# Mitigating Methane in Jordan: National Inventory, Emission Projections, and Policy Pathways

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**Abstract**  Jordan currently lacks a comprehensive national methane inventory with uncertainty analysis that integrates multi-sectoral sources, future projections, and mitigation pathways. This study develops Jordan's national methane inventory and assesses emission trajectories and mitigation potential through 2050. Methane emissions from the energy, transport, agriculture, solid waste and wastewater sectors were quantified using the Low Emissions Analysis Platform–Integrated Benefits Calculator (LEAP-IBC), based on national activity data and IPCC emission factors. Stakeholder-validated intervention scenarios were evaluated against a business-as-usual trajectory. Baseline methane emissions in 2022 were estimated at 217.1 Gg $CH_4$ (109.2–358.7), dominated by the waste sectors (71%)—driven by municipal waste (66.5%) and domestic wastewater (4%)—followed by agriculture (22%), energy (7%), and transport (0.5%). Using $GWP_{100} = 28$, 2022 emissions equal 6,082.9 Gg $CO_2$-eq (3,058.1–10,043.7) and are projected to increase to ~11,100 Gg $CO_2$-eq (5,500–18,300) by 2050 under business-as-usual scenario, corresponding to a rise from ~217 to ~397 Gg $CH_4$ $yr^{-1}$. Implementing the full mitigation package reduces emissions by up to 44.6% by 2030 and 59.8% by 2050 (to ~159 Gg $CH_4$ $yr^{-1}$), with solid-waste interventions providing the largest and most robust reductions.

**Keywords**  Methane · Jordan · LEAP-IBC · Emission Inventory · Mitigation Potential

## 1 Introduction

Methane ($CH_4$) is a powerful greenhouse gas (GHG) whose atmospheric concentration has more than doubled since pre-industrial times (Nisbet et al., 2023). Methane atmospheric lifetime is roughly a decade with the perturbation lifetime, relevant for dealing with emission reductions, is $11.8 \pm 1.8$ years (IPCC, 2021). Therefore, Methane is one of the short-lived climate pollutants (SLCPs) that contributes approximately one-third of current global warming (World Economic Forum, 2024). Methane is linked directly to environmental degradation and indirectly to adverse human health impact as methane contributes to the formation of tropospheric ozone ($O_3$), which is a short-lived pollutant with detrimental effects on people, ecosystems and crops (Shindell & Smith, 2019).

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Understanding of methane's effect on radiative forcing has recently improved, leading to an upward revision since the Sixth Intergovernmental Panel on Climate Change (IPCC) Assessment (Etminan et al., 2016; IPCC, 2021; Shindell et al., 2017). Because methane harms public health and agriculture as well as the climate, its total social cost per tonne is estimated to be 50–100× higher than $CO_2$'s, depending on the discount rate (Shindell et al., 2017, 2024).

Recent global assessments show that atmospheric methane concentrations increased sharply between 2000 and 2020, driven primarily by the fossil, agriculture, waste and biomass burning activities, reaching unprecedented levels in the past decade (Saunois et al., 2025). For that reason, reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of global warming and to limit temperature rise to 1.5 °C (Nisbet et al., 2020).

Regional measurement-based studies reinforce the importance of the waste sector in East Asia methane budgets. In Kuwait, Al-Shalan et al. (2022) combined mobile $CH_4$ plume detection with high-precision analyses and found landfill emissions to be the largest observed source (with smaller contributions from fossil fuels, wastewater, and ruminants). Their isotopic source-mix analysis also indicates that commonly used bottom-up inventories can misattribute the dominant source category, underscoring the need for improved waste-sector characterization and mitigation in national inventories across the region. Recent satellite-based analyses further support the importance of waste-sector methane, mapping monthly mean column $CH_4$ over the Arab countries (2020–2022) including Jordan and revealing strong seasonal variability with localized concentration hotspots over landfills (Alcibahy et al., 2025).

In addition to ratifying the Paris Agreement in 2016, Jordan also is a signatory to the UN Global Methane Pledge to support global efforts to reduce methane emissions by at least 30% by 2030 (CCAC, 2026a). This aligns with Jordan's other commitments, as the country joined the Climate and Clean Air Coalition (CCAC) to raise awareness and elevating regional engagement on SLCPs (CCAC, 2026b).

Existing research on methane in Jordan exhibits a pronounced focus on individual emission sources or specific sites, with the solid waste sector receiving predominant attention. Studies such as Alrbai et al. (2022), optimizing landfill gas recovery at Al-Ghabawi landfill which is the largest landfill in the country, and Al-Ghazawi and Zboon (2021), assessing Irbid's composting plant, exemplify this site-specific approach, quantifying local efficiency gains or emission avoidance but lacking national extrapolation. Similarly, research on Al-Akaider landfill, the second largest landfill in the country, by Al-Ajlouni (2022), composting in Al-Karak (Al-Nawaiseh et al., 2021), or produce waste potential in markets (Papirio et al., 2022) remained confined to single facilities or waste streams. Even broader analyses, like Abu-Qdais et al. (2022) assessment of all landfills in the country or Myyas et al. (2023) review of national biomass potential, were fundamentally anchored within the waste management sector (Al-Zoubi et al., 2024). While offering valuable insights into waste-related methane—such as scenario comparisons demonstrating composting's mitigation efficacy by Abu-Qdais et al. (2019) or early projections for wastewater and landfill emissions (Al-Ghazawi & Abdulla, 2008; AlQaraleh et al., 2024; Qteishat et al., 2024)—these studies share a critical limitation. They primarily address isolated components of Jordan's methane profile. Consequently, a significant gap persists: the absence of an uncertainty-based comprehensive, multi-sectoral national methane inventory integrating projections and mitigation pathways across all key sources, including agriculture and energy, beyond the well-studied waste domain.

This study presents a comprehensive methane inventory for Jordan, bridging a critical data void needed for evidence-based climate and health policies. By leveraging advanced energy and non-energy resources modeling, we project methane emissions and reduction potentials from 2022 to 2050 across its sources sectors. Four scenarios are evaluated: a baseline scenario reflecting current policies relative the baseline year of 2022, alongside three mitigation scenarios extracted from the planned or suggested national plans, policies, commitments, projects, strategies as well as expert elicitation— short-term, covering the ongoing until 2029; mid-term, spanning 2030 to 2040; and long-term, extending from 2041 to 2050—that outline the implementation of climate change mitigation interventions planned for future pursuit by local authorities.

## 2 Methodology

The applied methodology integrates data collection, stakeholder engagement, and modeling using the Low Emissions Analysis Platform–Integrated Benefits Calculator (LEAP-IBC) (Kuylenstierna et al., 2020) at the sectoral level.

### 2.1 Study Boundaries

#### 2.1.1 Transport and Energy Sectors

Jordan's transport sector is dominated by road-based travel and private vehicles, with limited public transport use (about 13% of trips) and no rail system, with ongoing reforms such as the rapid buses, fare integration, and Intelligent Transportation Systems (ITS) aim to improve efficiency and reduce emissions (Morad et al., 2022). Jordan's energy sector supplies electricity and fuels across all end-use sectors but remains highly dependent on imported fossil fuels (92% of primary energy) with the rest covered by renewable energy (Abu-Rumman et al., 2020).

