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# Air Pollution, Water, Sanitation and Hygiene (WASH) and Attributable-Mortality Indicators in Saudi Arabia: A National Ecological Analysis with a 1990–2020 PM2.5 Exposure Series

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**Abstract** **Objectives:** Exposures and WASH service performance are interconnected determinant factors of avoidable mortality and health. A secondary analysis has been carried out in the context of a national-level indicator-based assessment of the situation with exposure/WASH in Saudi Arabia, based on the long-term national level exposure time-series data of urban air pollution PM2.5, household environment and WASH behavior profile, wastewater treatment regional benchmarks, attributable mortality, and SDGs-aligned service indicators. **Methods:** A secondary, retrospective ecological analysis using the national-level indicators of Saudi Arabia in three independent, analyzed datasets has been conducted. The key outcomes included World Health Organization age-standardized modeled mortality per 100,000 attributable to household and ambient air pollution (SDG 3.9.1), mortality per 100,000 attributable to unsafe WASH (SDG 3.9.2, 2019 only), safely managed sanitation (%), safely treated domestic wastewater flows (%), primary reliance on clean fuels (%), and urban population-weighted PM2.5 (SDG 11.6.2, μg/m³). Variables used additionally were: (i) 1990-2020 time-series of urban PM2.5 exposure in Saudi Arabia with summations per decade, annual change, smoothening and OLS regression models, (ii) national household environment and WASH-related practices including drinking water source, water saving devices, waste sorting, e-waste management and perceived pollution in one cross-section in 2022 reported by GASTAT Household Environment Survey, and (iii) GCC benchmarking of household-only percentage share of safely treated domestic wastewater flow using SDG 6.3.1 indicator report year. **Results:** The air pollution-attributable mortality in Saudi Arabia went down from 113.3 to 91.2 per 100,000 between 2010 and 2019 (-22.1, -19.51%, AAPC -2.38 %/year), whereas the endpoint PM2.5 values showed almost no difference in 2010-2019 (from 56.6 to 57.2 μg/m³, +1.06%, AAPC +0.12%/year). Meanwhile, the 1990-2020 PM2.5 exposures in Saudi Arabia reached its peak value in 2012 at 65.81 μg/m³ and went down to 53.15 μg/m³ in 2020 with the OLS regression slope +0.517 μg/m³/year (95% CI 0.351-0.683), while the slopes in 2000-2020 and 2010-2020 periods were not statistically significant. The safely managed sanitation improved slightly from 79% to 80% (2000-2022, +1.27%, AAPC +0.06 %/year). The safely treated domestic wastewater went up from 80% to 85% (2020-2022, +6.25%, AAPC +3.08 %/year). Primary reliance on clean fuels is at 100% for 2000-2022. Cross-section in 2022 of household practices showed that 49.06% of households use bottled water as the source for drinking water and the presence of water-saving devices is quite uncommon (34.34%), but there is a high level of e-waste disposal to public bins (73.11%) and low percentage of proper recycling (11.07%). In terms of SDG 6.3.1 benchmarking of safely treated domestic wastewater percentage among peers using the different years of last available reports (2022-2024), Saudi Arabia demonstrates higher coverage (87.65%) than the global average (55.78%), but still lower than some GCC members and lower domestic coverage (58.43%). **Conclusion:** There was a reduction in air pollution-attributable mortality in Saudi Arabia in 2010-2019 despite low reduction of PM2.5 levels, while there are high and volatile levels with an increasing slope observed in the 1990-2020 exposure time-series. No correlation between them was found. Some slight improvement has occurred in the WASH indicators, although their baseline is high. Maximum differences are observed for safely treated domestic wastewater in a short period 2020-2022. Household profiling and wastewater benchmarking show priority aspects of monitoring and policymaking beyond mere WASH service coverage.

**Key Words:** Saudi Arabia, Air Pollution, Particulate Matter, Water, Sanitation and Hygiene (WASH), Wastewater Treatment, Ecological Study, Time-Series Analysis, Environmental Health Indicator

## INTRODUCTION

Exposures and WASH services remain major determinants of diseases and mortality that can be prevented [1]. Particulate matter (PM2.5) is consistently linked with cardiopulmonary morbidity and mortality, and updates to the World Health Organization guidelines highlight that a significant health burden exists for a wide range of exposure, necessitating monitoring and measures even in environments of rapid infrastructural development [2]. Global comparative risk assessments identify air pollution as the leading cause of the attributable mortality reflecting intensity and characteristics of the underlying populations [1-3].

In parallel, WASH services affect the infectiousness and safety of water, sanitation and hygiene by providing safe containment and processing of the human waste products. Modern monitoring emphasizes safely managed sanitation and safely treated domestic wastewater over the mere existence of service access [4-5]. While the indicators cannot substitute for each other, the first captures the households' access to sanitation whose excreta are safely managed, and the second measures the domestic wastewater flow treated to the standard (alongside other sources of wastewater) [4-7]. The issues of PM2.5 pollutions and its management are relevant for Saudi Arabia because of rapid urbanization, demographic transformation and continuing infrastructure growth. The dust pollution is a dominant factor behind ambient PM2.5 pollutions in the Arab Peninsula, PM2.5 levels vary depending on the climate region and the city [9-11]. The urban annual mean PM2.5 indicators is standardized and therefore can be compared over time and across countries, although longer term time-series structure, volatility and presence of any non-monotone trends can benefit the assessment [12].

Mortality attributable to household and ambient air pollution takes into account both the exposure and the baseline risk and clinical services available, therefore divergence between the exposure metrics – e.g., PM2.5-and the attributable mortality metric might reflect the shifts in the population vulnerabilities, risk distribution, access to care, or estimation methods rather than exposure levels alone [8]. These factors cannot be disentangled using aggregate indicators. The mortality indicator encompasses both household and ambient air pollution [3,13], while the PM2.5 series describe only the ambient exposure. In the same manner WASH services captured by the safely managed sanitation and safely treated domestic wastewater measures include complementary aspects of service coverage and performance of the downstream system. At the same time, such coverage indicators might hide the problems with quality and the pathways of exposure such as drinking water access patterns, water saving practices and household waste handling. The latter factors can be better assessed by the means of national statistical surveys [4,14]. Some Saudi studies examined PM2.5 burden, sources or spatiotemporal pattern, but, to the best of authors' knowledge, none of those studies combined the long-term exposure trend with SDG-aligned WASH indicators, national household environment and wastewater benchmarks. Therefore, the aim was to estimate the absolute, relative and annualized changes in standardized air pollution and WASH indicators during their available reporting periods, including an exposure series of PM2.5 from 1990 to 2020. The additional aims were to characterize the 2022 national household environment and WASH practices and to compare domestically treated safely domestic wastewater to regional peers.

