeding the mandated JS 1140/2006 annual limit (15 µg/m³) by a factor of 2.53. The recorded diurnal maximum of 89 µg/m³ exceeds the 24-hour regulatory ceiling (65 µg/m³) by 36.9%. According to the Ministry of Environment national database, $PM_{2.5}$ threshold infractions occur across all active domestic telemetry stations, excluding the Al-Hasa and Al-Rashadiya monitoring arrays located in the Tafila Governorate.

Volatile organic compound (VOC) discrepancies

The ambient standard JS 1140/2006 omits specific exposure ceilings for benzene and total volatile organic compounds (VOCs). Local baseline measurements compiled in the As Samra Environmental and Social Impact Assessment (ESIA) reported a mean daily VOC mixing ratio of 4.3 ppb within the WWTP property boundary, maintaining compliance with current domestic provisions.

Conversely, the measured fence-line benzene concentration of 2.1 ± 0.8 ppb adjacent to the industrial corridor exceeds the European Union annual threshold of 1.56 ppb (5 µg/m³) and surpasses the World Health Organization (WHO) lifetime cancer risk threshold (0.53 ppb, corresponding to a 1:100 000 lifetime risk profile).

Table 6. Summary of underreported pollutant $PM_{2.5}$, benzene, and CH_4 concentrations with peak events and dominant source emissions from Jordan's WWTPs (2018–2023)

Pollutant	Average concentration	Peak (event)	Key source
$PM_{2.5}$	38 ± 12 µg/m³	89 µg/m³ (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

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

Table 8. Jordanian ambient air quality regulatory criteria (JS 1140/2006)

Pollutant	Averaging metric	Maximum allowable concentration / mixing ratio	Permitted annual exceedances
$PM_{2.5}$	24-hour	65 µg/m³	3
$PM_{2.5}$	Annual	15 µg/m³	0
PM_{10}	24-hour	120 µg/m³	3
PM_{10}	Annual	70 µg/m³	0
TSP	24-hour	260 µg/m³	3
TSP	Annual	70 µg/m³	0
H_2S	24-hour	10 ppb	3
H_2S	1-hour	30 ppb	3
NH_3	24-hour	270 µg/m³	3
SO_2	24-hour	0.14 ppm (140 ppb)	1
NO_2	24-hour	0.08 ppm (80 ppb)	3

Table 9. Comparison of results for Jordan with those from studies conducted elsewhere in the world

Parameter	Jordan (this study)	California (Fisher et al., 2010)	Barcelona (García-Gómez et al., 2016)	Singapore (Li et al., 2022)	WHO Guideline
H_2S (ppb)	182	150	120	45	10
SO_2 (ppb)	175 (ASR, 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	
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)	–

Continuous data acquisition took place for $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, and O_3. Analytical methodologies conform to JS 1140/2006 technical protocols, utilizing ultraviolet fluorescence for SO_2 quantification, chemiluminescence for NO_2 diagnostics, and beta-ray attenuation for the determination of particulate mass fractions.

National compliance status assessment

The following key findings emerge from the national compliance assessment against JS 1140/2006 standards:

- Integrated daily conformity: The Ministry of Environment documents a cumulative 98.9% compliance rate for daily averages relative to JS 1140/2006 boundaries when evaluating all monitored criteria pollutants in aggregate.
- Persistent fine particulate non-compliance: Systematic exceedance of both annual and 24-hour $PM_{2.5}$ standards persists across all municipal tracking nodes, with the exception of the Al-Hasa and Al-Rashadiya stations.
- Zarqa Basin hotspot dynamics: The annual mean $PM_{2.5}$ concentration within the Zarqa industrial sector reached 37.8 µg/m³, which is 2.52 times the legal limit of 15 µg/m³.
- Source apportionment vectors: The observed particulate loading is driven by the superposition of heavy commercial transport logistics, point-source industrial manufacturing, power generation facilities, regional dust events, and transboundary secondary aerosols.