#### 2.1.2 Agriculture Sector

As of 2022 agriculture' contributes to the GDP by 5.6% accounting for about 16% of the total export. Livestock accounts for approximately 55% of total agricultural outputd ominated by small ruminants, especially sheep and goats, that are widely distributed playing a critical role in rural livelihoods. In parallel, cattle production is largely intensive, relying on high yield imported breeds and concentrated near urban centers (Perosino, 2023). The primary agricultural GHG emissions sources include enteric fermentation and manure management (The World Bank, 2022).

#### 2.1.3 Solid Waste

Population growth and demographic change have driven a sharp increase in municipal solid waste generation, alongside food industrial expansion (Al-Hamamre et al., 2017). Municipal solid waste, ~50% organic, are primarily managed by local municipalities and joint service councils with minimal involvement from the private sector. Approximately 50% of solid waste is disposed of at the Al-Ghabawi sanitary landfill, near the capital Amman, that operates a landfill-gas collection system that supports on-site electricity generation of about 4.8 MW and generation capacity is expected to increase as additional landfill cells are completed and brought into operation, extending the site's functional lifespan (cells 1–9) to around 2035 (Shaheen, 2025). By contrast, the remaining waste in Jordan is largely disposed of in open or poorly managed sites lacking sanitary controls, while informal recycling accounts for less than 10% of waste handling, underscoring structural weaknesses in the national solid-waste management system (AlQaraleh et al., 2024; Hajar et al., 2020).

#### 2.1.4 Wastewater Sector

Twenty-Three Waste Water Treatment Plants (WWTP) produce 100% dried sewage sludge that most dumped in landfills and provide service to about 68% of the population with total inflow of 300,000 $m^3$/d, of which about 250,000 $m^3$/d inflows to As-Samra WWTP (Al-Zboon & Al-Ananzeh, 2008). The As-Samra WWTP is Jordan's largest wastewater facility (serving 60% of the population) and a cornerstone of methane recovery and national water reuse, producing around 71% of Jordan's total reclaimed wastewater for agricultural irrigation (Alraggad & Ahmad, 2021). Anaerobic digestion of sewage sludge generates biogas that is conditioned and utilized on-site to produce electricity, yielding a total installed biogas-based capacity of approximately 10.7 MW (Al-Dahidi et al., 2024).

### 2.2 Activity Data

Sectoral activity data covering 2019–2023 were systematically compiled through direct coordination with relevant Jordanian ministries and authorities, following an official request issued by Jordan Ministry of Environment under the national project *"Jordan – Deliver Policy Analysis and Recommendations on SLCP Mitigation"* (Climate and Clean Air Coalition, 2022) that supports the identification of priority SLCP mitigation measures for Jordan's revised National Determined Contributions (NDCs). While Socio-economic drivers were sourced from Jordan Department of Statistics (DoS 2026) and Jordan's National Communications to the UNFCCC (MoEnv, 2017, 2020, 2021, 2022a, b).

Following the compilation and evaluation of activity data for the period 2019–2023, and in close consultation with the Ministry of Environment, the 2022 dataset was identified as the most reliable, internally consistent across sectors, and with stronger alignment with official national statistics. Accordingly, 2022 was selected as the baseline year for emissions estimation, and mitigation analysis.

In 2022, Jordan's population was approximately 11.35 million, growing at an annual rate of 2%, while gross domestic product (GDP) reached USD 49.4 billion with a growth rate of 2.4% per year. Average annual income was estimated at USD 4,352 per person, providing the socio-economic baseline used to drive sectoral activity and emissions projections in the analysis.

Comprehensive activity data were compiled from official national sources. Energy- and transport-related fuel consumption totals ($\pm 10\%$) were obtained from the Ministry of Energy and Mineral Resources (MEMR), the Land Transport Regulatory Commission (LTRC), and the Civil Aviation Regulatory Commission (CARC) (Table 1). Livestock population trends by animal type for the period 2019–2022 were sourced from the Ministry of Agriculture (MoA) and are presented in Table 2. Data on annual municipal solid waste generation for 2019–2023 are summarized in Table 3, based on records from the Greater Amman Municipality (GAM) and the Ministry of Local Administration (MoLA). While GAM

**Table 1** Fuel consumption in Jordan (2022) - by sector - in thousand tons of oil equivalent

| Category | Fuel | Fuel Consumption (ktoe) in 2022 |
|---|---|---|
| Energy | Coal | 225.8 |
| | Diesel | 508.2 |
| | Gasoline | 0.2 |
| | Kerosene | 72.5 |
| | LPG | 599.3 |
| | Natural Gas | 3,443.4 |
| | Heavy Fuel Oil | 1630 |
| | Other Fuels | 307 |
| Transportation | Diesel | 1,151.6 |
| | Fuel Oil | 4.2 |
| | Gasoline | 1,459.8 |
| | Jet Fuel | 307.7 |

**Table 2** Livestock population trends in Jordan (2019–2022) by animal type

| Animal type | 2019 (thousand head) | 2020 (thousand head) | 2021 (thousand head) | 2022 (thousand head) |
|---|---|---|---|---|
| Poultry | 1,961 | 1,565 | 1,977 | 1,530 |
| Sheep | 3,107.2 | 3,503.5 | 3,162.7 | 3,513 |
| Goats | 3,973.0 | 4,430.8 | 3,940.7 | 4,354 |
| Cattle | 92.6 | 91.5 | 93.3 | 91.5 |
| Camels | 10.87 | 10.8 | 11.0 | 11.0 |

is responsible for solid waste management within the capital, MoLA oversees waste management across all other municipalities in Jordan. Lastly, national wastewater statistics were obtained from the Ministry of Water and Irrigation (MWI) and are presented in Table 4.

## 2.3 LEAP-IBC Modeling Framework

LEAP-IBC is a scenario-based modeling framework developed by the Stockholm Environment Institute to assess energy systems, emissions, and mitigation pathways across sectors (Heaps, 2009). In LEAP, we estimated emissions using a bottom-up activity-based approach, where sectoral activity data, driven by demographic, economic, and technological assumptions, are multiplied by emission factors which allows LEAP to model GHGs and SLCPs, and then further process them to assess climate impacts. This integrated structure enables LEAP-IBC to link sectoral methane mitigation measures directly to national emissions trajectories and downstream climate outcomes, providing a basis for evaluating mitigation scenarios and policy options. The framework of the LEAP-IBC model is described in detail in our previous work using LEAP-IBC (Al-Shurafat et al., 2025).