## METHODS

### Study Design and Setting

The current study is a secondary, retrospective, ecological analysis on a country-level (population-level) scale in Saudi Arabia based on national publicly available indicators of environmental exposures and WASH-related endpoints. There were three components included in the analysis having different designs and levels of aggregation, these include:

- Ecological analysis of country-year indicator values including time-series for 1990-2020 of annual urban PM2.5
- Cross-sectional description of published national household percentages for 2022
- Cross-sectional analysis of country-level SDG 6.3.1 estimates for the latest reporting year. Components of the analysis have been conducted independently without pooling them together into one longitudinal study. Pre-defined indicators set and exploratory nature of the study are highlighted below

### Sources of Data and Indicator Domains

Online datasets on environmental exposure, mortality attributable, and WASH related issues (available free of charge) have been considered as a data source in this paper. Main indicators of the research are as follows:

- Mortality attributable to household and ambient air pollution (SDG 3.9.1, WHO, age-standardized, deaths per 100,000 population) [15-17], it is a modeled indicator
- Mortality attributable to unsafe WASH services (SDG 3.9.2, WHO, deaths per 100,000 populations, 2019 only) [15-17]
- Proportion of the population using safely managed sanitation services (SDG 6.2.1a, UNICEF/WHO) [4]
- Proportion of domestic wastewater flows safely treated (SDG 6.3.1, UN-HABITAT, WHO) [5,6],
- Proportion of the population with primary reliance on clean fuels and technology (SDG 7.1.2, WHO) [18-20]
- Annual urban mean PM2.5 in µg/m³ (SDG 11.6.2, WHO) [12]. The earliest and latest years in the data set for Saudi Arabia on each of the main indicators along with correspondent standardized change measures (the end points are different for different indicators)
- Time series on PM2.5 (1990-2020): Annual population-weighted mean PM2.5 in urban areas (World Bank

World Development Indicators, EN.ATM.PM25.MC.M3, derived from Global Burden of Disease exposure model) [21]. Time series on PM2.5 differs from the indicator

- In overlap years (e.g., 59.84 versus 56.6 µg/m³ in 2010), the value taken at the time of data extraction is used, however, sometimes other sources revise previously reported values (for example, 68.4 µg/m³ for 2020 in July 2026 release)
- Household environment/WASH practice profile from the GASTAT Household Environment Statistics Publication 2022 (a national survey of the household in all regions of Saudi Arabia carried out by computer-assisted telephone/web interview, national percentages) [14]: national distribution of household reliance on the water source, use of water-saving devices, practice of the solid waste disposal, segregation practice, the practice of the e-waste disposal and the burden of air pollution, noise and visual pollution as well as the interest in environmental topics
- Benchmarking of the regions on safely treated wastewater (SDG 6.3.1, United Nations Sustainable Development Goals database, last report year per country) [5,7,22]: compilation of the Gulf Cooperation Council countries on "safely treated wastewater" percentage (disaggregated values, if possible)

**Outcome and Derived Measures**

In relation to the core indicators, the following metrics of interests were selected: a) absolute change (end-start), b) percent change relative to baseline and c) annualized metrics (absolute change divided by years). For percent change metric, calculation was as 100*(end-start)/start (with zero base value for any indicator). Average annual percent change (AAPC) was calculated for the pair of endpoints as 100*[(end/start) ^(1/Δt) –1], where Δt = number of years between endpoints (end year-start year), compound rate corresponds to Compound Annual Growth Rate (CAGR) between two endpoints and not to joinpoint-model AAPC [23]. Change metrics were not calculated for indicators with one point only.

The other measures include:

- **Decades Summaries:** Mean, SD, min, max, start and end values and decade-wise growth (in percent): compounded annual growth rate, CAGR, for each decade over nine annual intervals in the decade. SD is a sample standard deviation (n-1). The single observation in 2020 is reported as a separate year and not decade summary
- **Dynamics:** Year-on-year percentage change, the difference from baseline (1990) and centered 3-year moving average to filter the short-term dynamics (years after 1990 and prior to 2020)
- **Trend Models:** OLS (Ordinary Least Squares) regression was fitted to the periods (years) to quantify slope (in µg/m³ per year), 95% confidence intervals, p-values and R2 for the PM2.5 data (in 1990-2020 period and also 2000-2020, 2010-2020, 1990-2010 periods) and for projections until 2030, the model for PM2.5 was: $PM2.5_t = \beta0 + \beta1 * year_t + \varepsilon_t$. 95% CI on β1 is based on t-formula. Projections till 2030 year were also provided (in relation to selected windows) along with 95% prediction interval (one value). Projection assumes constant linear trend and does not consider the uncertainty associated with model specification. There are three windows of observation for the PM2.5 estimates based on decades to show the sensitivity to period, no joinpoints were defined in these windows

Household indicators profiles are presented as proportions (%), regional wastewater benchmarking results include percentage-based information in the form of provisional ranking due to the differences in the reporting years and disaggregation for different countries.

**Statistical Analysis**

Descriptive and comparative analysis was conducted. Descriptive summary of the core indicators includes baseline, end values, changes (absolute and percentage) and annualized metrics, in addition to the PM2.5 the descriptive summary was supplemented with regression-based trend analysis. Regional benchmarking on safely treated wastewater and analysis of the household practice profiles were provided in addition to core indicators analysis.

**Ethics and Reporting**

The current study is using secondary aggregate (group level) data without any personal data, therefore, there is no need in ethics review board approval and informed consents. Methods used, derived measures and results of the analysis are reported here in order to follow observation/studies estimates requirements for reproducibility and reuse of the study [24,25]. All indicators used in this study are publicly available from above mentioned sources [4-7,12,14-22]. Analytical dataset and scripts for its processing and analysis (Python language) are available from the corresponding author upon request.