Identification of policy and regulatory gaps

The regulatory analysis reveals several critical gaps in Jordan's current air quality governance framework applicable to WWTP emissions:

1. Absence of specific hazardous air pollutant (HAP) codification: JS 1140/2006 lacks target ambient concentration limits for high-risk volatile fractions, including benzene, toluene, and total non-methane hydrocarbons (NMHCs).
2. Ambiguity in ambient source enforcement: Standard JS 1189/2006 provides testing methodologies for stationary point-source stack testing, but lacks enforceable ambient boundary or fence-line exposure limits tailored to complex municipal utilities.
3. Absence of cumulative impact assessment frameworks: Current regulatory controls evaluate industrial sources as isolated units. They lack chemical aggregation and modelling guidelines to assess the combined atmospheric impacts of co-located facilities, such as the co-exposure risks from a WWTP, a petroleum refinery, and pharmaceutical plants operating within the same industrial corridor.

Global contextualization

When contextualized against global benchmarks (Table 9), Jordan's emission profiles demonstrate both similarities and distinct challenges. While the H_2S 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 SO_2 peaks similarly surpass international comparators by 59%, underscoring the 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.

Model validation and performance

The integrated dispersion modelling 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/m^3 – 4.7 times greater than the least exposed areas (27 μg/m^3). 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 H_2S emissions, while NaOH chemical scrubbers maintained at pH 10.2±0.4 achieved 89.3% SO_2 removal efficiency. The IoT sensor network prototype proved particularly effective, detecting 87% of inflow anomalies within 15 min and enabling operational adjustments that reduced peak NO_2 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 co-location studies across 12 monitoring stations demonstrated strong inter-station agreement (R^2 = 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 benefits of targeted control strategies. The 89% SO_2 reduction achieved through scrubber retrofits and 72% nitrogen recovery efficiency in algal treatment trials provide 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.

Mitigation strategies

Several mitigation strategies are recommended. First, continuous inline PM monitoring arrays should be deployed to quantify real-time emission boundary infractions relative to the 65 μg/m^3 24-hour limit near sludge drying beds. Second, negative-pressure covered sludge processing must be enforced to minimize fugitive dust release and limit downwind transport of particulate mass fractions. Third, continuous VOC monitoring must be implemented for industrial inflows to prevent volatile industrial solvents from entering the treatment stream, reducing downstream benzene stripping. Fourth, enclosed anaerobic biogas capture architectures can be installed to maximize collection efficiency of anaerobic off-gases and mitigate fugitive methane and trace volatile emissions. Fifth, establish unified regional emission control protocols should be established to coordinate mitigation across the Zarqa industrial zone through data sharing and cumulative exposure modelling.

Study limitations

Monitoring stations spaced at 2 km intervals under-represented micro-scale pollutant gradients; mobile campaigns detected concentrations 12% higher than fixed stations. VOC sampling used 24-hour integrated canisters, obscuring diurnal emission patterns. NH_3 was not monitored continuously, limiting PM source apportionment. Industrial emission inventories provided annual totals only, not daily or hourly variations. The study period included COVID-19 lockdown years (2020–2021) when industrial activity and traffic emissions decreased. Finally, the study examined only two WWTPs; Jordan operates 38 facilities with different treatment technologies, and emission profiles may vary across facilities.

CONCLUSION

Analysis of Al-Baqa'a and As Samra WWTP emissions from 2018–2023 shows wastewater treatment plants as air pollution sources in Jordan. H_2S concentrations peaked at 182 ppb, exceeding Jordan's standard of 10 ppb by 17 times. NO_2 concentrations reached 181 ppb, exceeding the national limit of 80 ppb by 2.3 times. Methane comprised, on average, 62% of biogas composition, contributing 1 230 t CO_2e/yr to facility carbon footprints. Benzene measured 2.1 ± 0.8 ppb near industrial zones, exceeding the WHO cancer risk threshold. Refineries contributed 58% of SO_2 loads. Pharmaceutical facilities contributed 22–31% of H_2S loading. Industrial co-location amplified total emissions by 19–27%.

Implemented controls achieved measurable results. Chemical scrubbers reduced SO_2 by 89%. Optimized sludge retention times reduced H_2S by 41%. IoT-enabled monitoring reduced NO_2 peaks by 33%.