Methane emissions were modeled across both energy and non-energy sectors. Energy-related methane emissions arise from fuel combustion as well as fuel extraction, processing, and transport activities in sectors including power generation, industry, and transport. Non-energy methane emissions were estimated from livestock (enteric fermentation and manure management), solid waste (municipal solid waste disposal), wastewater treatment, and fugitive releases, using sector-specific activity data and stakeholder-validated, IPCC-consistent emission factors and calculation

**Table 3** Municipal solid waste data for Jordan (2019–2023)

| Items | Quantity for 2019 (tons) | Quantity for 2020 (tons) | Quantity for 2021 (tons) | Quantity for 2022 (tons) | Quantity for 2023 (tons) |
|---|---|---|---|---|---|
| Solid waste of MOLA | 1,662,939 | 1,795,410 | 2,649,479 | 2,914,427 | 1,732,412.5 |
| Solid waste of GAM | 1,456,074 | 137,4835 | 1,350,539 | 1,368,886 | 1,406,023 |
| **TOTAL** | **3,119,013** | **3,170,245** | **4,000,018** | **4,283,313** | **3,138,436** |

**Table 4** Wastewater treated and sludge produced for Jordan (2019–2022)

| Items | Quantity for 2019 | Quantity for 2020 | Quantity for 2021 | Quantity for 2022 |
|---|---|---|---|---|
| Quantities of sludge produced from sewage plants (tons/year) | 105,125 | 108,278 | 111,527 | 114,872 |
| Quantities of Wastewater treated (Million Cubic Meter (MCM)/year) | 186 | 187 | 196 | 215 |

methodologies. Total national methane emissions were derived by aggregating emissions across all modeled sources.

### 2.4 Emissions Estimation

Across all sectors, annual methane emissions were calculated with a bottom-up Eq. (1) where $A(t)$ is the projected activity level and $EF$ is the corresponding emission factor or equation. Under the baseline scenario, population and GDP growth propagate consumption through these activity-level linkages, producing internally consistent methane trends. Under mitigation scenarios, the same socio-economic drivers are retained, while emissions diverge through changes in recovery rates, treatment pathways, technology shares, and control measures.

$$CH_4(t) = A(t) \times EF \tag{1}$$

For the energy and transportation sectors, methane emissions were calculated using Eq. (2) where $E$ is sector methane emissions, $Cjk$ is fuel consumption, and $EFjk$ is the emission factor (See Table 5) for fuel type j in sector k.

$$E = \sum_{j} \sum_{k} C_{jk} EF_{jk} \tag{2}$$

Methane emissions from the livestock sector were estimated based on the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories Tier-1-style population-based methodology that separately accounts for enteric fermentation and manure management pathways while applying a consistent emissions-control adjustment (IPCC, 2006, 2019 chap. 10). For both pathways, emissions were computed as the product of animal population and the corresponding emission factor, reduced by the share of agricultural emission controls implemented using Eq. (3): where $Animals_i$ is the annual population of livestock category $i$, $EF_{i,p}$ is the methane emission factor (kg CH$_4$ animal$^{-1}$ yr$^{-1}$) for category $i$ and pathway $p$ (Look Table 5), and AEC represents agricultural emission controls and is expressed as a percentage reduction in emissions. As no empirical estimates were available, AEC values were derived based on expert judgment. Accordingly, AEC was assumed to be 0% for enteric fermentation and 5% ($\pm$20%) for manure management, reflecting the limited application of emission control practices and the fact that only a small proportion of manure is directly applied to land by farmers.

$$CH_4 = \sum_{i} \left[ Animals_i \times EF_{i,P} \times \left( \frac{100 - AEC}{100} \right) \right], P : pathway = \{\text{enteric fermentation, manure management}\} \tag{3}$$

**Table 5** Summary of methane emission factors for energy and agricultural sources

| Sector | Source/Fuel/Animal | EF (Central) | EF Min** | EF Max** | Unit | IPCC Category/Reference |
|---|---|---|---|---|---|---|
| Energy | Coal (imported & oil shale) | 3 | 1 | 10 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Table 2.2 (1.A.1, 1.A.2) |
| | Diesel | 10 | 3 | 30 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Table 2.4 (1.A.1–1. A.4) |
| | Gasoline | 10 | 1 | 30 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Tables 2.2–2.5 |
| | Kerosene | 10 | 1 | 30 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Tables 2.2–2.5 |
| | LPG | 10 | 1 | 15 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Tables 2.4–2.5 (1.A.4) |
| | Natural Gas | 90*** | 63 | 117 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy (fugitive & combustion) |
| | Heavy Fuel Oil | 3 | 1 | 10 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Table 2.2 |
| | Other Fuels | 3 | 1 | 10 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Table 2.2 |
| Transport | Diesel | 10 | 3 | 30 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Road Transportation, Table 3.2.2 |
| | Fuel Oil | 3 | 1 | 10 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Table 2.2 & Table 3.2.2 |
| | Gasoline | 10 | 1 | 30 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Road Transportation, Table 3.2.2 |
| | Jet Fuel | 0.5 | 0.2 | 1.0 | kg CH₄/TJ | IPCC, 2006, Vol. 2: Energy, Table 3.6.5 (1.A.3.a) |
| Agriculture* | Cattle – Manure | 5.0 | 3.5 | 6.5 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–14 (mild climate) |
| | Cattle – Enteric | 55.0 | 38.5 | 71.5 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–10 |
| | Sheep – Manure | 0.20 | 0.14 | 0.26 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–15 |
| | Sheep – Enteric | 5.0 | 3.5 | 6.5 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–10 |
| | Goats – Manure | 0.20 | 0.14 | 0.26 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–15 |
| | Goats – Enteric | 5.0 | 3.5 | 6.5 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–10 |
| | Camels – Manure | 2.2 | 1.54 | 2.86 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–15 |
| | Camels – Enteric | 46.0 | 32.2 | 59.8 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–10 |
| | Poultry – Manure | 0.02 | 0.014 | 0.026 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–15 |
| | Poultry – Enteric | 0.0 | 0.0 | 0.0 | kg CH₄/animal/yr | IPCC, 2006, Ch. 10, Table 10–10 |

* Livestock population estimates are within ± 10%, according to IPCC, 2006 Ch.10

**Uncertainties expressed as 95% confidence limit

***The average methane emission factor of 90 kg CH₄/TJ was estimated to represent fugitive emissions from natural gas transmission to power plants in Jordan, rather than combustion emissions only. The estimate is based on IPCC, 2019 Refinement Tier 1 default factors for natural gas transmission systems under IPCC category 1.B.2.b.iv (IPCC, 2019). IPCC, 2019 provides default emission factors in units of tonnes CH₄ per million m³ of gas transported (e.g., 3.36 t CH₄ per million m³ for systems with limited leak detection and repair). This volumetric factor was converted to an energy-based factor using a typical natural gas net calorific value (~ 38 TJ per million m³), yielding approximately 90 kg CH₄/TJ as a central estimate. An uncertainty range of ± 30% (63–117 kg CH₄/TJ), consistent with IPCC guidance for Tier 1 uncertainty treatment

Methane emissions from municipal solid waste disposal sites were estimated using the empirical IPCC Default Method (DM), as outlined in the 2019 Refinement IPCC Guidelines (IPCC, 2006, 2019 chap. 3 vol 2) that is suitable for data-limited contexts and widespread application in national-scale inventories.