## RESULTS

In case of analyzed indicators mortality due to air pollution, both indoor and ambient reduced from 113.3 deaths/100k population in 2010 to 91.2 deaths/100k population in 2019 (absolute change -22.1 deaths, -19.51%) indicating decline of mortality burden in 2019, as just two data points were used, no trend was estimated. However, the annual mean concentration of PM2.5 in urban areas increased very little from 56.6 µg/m³ in 2010 to 57.2 µg/m³ in 2019 (absolute change +0.6, +1.06%). This indicates that the value of annual urban mean of PM2.5 did not show significant changes and

Table 1: Endpoints and Direction of Change (Endpoints Represent the Earliest/Latest Year that an Indicator Is Observed. Windows Vary, Making Percent Change an Invalid Measure of Public Health Significance. Mortality Estimates (SDG 3.9.1, 3.9.2) Are Estimates from the WHO. N/A Not Applicable)

| Indicator | Unit | Start year | Start | End year | End | Abs change | Change (%) | Direction |
|---|---|---|---|---|---|---|---|---|
| Mortality attributable to household and ambient air pollution, age-standardised (SDG 3.9.1) | per 100,000 | 2010 | 113.3 | 2019 | 91.2 | −22.1 | −19.51 | Decrease |
| Mortality attributed to unsafe WASH services (SDG 3.9.2) [15,16] | per 100,000 | 2019 | 1.9 | 2019 | 1.9 | NA | NA | Single year |
| Safely managed sanitation services (SDG 6.2.1a) [4] | % | 2000 | 79 | 2022 | 80 | +1.0 | +1.27 | Increase |
| Safely treated domestic wastewater flows (SDG 6.3.1) [5,6] | % | 2020 | 80 | 2022 | 85 | +5.0 | +6.25 | Increase |
| Primary reliance on clean fuels and technology (SDG 7.1.2) [18–20] | % | 2000 | 100 | 2022 | 100 | 0.0 | 0.00 | No change (reported 100%) |
| PM2.5, urban annual mean, population-weighted (SDG 11.6.2) [12] | µg/m³ | 2010 | 56.6 | 2019 | 57.2 | +0.6 | +1.06 | Increase |

Table 2: Trend Metrics (Duration, Annual Absolute Change, AAPC, Note: Time Period= Ending Year-Starting Year. Yearly Absolute Rate of Change=(End-Start)/Time Period. AAPC= 100 X [(End/Start) ^ (1/Time Period) –1] Calculated Using Only Two Endpoints (Compound Annual Rate Calculation, Not Joinpoint-AAPC [23]). N/A: Not Applicable)

| Indicator | Start year | End year | Duration (years) | Annual absolute change | AAPC, endpoint-based (%/year) | AAPC available | Trend interpretable |
|---|---|---|---|---|---|---|---|
| Mortality attributable to household+ambient air pollution | 2010 | 2019 | 9 | −2.46 | −2.38 | Yes | Endpoints only |
| Mortality attributed to unsafe WASH services | 2019 | 2019 | NA | NA | NA | No | No (single year) |
| Safely managed sanitation services | 2000 | 2022 | 22 | +0.05 | 0.06 | Yes | Endpoints only |
| Safely treated domestic wastewater flows | 2020 | 2022 | 2 | +2.50 | 3.08 | Yes | Endpoints only |
| Primary reliance on clean fuels | 2000 | 2022 | 22 | 0.00 | 0 | Yes | Endpoints only |
| PM2.5 urban annual mean | 2010 | 2019 | 9 | +0.07 | 0.12 | Yes | Endpoints only |

Table 3: Ranked Magnitude of Change Across Indicators

| Indicator | Domain | Abs change | Change (%) | AAPC (%/year) | Direction | Rank by \|% change\| (descriptive) |
|---|---|---|---|---|---|---|
| Mortality attributable to household+ambient air pollution | Air pollution health burden | −22.1 | −19.51 | −2.38 | Decrease | 1 |
| Safely treated domestic wastewater flows | WASH systems performance | +5.0 | +6.25 | 3.08 | Increase | 2 |
| Safely managed sanitation services | WASH coverage | +1.0 | +1.27 | 0.06 | Increase | 3 |
| PM2.5 urban annual mean | Air quality exposure | +0.6 | +1.06 | 0.12 | Increase | 4 |
| Primary reliance on clean fuels | Household energy | 0.0 | 0.00 | 0 | No change | 5 |
| Mortality attributed to unsafe WASH services | WASH health burden | NA | NA | NA | Single year | Not ranked |

Table 4: Weighted Average Annual Exposure to PM2.5 (µg/M³): Descriptive Statistics by Decade, Saudi Arabia (1990-2020)

| Period | Years, n | Start year | End year | Start value | End value | Mean | SD* | Min | Max | CAGR, %† |
|---|---|---|---|---|---|---|---|---|---|---|
| 1990s | 10 | 1990 | 1999 | 46.80 | 53.25 | 48.09 | 2.34 | 46.65 | 53.25 | 1.45 |
| 2000s | 10 | 2000 | 2009 | 54.82 | 59.62 | 58.17 | 1.69 | 54.82 | 59.62 | 0.94 |
| 2010s | 10 | 2010 | 2019 | 59.84 | 58.62 | 60.58 | 4.43 | 51.09 | 65.81 | −0.23 |
| 2020 (single year) | 1 | 2020 | 2020 | 53.15 | 53.15 | 53.15 | NA | 53.15 | 53.15 | NA |

Source: World Bank WDI Indicator EN.ATM.PM25.MC.M3 (Version of Release Extracted) [21], Values in µg/M³. *Sample SD (N − 1). †CAGR = 100 × [(End/Start) ^ (1/9) − 1] Across Nine Annual Periods of Each Decade. The Line for 2020 Represents A Single Data Point, Not A Decade Summary. NA, Not Applicable)

is relatively stable in the studied period. WASH system performance indicators provide evidence of slight to moderate improvement, which includes increase in safely managed sanitation service from 79% in 2000 to 80% in 2022 (+1.0, +1.27%). It could be partially due to rounding of whole numbers, domestically safely treated wastewater increased from 80% in 2020 to 85% in 2022 (+5.0, +6.25%). The use of clean fuels among the general population for 2000-2022 is reported as 100%, however, it should not be taken as the proof as there might be rounding [18,19]. The mortality caused by the unsafe WASH is only one-year statistic: 1.9 deaths/100k in 2019 (Table 1).