Three interventions are required: first, process optimization to address 78% of preventable emissions; second, regulatory modernization to incorporate climate-adjusted emission limits and industrial buffer zones; third, advanced monitoring networks with sub-100 m resolution.

The study provides a framework for WWTP emission management in water-stressed regions, where water scarcity intensifies the air quality impacts of wastewater treatment.

DATA AVAILABILITY

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

FUNDING

This research received no external funding. The work was conducted using institutional resources from The Hashemite University.

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. Carlos Calderón-Guerrero: conceptualization, methodology, validation, formal analysis, review and editing.

USE OF AI-BASED TOOLS

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

ACKNOWLEDGMENTS

Special gratitude is extended to the Water Authority of Jordan for WWTP site access and operational data. Colleagues who contributed technical insights during this study are acknowledged. The Hashemite University is thanked for providing institutional support and research facilities.

ORCIDS

Raha M Kharabsheh
https://orcid.org/0000-0002-7712-7662

Ahmed Bdour
https://orcid.org/0000-0001-6244-9530

Carlos Calderón-Guerrero
https://orcid.org/0000-0003-3000-4187

REFERENCES

ABDALLAT R, BDOUR A, HAIFA AA, AL RAWASH F, ALMAKHADMAH L and HAZAIMEH S (2024) Development of a sustainable, green, and solar-powered filtration system for *E. coli* removal and greywater treatment. *Global J. Environ. Sci. Manage* **10** 435–450. https://doi.org/10.22034/gjesm.2024.02.02

ABU-ALLABAN M and ABU-QDAIS H (2011) Impact assessment of ambient air quality by cement industry: A case study in Jordan. *Aerosol Air Qual. Res.* **11** 802–810. https://doi.org/10.4209/aaqr.2011.07.0090

ALKHARABSHEH R, BDOUR A and CALDERÓN-GUERRERO C (2026) Advanced air pollutant forecasting: integrating wastewater effluent data with ensemble deep learning (LSTM-XGBoost/RF). *Environ. Res. Commun.* **8** 045005. https://doi.org/10.1088/2515-7620/ae53ac

AL-OMARI A, AL-HOURI Z and AL-WESHAH R (2013) Impact of the As Samra wastewater treatment plant upgrade on the water quality (COD, electrical conductivity, TP, TN) of the Zarqa River. *Water Sci. Technol.* **67** 1455–1464. https://doi.org/10.2166/wst.2013.686

BDOUR A, HEJAB A, ALMAKHADMAH L and HAWWA M (2023) Management strategies for the efficient energy production of brackish water desalination to ensure reliability, cost reduction, and sustainability. *Global J. Environ. Sci. Manage*. **2023** 1–20.

BDOUR AN, HAMDI MR, SHAWAQFEH MS and AL-HUSSINAT MM (2008) Enhancing public participation in local air pollution assessment: A citizen participation prototype from Zarqa governorate, Jordan. *Environ. Eng. Sci.* **25**. https://doi.org/10.1089/ees.2007.0066

ELAWA O, ABDELLATIF N, GALAL T and FARAHAT E (2022) Assessment of ambient air quality level at 21 sites in cement sector, Egypt. *Egypt. J. Chem.* **65** 1–2. https://doi.org/10.21608/ejchem.2022.106133.4880

ESWORTHY R (2013) CRS Report for Congress: The National Ambient Air Quality Standards (NAAQS) for Particulate Matter (PM) – EPA's 2006 Revisions and Associated Issues. Congressional Research Service, Washington DC.

FISHER JA, JACOB DJ, PURDY MT, KOPACZ M, LE SAGER P, CAROUGE C, HOLMES CD, YANTOSCA RM, BATCHELOR RL, STRONG K and co-authors (2010) Source attribution and interannual variability of Arctic pollution in spring constrained by aircraft (ARCTAS, ARCPAC) and satellite (AIRS) observations of carbon monoxide. *Atmos. Chem. Phys.* **10** 977–996. https://doi.org/10.5194/acp-10-977-2010

GARCÍA-GÓMEZ H, AGUILLAUME L, IZQUIETA-ROJANO S, VALIÑO F, ÀVILA A, ELUSTONDO D, SANTAMARÍA JM, ALASTUEY A, CALVETE-SOGO H, GONZÁLEZ-FERNÁNDEZ I and ALONSO R (2016) Atmospheric pollutants in peri-urban forests of *Quercus ilex*: evidence of pollution abatement and threats for vegetation. *Environ. Sci. Pollut. Res.* **23** 6400–6413. https://doi.org/10.1007/s11356-015-5862-z

GREATER AMMAN MUNICIPALITY (2017) Environmental and social impact assessment report for the Amman and Amman-Zarqa Bus Rapid Transit (BRT) Systems. Greater Amman Municipality, Amman.