Methane emissions from landfills were calculated using Eq. (4) where MSWT is total municipal solid waste generated (metric tonne yr$^{-1}$); MSWF is the fraction of MSW disposed at solid waste disposal sites; DOC is the fraction of degradable organic carbon in MSW; $DOC_f$ is the fraction of DOC that decomposes; $F$ is the methane fraction in landfill gas (default 0.5); MCF is the methane correction factor; 16/12 is the molecular-weight ratio of $CH_4$ to C; and OX is the oxidation factor for methane in the landfill cover.

$$CH_4 = (MSWT \times MSWF \times DOC \times DOC_f \times F \times MCF \times \frac{16}{12} \times (1 - R)) * (1 - OX) \qquad (4)$$

For Jordan, the DOC fraction was set to 0.25, as recommended by Al-Ghazawi and Abdulla (2008) to reflects the high organic that lies within the IPCC expected range (0.14–0.28) (IPCC, 2000 tbl. 5.2), though higher than the Mediterranean regional approximate average of 0.18 (Smith et al., 2001), a difference implies an elevated methane generation potential. The $DOC_f$ IPCC default value of 0.5 used (IPCC, 2006, 2019 tbl. 3.5), reflecting incomplete degradation of organic carbon under landfill conditions. The MCF was set to 0.5, consistent with semi-aerobic managed landfill practices (IPCC, 2006 tbl. 3.1). A default methane fraction F = 0.5 was used, representing typical landfill gas composition (IPCC, 2006 tbl. 3.5). In Jordan, approximately 90% of municipal solid waste is disposed of in landfills or dumpsites, while only 6–10% is formally recycled (Abu-Qdais et al., 2022). Gas recovery at the Al-Ghabawi landfill was estimated at approximately 4.8 MW of installed electrical capacity; assuming typical landfill gas engine efficiencies of 30–40% and the lower heating value of methane, this corresponds to an estimated recovery of about 8,600 t $CH_4$ yr$^{-1}$, with a plausible range of 7,600–10,100 t $CH_4$ yr$^{-1}$ under continuous operation (Shaheen, 2025).

Methane emissions from wastewater treatment were estimated using the IPCC guidelines (IPCC, 2006, 2019 chap. 6). This approach relates methane generation directly to the biochemical oxygen demand (BOD) load, which serves as the principal indicator of organic matter available for anaerobic degradation in wastewater systems. The method is widely applied in national inventories due to its simplicity and suitability for data-limited contexts. Accordingly, methane emissions from wastewater were calculated using Eq. (5): where $ME_{WW}$ is methane emissions from wastewater (Gg $CH_4$ yr$^{-1}$), D is the annual organic material in wastewater expressed as BOD (Gg yr$^{-1}$), FA is the fraction of wastewater that is anaerobically treated, EF is the methane emission factor (Gg $CH_4$ per Gg BOD), and R is the fraction of methane recovered.

$$ME_{WW} = D \times FA \times EF \times (1 - R) \qquad (5)$$

Based on the reported wastewater volume activity in the baseline year and organic strength, the total annual BOD load was estimated by multiplying the reported 215 million m3 yr$^{-1}$ of wastewater in 2022 with an average BOD concentration of 650 mg L$^{-1}$ as suggested by Al-Ghazawi and Abdulla (2008) and this corresponds to an annual organic load of approximately $1.40 \times 10^8$ kg BOD yr$^{-1}$ ($\approx$ 140 Gg BOD yr$^{-1}$). The FA was set to 0.6, reflecting the prevalence of anaerobic or partially anaerobic treatment processes (IPCC, 2006, 2019 chap. 6). An EF of 0.25 Gg $CH_4$ per Gg BOD was adopted, consistent with IPCC default values for domestic wastewater systems (Al-Ghazawi & Abdulla, 2008). Methane recovery (R) was assumed to be 50%, accounting for the biogas capture at As-Smara WWTP, the largest facility in the country.

The adopted values and associated uncertainties for activity data and emission parameters are summarized in Tables 6 and 7.

## 2.5 Future Projections

Future methane emission trajectories in LEAP-IBC were constructed by projecting sectoral activity levels from the calibrated 2022 baseline, rather than by extrapolating emissions directly. Consistent with LEAP's scenario-based structure, activity variables were linked to key socio-economic drivers, namely population growth and GDP growth, using the built-in GrowthAs() function. This function updates the value of a dependent variable based on the growth rate of an independent driver variable so for a given

**Table 6** Uncertainty ranges for parameters used in landfill methane estimation

| Parameter | Adopted value | Uncertainty range | Basis | Source |
|---|---|---|---|---|
| Total municipal solid waste generated (MSWT) | 4,000,000 MT | ± 5% | National waste statistics | This study, Section 2.1, Study Boundaries |
| Fraction of MSW disposed at disposal sites (MSWF) | 90% | ± 2% | National waste statistics | Abu-Qdais et al. (2022) |
| Degradable Organic Carbon (DOC) | 0.25 | ± 10% | Country-specific waste composition | Al-Ghazawi and Abdulla (2008) |
| Fraction of DOC decomposed (DOCf) | 0.50 | ± 20% | IPCC default | IPCC (2006), Vol. 2, Ch. 3 |
| Methane Correction Factor (MCF) | 0.60 | ± 20% | Partially managed landfill conditions | IPCC (2006), Vol. 2, Ch. 3 |
| Methane fraction in landfill gas (F) | 0.50 | ± 5% | IPCC default | IPCC (2006), Vol. 2, Ch. 3 |
| Methane recovery (R) | 8,600 t CH$_4$ yr$^{-1}$ | ± 10% | Estimated from electricity generation | Shaheen (2025) |

**Table 7** Input parameters and uncertainty ranges for wastewater methane estimation

| Parameter | Symbol | Adopted value | Uncertainty range | Basis | Source |
|---|---|---|---|---|---|
| Annual organic load in wastewater (BOD) | BOD | 140 Gg BOD yr$^{-1}$ | ± 30% | Calculated from wastewater volume and concentration | This study |
| Fraction of wastewater treated anaerobically | FA | 0.60 | ± 10% | Default assumption for treatment mix | IPCC (2006), Vol. 5, Ch. 6 |
| Methane emission factor | EF | 0.25 Gg CH$_4$ Gg$^{-1}$ BOD | ± 30% | IPCC default for domestic wastewater | IPCC (2006), Vol. 5, Ch. 6 |
| Methane recovery fraction | R | 50% | ± 10% | Partial biogas recovery at As-Samra WWTP | Assumed based on operational data |

activity variable $A$, linked to a socio-economic driver $X$, its temporal evolution is defined by Eq. (6): where A(t) is the activity level in year t, X(t) is the value of the driving variable (population or GDP) in year t, and ε is the elasticity parameter: ε = 1 implies proportional growth, ε < 1 implies slower growth than the driver, ε > 1 implies faster growth than the driver, and ε = 0 implies no dependence on the driver.

$$A(t) = A(t - 1) \times \left( \frac{X(t)}{X(t-1)} \right)^{\varepsilon} \qquad (6)$$

In the energy and transport sectors, future methane emissions were projected by scaling two drivers of fuel use using the GrowthAs() function: (i) an indexed Activity Level (entered as Percent; Saturation) that evolves with GDP growth to represent

macroeconomic expansion, and (ii) Annual Energy Intensity (fuel use) that evolves with population growth to reflect demographic-driven demand. LEAP then computes fuel consumption internally as the product of the GDP-scaled activity index and the population-scaled energy intensity, and methane emissions are subsequently calculated by applying fuel-specific, IPCC-consistent emission factors to the resulting fuel use. This structure ensures that projected methane trends emerge from changes in underlying economic and demographic drivers. Then CH$_4$ is computed in LEAP from FuelUse(t) using the fuel-specific methane emission factors (See Eqs. 7 and 8).