An average of −2.46 annualized deaths per 100,000 from air-pollution attributable mortality per year between 2010 and 2019 has been observed, which corresponds to an AAPC of -2.38% per year. Urban fine particulate matter had an insignificant increase of around 0.07 micrograms per cubic meter per year and an AAPC of +0.12%. This implies that there was no significant difference between endpoints. In regards to the measures of the water, sanitation and hygiene system, the most pronounced annualized improvement was recorded for safely managed domestic wastewater flows, which rose to an average annual increase of about 2.5 percentage points in the years 2020-2022 and had an AAPC of +3.08%, although on the

Table 5: Household Environment and WASH-Related Practices and Perceptions, Saudi Arabia, 2022 (GASTAT Household Environment Statistics Publication 2022 [14]

| Domain | Indicator / category | Saudi Arabia 2022 (%) |
|---|---|---|
| Drinking water source | Bottled water (primary) | 49.06 |
| | Public network water (primary) | 28.73 |
| | Tanker water (primary) | 21.66 |
| | Other sources (primary) | 0.55 |
| Water efficiency | Households using water-saving devices/tools | 34.34 |
| | Households not using water-saving devices/tools | 65.66 |
| Solid waste (household) | Dispose in public waste container | 99.44 |
| | Burning waste | 0.47 |
| | Burying waste | 0.06 |
| | Other disposal methods | 0.03 |
| Waste segregation | Triple segregation | 4.75 |
| | Food waste only segregation | 61.81 |
| | No segregation | 33.44 |
| E-waste | Disposed in public container | 73.11 |
| | Given to recycling entity | 11.07 |
| | Sold | 5.31 |
| | Other methods | 10.51 |
| Perceived household environmental pollutio | Visual pollution complaint | 46.95 |
| | Noise pollution complaint | 46.94 |
| | Air pollution complaint | 37.28 |
| | Light pollution complaint | 6.28 |
| Environmental interest | Households interested in environmental topics | 84.11 |
| Environmental priorities | Air pollution as top issue | 28.62 |
| | Increasing waste as top issue | 26.19 |
| | Desertification as top issue | 16.01 |
| | Climate change as top issue | 15.42 |
| | Drinking water scarcity as top issue | 13.31 |

Percentages of households nationally are reported without denominators and standard errors (in the publication). Each single response group (water source, water efficiency, solid waste disposal, segregation and recycling, electronic waste) totals to 100%)

basis of only two reporting points. There was an increase in safely managed sanitation by about 0.05 percentage points per year between 2000-2022, giving an AAPC of +0.06%. Clean fuel use was not changing, implying an AAPC of 0.0% per year. There was no trend ability for unsafe water, sanitation, and hygiene mortality as it represented one-point endpoint (Table 2).

In terms of ranking in order of magnitude, the highest absolute change was found in the death rate due to air pollution (−19.51%) followed by the rate of safely treated wastewater (6.25%). A smaller amount of absolute change was witnessed in the cases of the safe sanitation rate (1.27%) and the urban PM2.5 (1.06%), but there is no absolute change in the case of clean fuel use (0%), while the death rate attributed to unsafe WASH has only one point (Table 3).

Table 4 presents the population-weighted PM2.5 concentration trends in Saudi Arabia from the 1990s until the 2000s, which later became more volatile in the 2010s and finally saw a decline. On average, there were 48.09 μg/m³ of PM2.5 concentrations over the 1990s, with the SD value of 2.34, having risen from 46.80 to 53.25 μg/m³ during this period with the CAGR of around 1.45%. Then, the 2000s started to develop into the higher plateau (with the mean value equaling 58.17 μg/m³ and SD = 1.69) and further continued growing (from 54.82 to 59.62 μg/m³, CAGR ≈ 0.94%). During the 2010s, although the mean values for the decade are quite high (60.58 μg/m³), the standard deviation is the largest so far (SD = 4.43, range 51.09–65.81) and there even is some slight decline at the end of the period (59.84 to 58.62, CAGR = −0.23%). Thus, the period can be described as the one with a lot of annual changes rather than steady growth. The value for 2020 (53.15 μg/m³) represents a single measurement.

Table 5 presents the consolidation of national environment and WASH practices data of households into a multi-domain profile. It is found that bottled water forms the leading choice of primary drinking source – 49.06%, next is the public network water (28.73%) and tanker water (21.66%). These figures reflect the fact that most households opt for some drinking water source besides the public network. Information on water quality and safety is not covered by these data. The level of households' water-conservation behavior is low – 34.34% of households use water-saving devices compared to 65.66% who do not have water savings behavior (adoption measure), actual water savings was not measured. Households dispose of solid waste mainly through the utilization of public waste bins – 99.44%, very little burning of waste (0.47%) and burying of waste (0.06%) are observed (this is household practice, downstream collection and treatment were not considered). Waste segregation practices vary between households – 4.75% triple segregation, 61.81% segregation of food waste, 33.44% no segregation. In relation to e-waste, most households prefer disposal of e-waste through the utilization of public containers (73.11%), formal recycling channel utilization is low compared to that – 11.07% to recycling organizations. As for perception items, which are yes-no questions, not adding up to 100%, visual and noise pollution

Table 6: SDG 6.3.1 Benchmarking: Proportion of Wastewater Flows Safely Treated (%) Across GCC and Selected Comparators (Latest Reporting Year

| Country/region | Reporting year(s) | Total safely treated (%) | Domestic safely treated (%) | Industrial safely treated (%) | Order by total (provisional)† |
|---|---|---|---|---|---|
| Kuwait | 2024 | 100.00 | NR | NR | 1 |
| Bahrain | 2022-2024 | 99.96 | 94.12 | 104.91‡ | 2 |
| Qatar | 2024 | 99.95 | NR | NR | 3 |
| Oman | 2022 | 99.04 | NR | NR | 4 |
| United Arab Emirates | 2024 | 94.99 | NR | NR | 5 |
| Saudi Arabia | 2022-2024 | 87.65 | 58.43 | NR | 6 |
| World | 2024 | 55.78 | NR | NR | — |