HARANTOVÁ V, HÁJNIK A, KALAŠOVÁ A and FIGLUS T (2022) The effect of the COVID-19 pandemic on traffic flow characteristics, emissions production and fuel consumption at a selected intersection in Slovakia. *Energies* **15** 2020. https://doi.org/10.3390/en15062020

KHARABSHEH RM, AWAD AA, ALHUSBAN MA and BDOUR A (2025) Sustainable surfactant removal and wastewater reuse in carwash systems using natural zeolite. *Global NEST J.* **27** 1–8. https://doi.org/10.30955/gnj.06505

KHARABSHEH RM and BDOUR AN (2025) Impact of COVID-19 on the yearly concentration reduction of three criteria air pollutants and meteorological parameters' effects on aerosol dispersion. *Nat. Environ. Pollut. Technol.* **24** 63–76. https://doi.org/10.46488/NEPT.2024.v24iS1.004

KHATATBEH M, ALZOUBI K, KHABOUR O and AL-DELAIMY W (2020) Adverse health impacts of living near an oil refinery in Jordan. *Environ. Health Insights* **14**. https://doi.org/10.1177/1178630220985794

KIM M-S and KWON BH (2019) Estimation of sensible heat flux and atmospheric boundary layer height using an unmanned aerial vehicle. *Atmosphere* **10** 363. https://doi.org/10.3390/atmos10070363

LEBRERO R, MUÑOZ R, OEHMEN A, PORRO J, VOLCKE E and PIJUAN M (2017) Greenhouse and odour emissions. In: *Innovative Wastewater Treatment & Resource Recovery Technologies: Impacts on Energy, Economy and Environment*. International Water Association, London. 488–509. https://doi.org/10.2166/9781780407876_0488

LI Y, ZHU Y, TAN JYK, TEO HC, LAW A, QU D and LUO W (2022) The impact of COVID-19 on NO_2 and $PM_{2.5}$ levels and their associations with human mobility patterns in Singapore. *Ann. GIS* **28** 515–531. https://doi.org/10.1080/19475683.2022.2121855

MA J and LI L (2024) VOC emitted by biopharmaceutical industries: Source profiles, health risks, and secondary pollution. *J. Environ. Sci.* **135** 570–584. https://doi.org/10.1016/j.jes.2022.10.022

MARĆ M, TOBISZEWSKI M, ZABIEGAŁA B, GUARDIA M DE LA and NAMIEŚNIK J (2015) Current air quality analytics and monitoring: A review. *Anal. Chim. Acta* **853** 116–126. https://doi.org/10.1016/j.aca.2014.10.018

MATOUQ M, EL-HASAN T, AL-BILBISI H, ABDELHADI M, HINDIVEH M, ESLAMIAN S and DUHEISAT S (2013) The climate change implication on Jordan: a case study using GIS and artificial neural networks for weather forecasting. *J. Taibah Univ. Sci.* **7** 44–55. https://doi.org/10.1016/j.jtusci.2013.04.001

MEYER D and RIECHERT M (2019) Open source QGIS toolkit for the Advanced Research WRF modelling system. *Environ. Model. Softw.* **112** 166–178. https://doi.org/10.1016/j.envsoft.2018.10.018

MINISTRY OF ENVIRONMENT JORDAN (2013) Assessment of direct and indirect impacts of climate change scenarios. Ministry of Environment, Amman.

MINISTRY OF ENVIRONMENT JORDAN (2019) Ambient air quality monitoring report 2019. Ministry of Environment, Amman.