$$Activity_{\%}(t) = Activity_{\%}(t - 1) \times \frac{GDP(t)}{GDP(t-1)} \qquad (7)$$

$$FuelUse(t) = \frac{Activity_\%(t)}{100} \times \left[ EnergyIntensity(t-1) \times \frac{Population(t)}{Population(t-1)} \right]$$
(8)

For the agriculture sector, livestock populations were projected using a GDP-linked elasticity to capture income-driven growth in animal production and associated methane emissions from enteric fermentation and manure management, consistent with empirical evidence linking GDP to $CH_4$ emissions, particularly in low- and middle-income countries (Chang et al., 2021; Rokicki & Fayisa, 2026). A specified elasticity ($\varepsilon = 0.3$) set as recommended by a typical model called "Asiana" comes with the LEAP-IBC tool (See Eq. 9).

$$A_{livestock}(t) = A_{livestock}(t-1) \times \left( \frac{GDP(t)}{GDP(t-1)} \right)^{0.3}$$
(9)

For solid waste and wastewater, methane emissions were driven by population-based activity variables. Municipal solid waste generation, population whose waste is collected, and wastewater organic loads (BOD) were projected using Eq. 10.

$$A_{waste}(t) = A_{waste}(t-1) \times \frac{Population(t)}{Population(t-1)}$$
(10)

2.6 Warming Potential

To estimate contribution to climate change, methane emissions were converted to carbon dioxide equivalent ($CO_2$eq) using Global Warming Potentials (GWPs), which quantify the cumulative radiative forcing of a greenhouse gas relative to $CO_2$ over a specified time horizon. GWP is a standard metric for comparing and aggregating different greenhouse gases, and the chosen time horizon balances emphasis on near-term warming versus long-term climate stabilization (Solomon et al., 2013).

Consistent with Jordan's national GHGs reporting practices and its NDCs (MoEnv, 2021), this study adopts the 100-year time horizon ($GWP_{100}$) as the primary metric for reporting results, though we reported $GWP_{20}$ results also. According to Table 7.15 in IPCC AR6, the $GWP_{100}$ of fossil methane is $29.8 \pm 11$ (18.8–40.8), while non-fossil methane has a $GWP_{100}$ of 27.0 (16.0–38.0) (IPCC, 2021 tbl. 7.15). The emission was converted using Eq. 11:

$$CO_2eq = CH_4 \text{ (tonnes)} \times GWP_{100}$$
(11)

2.7 Mitigation Measures Identification and Stakeholder Engagement

The mitigation scenarios assessed in this study were derived from planned or suggested national policies, strategies, plans, projects, commitments and recommendations identified by relevant Jordanian line ministries and official stakeholders that are directly or indirectly related to the mitigation of SLCPs, in close coordination with the Jordanian Ministry of Environment. More than 40 representatives from relevant institutions participated in structured consultation workshops led by the Ministry of Environment, during which the proposed interventions were jointly reviewed and categorized into short-term (up to 2029), mid-term (2030–2039), and long-term (2040–2050) implementation horizons, in line with Jordan's National Climate Change Policy (MoEnv, 2022a). Based on the outcomes of these consultations, mitigation scenarios were subsequently modeled using LEAP-IBC. A follow-up validation workshop was then conducted with participating stakeholders to review the modeling assumptions and results, ensuring alignment with national priorities and strengthening confidence in the scenario outcomes. A detailed list and description of all mitigation measures are provided in Supplementary Material 1.

3 Results

3.1 National Methane Emissions (2022 Baseline)

In 2022, Jordan's methane emissions were dominated by non-energy sources, with the waste sector contributing approximately 71% of national emissions (municipal waste (66.5%) and domestic wastewater (4%)), followed by agriculture at 22%, while energy systems accounted for about 7% and transport less than 1% of total methane emissions, underscoring the overwhelming role of waste and livestock-related sources in the national methane profile.

Total methane emissions in Jordan were estimated at 217.1 Gg $CH_4$ in 2022, with an uncertainty range of 109.2–358.7 Gg $CH_4$. Non-energy sources dominated national emissions, contributing 200 Gg $CH_4$ (100.2–333.0), primarily from the waste sector at 154.0 Gg $CH_4$ (70.6–260.0) and agriculture at 47.0 Gg $CH_4$ (29.6–73.1). Methane emissions

from municipal solid waste landfills represented the largest single source, estimated at 144.5 Gg $CH_4$ (70.2–240.6), while domestic wastewater contributed 9.4 Gg $CH_4$ (0.4–19.3). Energy-related methane emissions were comparatively small at 15.1 Gg $CH_4$ (8.8–22.0), driven mainly by natural gas systems 13.8 Gg $CH_4$ (8.7–19.7), with transport contributing 1.1 Gg $CH_4$ (0.2–3.7), details are illustrated in Table 8. Overall, uncertainty ranges were widest for waste and agriculture, reflecting variability in waste composition, landfill management practices, livestock populations, and methane generation factors, whereas energy-sector emissions exhibited comparatively narrower uncertainty bounds.

These findings underscore the significant impact of landfill management practices on overall methane emissions mitigation in the sector. This waste-dominant emissions profile is consistent with regional atmospheric measurement evidence from Kuwait, where mobile plume mapping and isotopic analysis identified landfills as by far the largest observed methane source, in contrast to EDGAR inventories

that attribute a larger share to fossil fuel systems (Al-Shalan et al., 2022). That study also demonstrated that wastewater-related methane emissions are detectable but often underrepresented in national inventories, reinforcing the value of explicitly disaggregating landfill and wastewater pathways, as done here for Jordan.
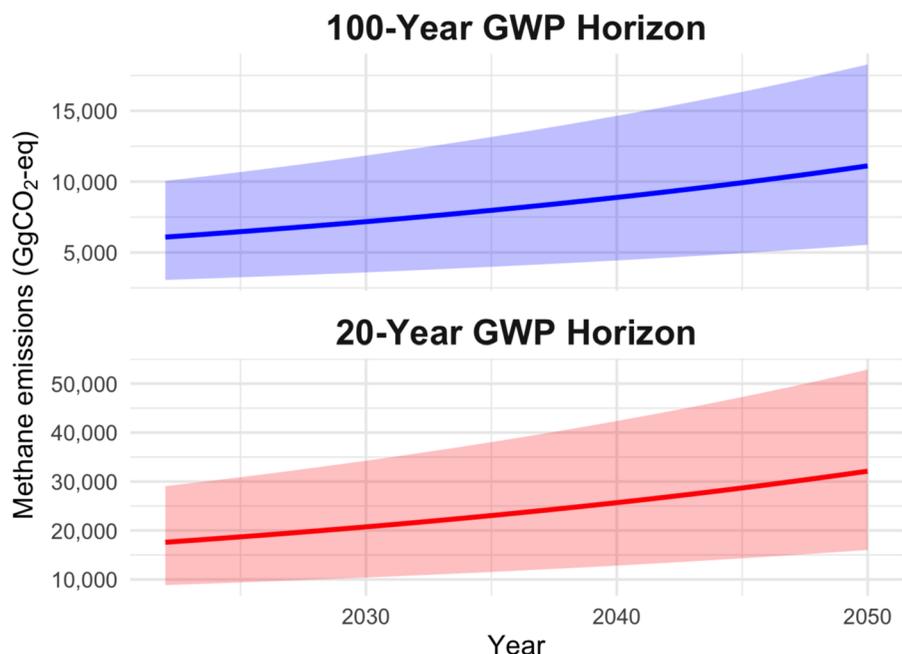
## 3.2 Methane Emissions Projection (2022–2050)