Source: UN SDG Global Database, indicator 6.3.1 [22]. NR, not reported (not zero). †Descriptive order only, reporting years and disaggregations vary across countries, and World is a reference value, not a ranking. ‡As published, values above 100% exceed the range for this indicator and are data quality issues, not values. The Saudi domestic value for 2022–2024 reporting period differs from the 2020–2022 national series in Table 1 due to a different reporting period)

Table 7: Ordinary Least-Squares Linear Trend Models for Population-Weighted Mean PM2.5 Exposure: Slope, Fit and Exploratory 2030 Extrapolations (The Estimated Regression of PM2.5_T=B0+B1*Year_T+Et Using OLS Was Conducted On the Annual Observations (N = Years). The Slope Confidence Intervals at 95% Level are Based on T-Statistics, Predictions for the Year 2030 Are Calculated by Extrapolation and Represent 95% Confidence Intervals for a Single Future Observation of Annual Value, Under the Assumption that the Linear Trend Will Persist. $R^2$ Is a Share of Between-Year Variance Explained by the Linear Trend)

| Model window | Years | Slope (μg/m³ per year) | 95% CI (slope) | p-value (trend) | $R^2$ | 2030 extrapolation (μg/m³) | 95% prediction interval, 2030 |
|---|---|---|---|---|---|---|---|
| Long-term (all years) | 1990–2020 (n = 31) | 0.517 | 0.351 to 0.683 | <0.001 | 0.583 | 68.45 | 59.09 to 77.81 |
| Mid-term (post-2000) | 2000–2020 (n = 21) | 0.099 | −0.181 to 0.378 | 0.468 | 0.028 | 61.06 | 51.35 to 70.76 |
| Recent (post-2010) | 2010–2020 (n = 11) | −0.559 | −1.557 to 0.438 | 0.237 | 0.152 | 51.52 | 32.99 to 70.05 |

complaint constitute the bulk of problems mentioned by households at about 47%, and 37.28% reported air pollution complaints, households' public engagement is high – 84.11% interested in environmental issues (attitude measure).

Saudi Arabia appears in the regional context in Table 6 regarding the safely treated wastewater. The total value of Saudi Arabia's safely treated wastewater equals 87.65% (reporting window 2022–2024), exceeding the world's benchmark (World: 55.78%), though being smaller than those of a number of peer countries (Kuwait: 100.00%, Bahrain: 99.96% and Qatar: 99.95%) where reporting year differs (2022-2024). In the case of Saudi Arabia, its domestic share (58.43%) was lower compared to its total share. According to SDG indicator 6.3.1, the domestic share of safely treated water is domestic flows treated safely per total domestic flows, while the total one is the sum of domestic and industrial flows in both numerator and denominator, the larger the total is the more of non-domestic flow has been treated [5,7]. The domestic value of Saudi Arabia (reporting window 2022-2024) is different from the national series in 2020-2022 Table 1 (85% in 2022) due to a different reporting round. The industrial value of Bahrain (104.91%) is larger than the range from 0% to 100%, it is given as published, noted as an inconsistency of data quality and cannot be interpreted. The presence of missing values in some peer country sub-columns shows incomplete disaggregation for the given SDG series of these countries, missing means "not reported", not zero, and the ranking by the total value is preliminary and descriptive only.

In Table 7, the trends and forecasts are shown as formal projections. Over the entire period (1990–2020, n = 31), the linear slope of the fitted model was +0.517 μg/m³ per year (95% CI 0.351 to 0.683, p<0.001), with moderate explanatory power ($R^2$ = 0.583), resulting in a 2030 value projection of 68.45 μg/m³ (95% prediction interval 59.09–77.81) if the linear trend would continue. However, the post-2000 period (2000–2020) had only a slightly positive trend with non-significant slope (+0.099, p = 0.468, $R^2$ = 0.028), characteristic of a period which saw much less increase, rather than a plateau with volatility. And the post-2010 period (2010-2020) had a slightly negative slope (−0.559) with non-significant trend (p = 0.237) and a wide prediction interval of 2030 levels (32.99–70.05). It should not, therefore, be considered a forecast of decreasing PM2.5 pollution levels in 2030. Both of the restricted-windows slopes did not differ significantly from zero, and both predictions are conditional on continuing trend windows.

Figure 1 gives the values of all measures at their start and end points in each individual panel and unit. Mortality rates, percentages and concentration measures do not share a common scale here. The highest endpoint changes are observed for mortality related to air pollution and for safely treated domestic wastewater, changes in urban PM2.5, sanitation and clean fuel measures remain relatively insignificant, unsafe WASH mortality is presented only as a single 2019 point.

Figure 2 provides evidence of a long-lasting rising trend starting from early 1990s into 2000s and continued up until early 2010s when a period of high exposure plateau emerged, followed by exposure peak. The presence of the moving average brings out the main trajectory features: relatively stable early years, increasing stage till late 1990s/early 2000s and following years, dominated by volatile periods. The recent fall down to 2019-2020 suggests an improvement but still the overall shape points on persistent exposure over long periods.