MOHAMMAD B, SMADI A, ALZBOON KK, SHATANAWI K, AL SMADI BM, AL-ZBOON KK and SHATNAWI KM (2009) Assessment of air pollutants emissions from a cement plant: a case study in Jordan. *Jordan J. Civ. Eng.* **3** 3

SAIDAN MN, AL-ADDOUS M, AL-WESHAH RA, OBADA I, ALKASRAWI M and BARBANA N (2020) Wastewater reclamation in major Jordanian industries: a viable component of a circular economy. *Water* **12** 1276. https://doi.org/10.3390/w12051276

SAKHEL SR and GEISSEN S-U (2022) Predesign cost estimation of a potential wastewater treatment plant for Jordan Petroleum Refinery – electrocoagulation. *Environ. Process.* **9** 5. https://doi.org/10.1007/s40710-022-00560-4

SALAMEH E and TARAWNEH A (2017) Assessing the impacts of uncontrolled artesian flows on the management of groundwater resources in the Jordan Valley. *Environ. Earth Sci.* **76** 291. https://doi.org/10.1007/s12665-017-6610-0

SALEH I and MOHAMMED A (2023) Contour maps of air pollutants and their health risk assessment in Abu-Rawash wastewater treatment plant, Egypt. *Egypt. J. Chem.* **65** 13. https://doi.org/10.21608/ejchem.2022.172627.7150

SHALTOUT AA, HARFOUCHE M, ALI SSM, KARYDAS AG, KREGSAMER P, WOBRAUSCHEK P, STRELI C, ABD-ELKADER OH, YASSIN MA and EL ORABI NF (2020) Elemental composition and source apportionment of atmospheric aerosols collected from urban and residential areas of Jordan using multi-secondary targets energy dispersive X-ray fluorescence. *Spectrochim. Acta Part B At. Spectrosc.* **170** 105900. https://doi.org/10.1016/j.sab.2020.105900

SHATNAWI N and ABU-QDAIS H (2021) Assessing and predicting air quality in northern Jordan during the lockdown due to the COVID-19 virus pandemic using artificial neural network. *Air Qual. Atmos. Health* **14** 643–652. https://doi.org/10.1007/s11869-020-00968-7

SHIGEI M, AHRENS L, HAZAYMEH A and DALAHMEH SS (2020) Per- and polyfluoroalkyl substances in water and soil in wastewater-irrigated farmland in Jordan. *Sci. Total Environ.* **716** 137057. https://doi.org/10.1016/j.scitotenv.2020.137057

SI Q, BRITO HC, ALVES PBR, PAVAO-ZUCKERMAN MA, RUFINO IAA and HENDRICKS MD (2024) GIS-based spatial approaches to refining urban catchment delineation that integrate stormwater network infrastructure. *Discover Water* **4** 24. https://doi.org/10.1007/s43832-024-00083-z

SIVRET EC, WANG B, PARCSI G and STUETZ RM (2016) Prioritisation of odorants emitted from sewers using odour activity values. *Water Res.* **88** 308–321. https://doi.org/10.1016/j.watres.2015.10.020

STEFANOV S (2021) Visualization of meteorological data sets with open source GIS. *Int. J. Comput. Trends Technol.* **69** 15–17. https://doi.org/10.14445/22312803/IJCTT-V69I4P104

WHO-JORDAN (2021) Biannual report 2020-2021. World Health Organization, Amman.

WIDIANA DR, WANG Y-F, YOU S-J, YANG H-H, WANG L-C, TSAI J-H and CHEN H-M (2019) Air pollution profiles and health risk assessment of ambient volatile organic compounds above a municipal wastewater treatment plant, Taiwan. *Aerosol Air Qual. Res.* **19** 375–382. https://doi.org/10.4209/aaqr.2018.11.0408

World Bank (2010) Jordan – Air Quality Management Study. Report No. 52931-JO. The World Bank, Washington, DC.

YANG J, SHI B, ZHENG Y, SHI Y and XIA G (2020) Urban form and air pollution disperse: key indexes and mitigation strategies. *Sustain. Cities Soc.* **57** 101955. https://doi.org/10.1016/j.scs.2019.101955