When expressed in $CO_2$-eq using a $GWP_{100}$ of 28, Jordan's 2022 methane emissions correspond to 6,082.9 Gg $CO_2$-eq (3,058.1–10,043.7 Gg $CO_2$-eq), with non-energy sources accounting for more than 90% of total $CO_2$-eq emissions. The waste sector alone contributed 4,310.7 Gg $CO_2$-eq (1,976.9–7,278.8 Gg $CO_2$-eq), while agriculture accounted for 1,314.9 Gg $CO_2$-eq (828.5-2,045.7 Gg $CO_2$-eq). Energy and transport together represented a comparatively small share, totaling 457.2 Gg $CO_2$-eq (252.7–719.2 Gg $CO_2$-eq).

**Table 8** Tier 1 methane emissions by sector and sub-sector in Jordan (2022), reported in mass of $CH_4$ and as $CO_2$-equivalent at $GWP_{100}$ of 28 (central estimate; uncertainty range in parentheses)

| Sector | Sub-sector | Methane emissions (Gg $CH_4$) | Methane emissions (Gg $CO_2$-eq), $GWP_{100}$ |
|---|---|---|---|
| Energy & Transport | **Total demand-related $CH_4$** | **16.3 (9.0–25.7)** | **457.2 (252.7–719.2)** |
| | Transport (total) | 1.1 (0.2–3.7) | 31.5 (5.5–103.7) |
| | └ Gasoline ICE | 0.6 (0.1–2.1) | 17.5 (1.7–57.7) |
| | └ Diesel | 0.5 (0.1–1.6) | 13.8 (3.7–45.5) |
| | Energy (total) | 15.2 (8.8–22.0) | 425.7 (247.2–615.5) |
| | └ Natural gas | 13.8 (8.7–19.7) | 386.5 (243.5–552.6) |
| | └ Oil | 0.7 (0.1–0.8) | 20.0 (1.8–22.0) |
| | └ LPG | 0.3 (0.0–0.4) | 7.4 (0.7–12.1) |
| | └ Diesel | 0.2 (0.0–0.7) | 6.2 (0.6–20.6) |
| | └ Kerosene | 0.13 (0.004–0.036) | 3.7 (0.1–1.0) |
| Non-Energy | **Total non-energy $CH_4$** | **200.9 (100.2–333.0)** | **5,625.7 (2,805.4–9,324.5)** |
| | Agriculture (total) | 47.0 (29.6–73.1) | 1,314.9 (828.5–2,045.7) |
| | └ Livestock (enteric + manure) | 47.0 (29.6–73.1) | 1,314.9 (828.5–2,045.7) |
| | └ Cattle | 5.5 (3.5–8.6) | 154.2 (97.1–240.5) |
| | └ Sheep | 18.4 (11.6–28.6) | 514.2 (323.9–802.1) |
| | └ Goats | 22.8 (14.3–35.5) | 639.6 (401.5–994.1) |
| | Waste (total) | 154.0 (70.6–260.0) | 4,310.7 (1,976.9–7,278.8) |
| | └ MSW landfills | 144.5 (70.2–240.6) | 4,046.3 (1,965.2–6,738.1) |
| | └ Domestic wastewater | 9.4 (0.4–19.3) | 264.4 (11.7–540.7) |
| National total | **All sectors** | **217.2 (109.2–358.7)** | **6,082.9 (3,058.1–10,043.7)** |

The projected methane emissions expressed as $GgCO_2$-eq indicate a steady increase from 2022 to 2050 under both 100- years and 20-years GWPs time horizons (Fig. 1). Presenting projections under the 20-year GWP is particularly relevant because methane is a short-lived climate pollutant with a disproportionately high warming impact over shorter timescales; thus, this perspective highlights the near-term climate benefits that could be achieved through rapid methane mitigation, while the 100-year GWP provides a complementary long-term climate context. Using the 100-year GWP, expected methane emissions increase from approximately 6,100 Gg $CO_2$-eq in 2022 to 11,100 Gg $CO_2$-eq by 2050, with uncertainty bounds reaching 5,500–18,300 Gg $CO_2$-eq. Under the 20-year GWP, expected emissions are substantially higher, rising from about 17,600 Gg $CO_2$-eq in 2022 to 32,100 Gg $CO_2$-eq in 2050, with uncertainty expanding to 16,000–52,900 Gg $CO_2$-eq (approximately $-50\%$ to $+65\%$ relative to the central estimate). Across both time horizons, uncertainty ranges remain proportionally large, indicating a consistently high relative uncertainty share, while absolute uncertainty increases over time, reflecting variability in activity data, emission factors, and mitigation effectiveness.

## 3.3 Emission Reduction Potential

Three scenarios reflect cumulative methane reduction potentials across different time horizons were modeled. The short-term scenario shows reductions achievable through immediate measures by 2030. The mid-term scenario combines these short-term reductions with additional benefits from medium-term measures implemented by 2040. The long-term scenario incorporates all previous reductions while adding further gains from long-term measures initiated later by 2050. This analysis assumes all implemented measures will continue operating through 2050, demonstrating how progressively adopting additional mitigation strategies can compound emission reductions over time. Figure 2 indicates that all scenarios start at roughly 217 Gg $CH_4$ yr$^{-1}$ in 2022 and rise to about 256 Gg $CH_4$ yr$^{-1}$ by 2030 under the baseline, whereas the mitigation pathways reduce 2030 emissions by up to 44.6% relative to that baseline. By 2040, baseline emissions rise further to 317 Gg $CH_4$ yr$^{-1}$, while the Short-Term scenario achieves a 36.0% reduction and the Mid-Term scenario reaches a 55.8% reduction. By 2050, baseline emissions reach 397 Gg $CH_4$ yr$^{-1}$, while the Long-Term scenario delivers the greatest mitigation, reducing emissions by 59.8% to 159 Gg $CH_4$

**Fig. 1** Projected methane emissions ($CO_2$-equivalent) from 2022–2050 under 20-year and 100-year GWP horizons; solid lines show expected values and shaded areas indicate uncertainty bounds