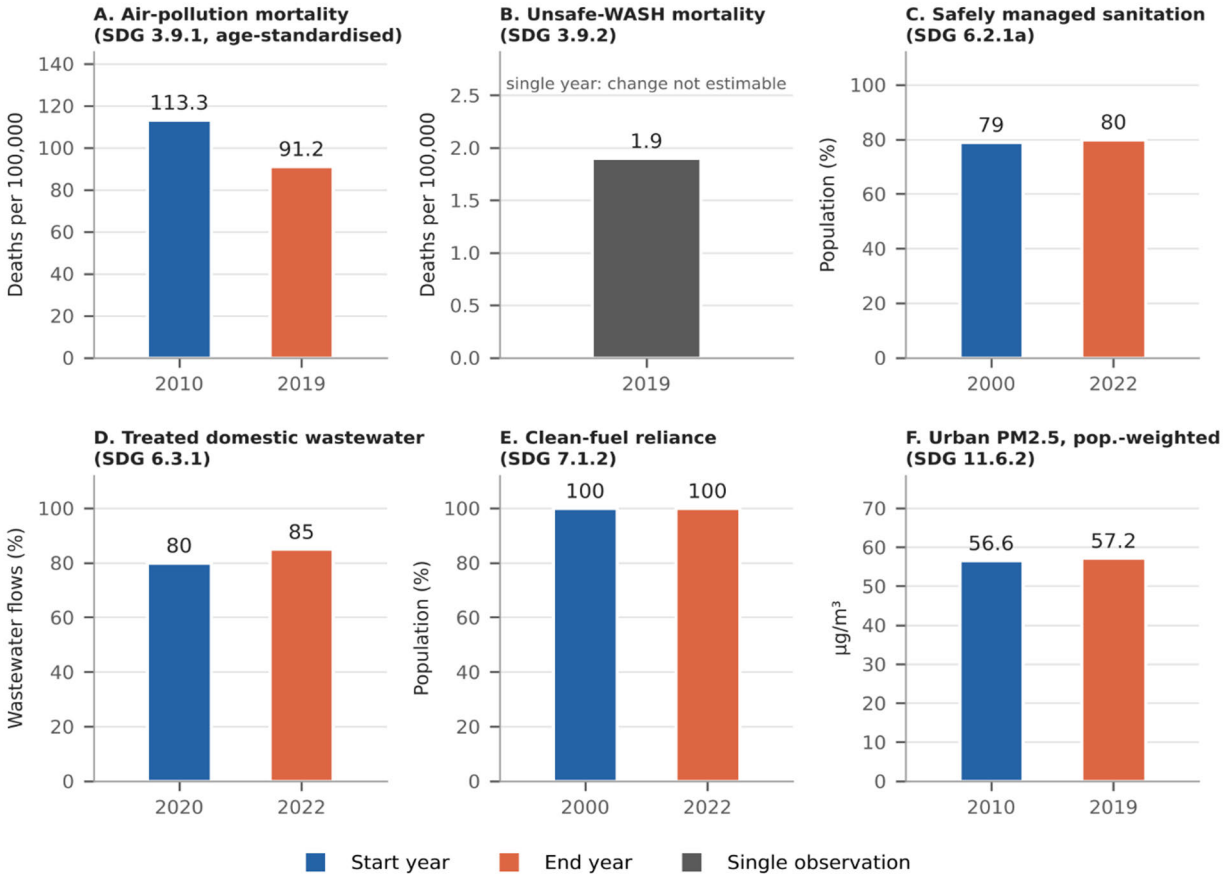



Figure 1: Values at Start and End Points of the Six Core Indicators (Each One Presented Separately and in A Unique Scale), (Saudi Arabia, Reporting Windows are Different for Each Indicator, Source Data Are Provided in Table 1)

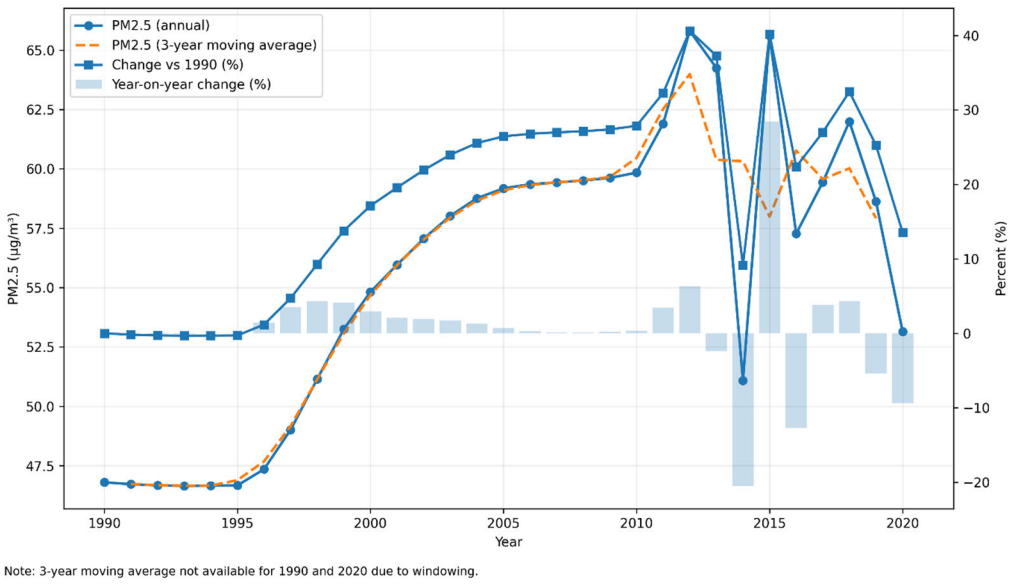



Figure 2: Population-Weighted Mean Annual PM2.5 Exposures, Saudi Arabia (1990-2020), Annual Values, 3-Year Moving Average (Undefined for 1990 and 2020), Change Vs 1990 (%) and Year-To-Year Change (%) (World Bank WDI EN.ATM.PM25.MC.M3 [21])

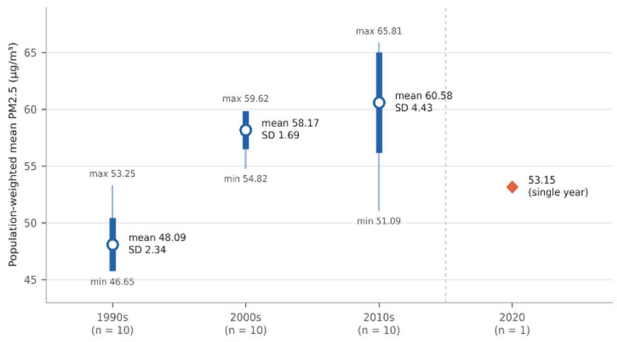



Figure 3: Mean Exposure ± Sample Standard Deviation and Range of Population-Weighted Mean Annual PM2.5 Exposures Per Decade, 1990s-2010s, with 2020 Value Separated, (Sources as in Figure 2)