**Fig. 2** Projected methane emissions in (Gg CH₄) from 2022 to 2050 under baseline and mitigation scenarios (Short-Term, Mid-Term, & Long-Term). Lines and points show annual methane emissions for each scenario, highlighting the divergence between the baseline trajectory and progressively mitigation pathways over time
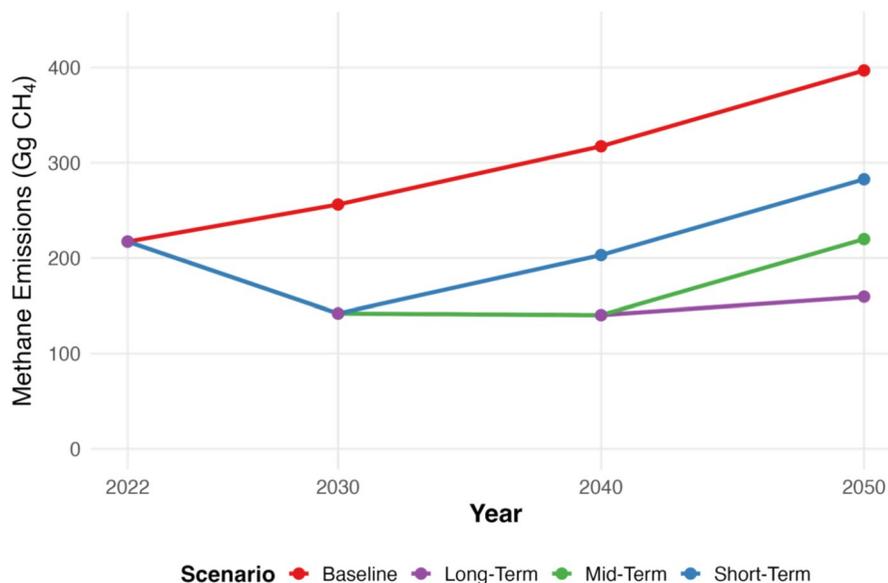


yr$^{-1}$. Overall, the results indicate that while early interventions deliver immediate methane reductions, sustained and long-term mitigation strategies are required to achieve substantial and lasting emission abatement over time. Given the scale of emissions growth and the availability of proven controls, the waste sector represents a low-regret and readily achievable methane mitigation target.

Identified measures along with relevant details such as their costs, feasibility, and expected ability to reduce methane are listed in the supplementary materials 1. However, herein, Table 9 presents the methane mitigation actions identified across sectors, organized by implementation horizon along with reduction potential, with the estimated annual methane reduction expressed in Gg CH₄ yr$^{-1}$ are reported for each action. The solid waste related measures exhibit the largest reduction potential across all scenarios, reaching approximately 65 Gg CH₄ yr$^{-1}$ in the Short-Term scenario and remaining substantial under Mid- and Long-term scenarios, reflecting its dominant role in national methane emissions. The energy sector provides the second-largest mitigation potential, with reductions of about 31 Gg CH₄ yr$^{-1}$ in the Short-Term scenario and 19 Gg CH₄ yr$^{-1}$ in the Long-Term scenario, while the agriculture sector shows more moderate reductions, and lastly the transportation sector contributes comparatively minor reductions (< 1 Gg CH₄ yr$^{-1}$).

## 4 Discussion

Our national methane inventory sectoral distribution is somehow consistent with EDGAR v8.1 estimates for Jordan (Crippa et al., 2016), which likewise indicate a waste-dominated methane profile. Based on EDGAR, 2022 estimates, Jordan's total anthropogenic methane emissions are approximately 214 Gg CH₄ yr$^{-1}$, dominated by the waste sector (~ 84%), followed by agriculture (~ 13%), while all other sectors together contribute only ~ 3% of total emissions (EDGAR, 2022). However, there is contrast with global assessments where waste contributes only ~ 20% of anthropogenic methane, 40% from agriculture and 35% from fossil fuel production and use (UNEP & CCAC, 2021). Heavy reliance on landfilling, limited landfill-gas capture, and a high organic fraction of MSW the main drivers of methane generation, underscoring landfill gas recovery, and organic waste management as key mitigation priorities.

The mitigation scenarios represent planned or proposed intervention pathways advanced by Jordanian official stakeholders, rather than hypothetical mitigation options. When assessed through a cost-effectiveness and implementation lens consistent with Global Methane Pledge (GMP) principles, the results indicate that Jordan can achieve substantial methane reductions—up to 40–50% below business-as-usual levels by 2050—by prioritizing high-impact, readily

**Table 9** Methane mitigation actions by sector and scenario (Gg CH$_4$ yr$^{-1}$, GWP$_{100}$=28)

| Sector | Scenario | Action | Methane reduction (Gg CH$_4$ yr$^{-1}$), ±50% |
|---|---|---|---|
| Agriculture | **Short-term** | Implementation of Agricultural Waste Management System No. 32 of 2024 | 1.59 |
| | | Cleaning livestock barns | 1.59 |
| | | Unprocessed waste collection centers | 1.59 |
| | | Ban on licensing random livestock barns | 1.59 |
| | | Distribution of Bacillus-based equipment | 1.59 |
| | | Monitoring caravans for manure transport | 1.59 |
| | | Supervision of fertilizer processing factories | 1.59 |
| | | Providing biogas units for small farms | 1.59 |
| | | Digital manure transport permits | 1.59 |
| | | Awareness campaigns and workshops | 1.59 |
| | | Farmer field schools | 1.59 |
| | **Mid-term** | Circular economy for farm waste | 1.55 |
| | | Protocol for hazardous biological waste | 1.55 |
| | | Providing biogas units for small farms | 1.55 |
| | | Manure transfer vehicle tracking systems | 1.55 |
| | | Development of waste management vehicles | 1.55 |
| | | Empowering women in waste management | 1.55 |
| | **Long-term** | Facility for breeding biological bacteria | 1.37 |
| | | Thermal sterilization systems for fertilizer processing | 1.37 |
| Waste & Wastewater | **Short-term** | Biogas from salt treatment plant | 0.71 |
| | | Recycling bank project in Amman | 10.77 |
| | | Organic waste processing plant (MBT) | 10.77 |
| | | Regulation of informal waste collectors | 5.39 |
| | | Enhanced operations in waste management | 5.39 |
| | | Methane collection et al.-Ekeider landfill | 26.94 |
| | | Solid waste awareness and studies | 5.39 |
| | **Mid-term** | Engineered sanitary landfills | 31.30 |
| | | Waste transfer stations | 6.26 |
| | | GPS-based guidance system | 3.13 |
| | | National waste management center | 6.26 |
| | | Biogas from Al-Husainiyat landfill | 6.26 |
| | **Long-term** | Circular economy for waste | 6.16 |
| | | Biogas from sludge (WWTPs) | 1.63 |
| | | Biomass use in cement factories | 30.82 |