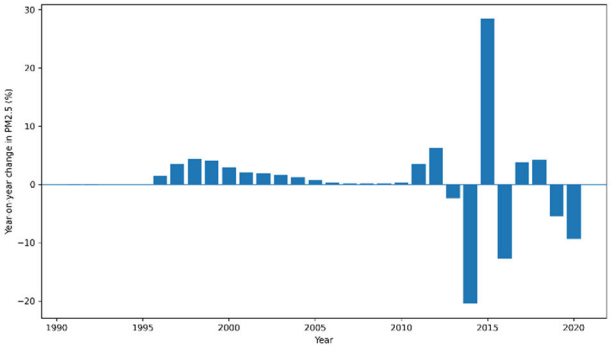



Figure 4: Year-On-Year Change %, 100 × (X_T - X_T-1)/X_T-1), In Population-Weighted Mean PM2.5 Exposure, Saudi Arabia (1990-2020)

Figure 3 demonstrates the decade-wise summary of population-weighted PM2.5 exposures and illustrates an increase in exposure from the 1990s to 2000s, while the 2010s demonstrated the highest averaged exposure in the considered period. Note the high standard deviation in the 2010s, pointing on higher variability compared to earlier decades. The single point of 2020 value is marked separately as it is not an aggregated measure.

Figure 4 highlights that the pattern of exposure growth since 2010 gets more and more unstable: early years demonstrate small year-to-year changes while late years exhibit volatile dynamics of high negative and positive changes, i.e., sharp drop followed by recovery. It reflects the possible effect of dust events; however, it doesn't demonstrate their actual presence due to lack of change-points analysis. Annual values varied in range 46.7 - 65.8 µg/m³, thus, the volatility cannot be explained by small denominator problem and must relate to the actual modelled data, implying that reporting window reflects at best few volatile years.

Figure 5 describes household practices (A), perception of pollution (B) and environmental issues' priority (C).

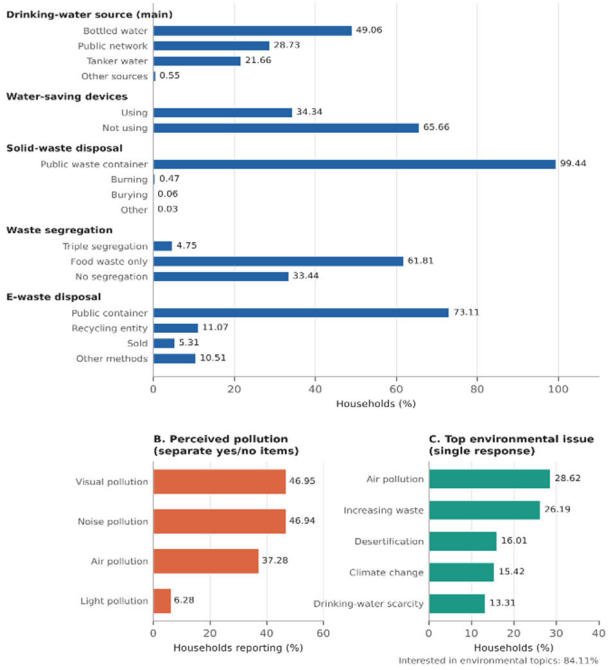



Figure 5: Household Environment and WASH-Related Practices (A), Perceived Pollution (B) And Environmental Interest and Priorities (C), Saudi Arabia, 2022 (GASTAT Household Environment Statistics [14])

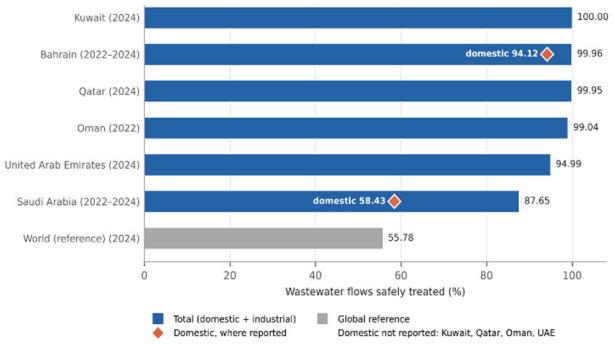



Figure 6: Total and Domestic Proportions of Safely Treated Wastewater (SDG 6.3.1), GCC Countries and World, The Last Reporting Year Is Shown Separately for Each of the Countries [22]

Drinking water comes mostly from bottled supply, installation of water-saving equipment is rare practice, waste management includes mainly putting of waste to communal containers, triple segregation is uncommon practice and e-waste ends up as general waste. Items for perception and attitude are shown separately as they don't relate to exposure or policy acceptance.

Figure 6 shows the positioning of Saudi Arabia within the region and highlights the fact that the total proportion of safely treated wastewater in Saudi Arabia is higher than the global reference but is lower than that of some GCC countries close to 100%. The high values of GCC countries

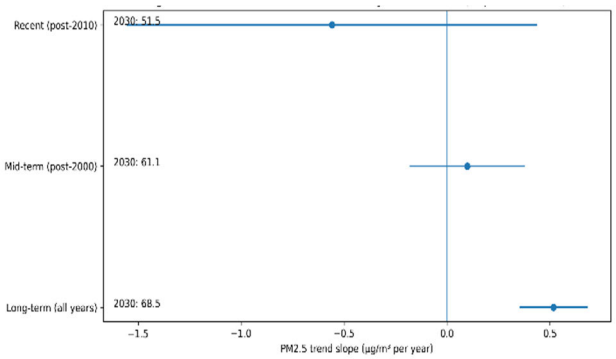



Figure 7: Estimates of OLS Slope (Points) With 95% Confidence Intervals Based on T-Values (Bars) for Population-Weighted PM2.5 Exposures by Window of Observations, annotated are Projected 2030 Values (95% Prediction Intervals Are in Table 7)

may represent the regional target but it is impossible to confirm it taking into consideration differences in reporting periods, definitions and infrastructure.

Figure 7 demonstrates that trend estimation of the exposure depends heavily on the chosen period of observation. Long-term estimation shows an increasing trend, mid-term (after 2000s) is near-flat, while the short-term exposure trend since 2010s turns to be negative with large uncertainty. The predicted values of 2030 annotated on the figure illustrate the sensitivity of such predictions: assumptions about continuation of the exposure pattern affect greatly the projection, thus, this figure is mainly useful to show uncertainty in the future.

## DISCUSSION

Indicators-based assessment of the exposure/mortality trend gap during 2010–2019 in Saudi Arabia relative to household behaviors and wastewater treatment standards of the region The exposure–mortality trend discrepancy during 2010–2019 occurred against the background of constant, but not increasing air pollution by PM2.5, and separate 1990–2020 exposure series demonstrate that the stable exposure over short window can be combined with general long-term tendency and short window volatility. The decade-long by decade-long analysis and annual exposure series make it clear that exposure did not demonstrate the monotone and smooth behavior, but, on the contrary, went through phases of sustained high values and interannual variability, including peak values in early 2010s followed by drop-offs in 2019-2020. It confirms the point that the exposure cannot be adequately estimated over a single decade-long window in cases where the whole period includes increases, plateau and volatility. The trend pattern is unknown without any explanation of its underlying mechanisms, similarly to the discrepancy demonstrated by Rojas-Rueda et al. in relation to GBD2017-based PM2.5 exposure and attributable mortality trend data: decline of PM2.5-attributable mortality since 2011 against increasing exposure concentrations in parallel with very high (87.9 μg/m³) population-weighted average exposure in 2017 [8].

It would be better to evaluate the above disparity under a broader conceptual framework which incorporates more than exposure, but also includes such factors as population composition, risks and underlying conditions, co-morbidities, and health care system characteristics among others [1,3]. The current data can provide no clues to the explanation of these disparities. The possible explanation can be stated as a hypothesis not confirmed within the present assessment: the development of health care sector and introduction of more effective methods for the prevention, early diagnostics and treatment of cardiometabolic and pulmonary diseases may potentially lead to reduction of mortality rate despite high levels of exposure. Changes in estimation approaches and linkages between exposures and mortality rates might have an effect on trend estimations, thus the analyses presented remain only exploratory in nature and generate hypotheses rather than prove any causal relationships [1,3]. Estimating the modeled data series for each report makes their comparison valid only if the endpoints are estimated within the same report. This point is supported by the results of regression models: the positive trend represents statistically significant association with the year, not the cause-and-effect relation, and neither of two short window slopes is different from zero.

The difference between the baseline indicators and indicators of improvements can be illustrated by tables in WASH domain [4]. The non-significant change of safely managed sanitation baseline from 2000 till 2022 demonstrates the very slow improvement in marginal situations when high coverage baseline was already achieved. Nevertheless, short-window (two-year) change in safely treated domestic wastewater between 2020 and 2022 shows the rapid changes in the system performance in spite of insignificant changes in the coverage [5-7]. In addition, the table of GCC benchmarking reveals the contextual information about the country: higher total safely treated domestic wastewater share in Saudi Arabia than the global reference value, but also lower compared with several counterparts' share indicates that "high performance" is a relative parameter and further improvements can be reached in spite of certain limitations introduced by the years of reporting, definition, infrastructure and content differences [5-7].

Also, household practices provide the deeper understanding of the patterns unexplained by the coverage indicators [14]. High share of bottled water, low use of water-saving devices and public management of electronic waste reflect particular exposure and sustainability paths connected with the behavior of the household not estimated by coverage indicators. The use of bottled water does not mean lack of access to safe network water, the public waste disposal also does not reflect the status of collection and treatment processes. The cross-sectional one-year data cannot be linked with the mortality and PM2.5 trends. At the same way, high prevalence of visual and noise pollution concerns and concerns about air pollution indicates that

environmental risks are well-known for households, but the perception-type questions are not the measure of exposure or policy acceptance [1,3]. The finding suggests that combination of exposure indicators with perceptions and behavior can be useful for secondary analysis.

These findings have methodological implications, pointing out the importance of time series density and consistent definition for the indicators-based assessment [7,25]. Numerous endpoints in WASH domain are still limited by the sparsely observed time frames and unsafe WASH mortality endpoint is a yearly estimate which does not allow applying the joinpoint regression approach [23,26,27]. While PM2.5 analysis allows to get more temporal dimension, it is still based on the country-level aggregation which does not reveal regional and episodic variations (such as dust) in exposure which could have a health significance [9-11]. Future work will benefit from the annual time series with consistent definition of the indicators, further disaggregation to sub-national level, population-weighted exposures and including additional environmental exposure endpoints (proxies of dust events and others) into assessment to support causal relationship. Thus, the implications are domain-specific and preliminary for air quality: exposure monitoring with sub-national estimates (tables 4 and 7), for wastewater: verification of safely treated domestic wastewater share before targets' setting (tables 1 and 6), for water consumption and waste: monitoring of devices adoption, waste segregation and e-waste management (Table 5).

### Limitations

Several limits apply to the study in which indicators reported by national agencies for different time periods and with non-uniform definition prevented the estimation of causal relations. Some endpoints had scarce observations or reporting periods, while the indicator of unsafe WASH mortality could not be segmented by year but was provided as a single-year endpoint only. Analysis included national-level aggregated indicators which make any inference to individual-level associations or causal relations impossible. Household behaviors/perceptions data are a single-year cross section which cannot show any change overtime. The mean PM2.5 levels are estimated at national mean which masks regional and episodic (e.g., dust-related) variation. Both mortality and PM2.5 endpoints are modelled estimates which are being updated in subsequent reports, indicator definitions and reporting procedures differ from country to country, while the 2020 PM2.5 series and domestic value of SDG 6.3.1 are changing between reports. No serial correlation, structural breaks and non-linearity were allowed in OLS models, no formal testing for the effect of individual years (e.g., the 2014-2015 swing) was done, and 2030 extrapolations are purely exploratory and highly sensitive to the historical period. GCC benchmarking is restricted by unequal reporting years, absence of disaggregated indicators and suspiciously high domestic value which should be verified by the reporting country.

## CONCLUSION

Using public national indicators, this study revealed the decreasing mortality attributable to air pollution over 2010–2019 but minimal changes in urban PM2.5 during that short window. The separate series of PM2.5 exposures over 1990–2020 revealed persistently high levels, increasing over that entire period with recent volatility in exposures. They represent descriptive patterns without any identification of the mechanism. There is only a small alteration in the indicators that have already started from a fairly high level to begin with, the maximum alteration took place during 2020-2022 (limited window), in terms of the number of safely treated domestic wastewaters. Household practices' profile and GCC benchmarking provide more descriptive insight about behaviour and wastewaters downstream treatment process.

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