**Table 9** (continued)

| Sector | Scenario | Action | Methane reduction (Gg CH$_4$ yr$^{-1}$), ± 50% |
|---|---|---|---|
| Transport | **Short-term** | Amman Bus Project (Phases I & II) | 0.04 |
| | | Electric buses in Amman | 0.0001 |
| | | Expansion of intelligent transport systems | 0.07 |
| | | Promotion of hybrid and electric vehicles | 0.00 |
| | | Increased public transport usage | 0.08 |
| | | Ring roads development | 0.07 |
| | | Solar-powered electric bus fleet study | 0.11 |
| | | Transport projecting system | 0.07 |
| | | ITS modernization | 0.07 |
| | | Public transport bus fleet modernization | 0.05 |
| | **Mid-term** | ITS gradual expansion | 0.09 |
| | | Bus fleet modernization | 0.05 |
| | | Carbon taxes on vehicles | 0.00 |
| | | Transition to alternative fuels | 0.09 |
| | | Bus rapid transit Phase II | 0.09 |
| | **Long-term** | Public transport fleet modernization | 0.09 |
| | | Mass transit improving | 0.09 |
| | | Low-carbon freight via rail | 0.04 |
| Energy | **Short-term** | Improving energy efficiency in industry | 13.70 |
| | | Rehabilitating electricity infrastructure | 6.85 |
| | | Clean energy training programs | 6.85 |
| | | Zero-emission electric vehicles program | 2.74 |
| | | Solar-powered charging stations | 0.68 |
| | **Long-term** | Renewable energy share increased to 27% | 7.13 |
| | | Transition to electric vehicles | 8.33 |
| | | Hydrogen energy | 3.33 |

deployable interventions already justified in national strategies. Differences among scenarios are driven primarily by mitigation yield, investment requirements, implementation readiness, and co-benefits, rather than technological feasibility.

Nisbet et al. (2020) emphasize that large and centralized methane sources—particularly landfills—are among the most cost-effective mitigation targets, as emissions can be rapidly reduced through improved site management rather than major structural change. In the United Kingdom, landfill methane emissions declined dramatically following the introduction of engineered landfill practices, including systematic landfill gas collection, installation of gas extraction wells, improved daily cover and waste compaction, and the utilization of captured methane for electricity generation. These measures required relatively modest investment compared with their climate benefits and delivered co-benefits such as reduced local air pollution and renewable energy production (Nisbet et al., 2020). Back to Jordan, the (Methane Collection et al.-Ekeider Landfill) intervention, represents the single largest planned reduction, estimated at 26.9 Gg CH$_4$ yr$^{-1}$. Landfill gas capture and flaring is a proven, high-confidence intervention in Jordan, as demonstrated by the Al-Ghabawi landfill system, largest landfill in the country. Although the intervention requires substantial upfront investment (approximately USD 45 million), its high absolute mitigation yield, long operational lifetime, and potential for energy recovery result in strong cost-effectiveness on a lifecycle basis, aligning with GMP priorities for near-term impact from large point sources. Additional solid waste-sector intervention

scenarios—specifically (Upgrading Landfills to Engineered Sanitary Facilities) and the (Organic Waste Processing Plant – MBT in the capital)—address methane formation at the source by reducing anaerobic decomposition of biodegradable waste. While capital-intensive (approximately USD 42 million for Mechanical–Biological Treatment (MBT)), these interventions deliver durable and structural emission reductions, reduce future landfill demand, and generate co-benefits such as compost or refuse-derived fuel. Their effectiveness depends on regulatory enforcement, sustained operational financing, and public participation, factors explicitly recognized in stakeholder planning frameworks and GMP implementation guidance.

The few identified wastewater measures identified are harder to implement in Jordan because they rely on sustained O&M capacity, and financing/PPP arrangements,. The near-term option—biogas from the Salt treatment plant (~4.2 million USD)—has limited national impact on methane emissions and still faces challenges to be implemented. The longer-term sludge-to-biogas projects (e.g., Al-Baqa'a, Madaba, Wadi Al-Arab; ~20 million USD) require stronger regulatory and grid-integration readiness, so they are best framed as targeted pilots rather than rapid, nationwide solutions.

In terms of agriculture related measures, modeled scenarios reflect regulatory and institutional interventions formally adopted or proposed by national authorities, such as (Enforcing of the Implementation of Agricultural Waste Management System No. 32 of 2024) and (Establishing Manure Collection Centers). These interventions require low capital investment (generally below USD 1 million per intervention) and play a foundational role in reducing unmanaged organic waste decomposition. Although their individual mitigation potential is modest (approximately 1.6 Gg CH$_4$ yr$^{-1}$ per intervention), their ease of application, high benefit-to-cost ratio and enabling function support scalable mitigation consistent with GMP emphasis on widespread, low-cost actions. Planned deployment of (Small-Scale Biogas Units for Farms which costs less than few thousand dollars each) further strengthens this pathway by directly capturing methane for productive energy use at low unit cost, delivering cumulative reductions alongside energy access and livelihood co-benefits. Our finding are corroborated by the analysis by Nisbet et al. (2025)

that demonstrates that agricultural sector methane mitigation is both technically feasible and, in many cases, among the lowest-cost climate actions available when efforts are targeted at well-identified emission hot spots.

Jordan's energy-sector methane mitigation portfolio is led in the short term by industrial energy-efficiency upgrades (13.70 Gg CH$_4$ yr$^{-1}$), supported by enabling measures such as electricity infrastructure rehabilitation (6.85; ~70 million USD) and clean-energy training (6.85; ~3 million USD), and solar-powered charging (0.68). Jordan's high solar irradiance (approximately 5–7 kWh m$^{-2}$ day$^{-1}$) has made solar PV one of the most cost-effective electricity options, with strong uptake in both grid-connected and domestic systems (Al-Habaibeh et al., 2023). By 2022, renewables already supplied nearly 30% of electricity generation, driven by rapid expansion of utility-scale and distributed solar PV, declining technology costs, supportive policies, and private-sector investment, although further expansion is constrained by regulatory, technical, and financial challenges (Salah et al., 2023). Over the long term, expanding renewables (7.13; ~900 million USD) and scaling EV adoption (8.33; ~1.5 Billion USD) offer substantial reductions but depend on sustained regulation, grid readiness, and affordable financing. In contrast, hydrogen (3.33; ~3 Billion USD) is the least certain option in the Jordanian context due to high infrastructure and safety requirements and concerns that hydrogen leakage can indirectly worsen climate and air-quality outcomes by affecting atmospheric OH, so it is best treated as a cautious, pilot-scale pathway rather than a core near-term mitigation lever.

Across the transport sector, the identified actions focus mainly on public transport expansion and modernization (Amman Bus/BRT phases, fleet renewal), traffic management and digitalization (ITS expansion, and CCTV/e-payment/tracking), and a smaller set of technology/fuel shifts (hybrid/EV promotion, electric bus pilots, alternative fuels in aviation/maritime, and rail freight), but their modeled methane reductions remain very low (generally < 1 Gg CH$_4$ yr$^{-1}$ per measure). The most feasible near-term gains in Jordan are likely from funded, operational measures that improve bus service and reduce congestion (bus upgrades and ITS), while EV scale-up, improve gasoline engines and fiscal instruments (e.g., carbon taxes) face greater adoption and implementation risks,

and mega-projects like BRT expansion and rail freight depend heavily on sustained financing and delivery capacity. All identified measures and their expected ability to reduce methane can be found in the supplementary materials 1.

# 5 Conclusion

This study provides a nationally grounded, multi-sectoral methane assessment that directly informs policy implementation and priority-setting in Jordan. By integrating a comprehensive inventory with intervention scenarios already advanced by national stakeholders, the analysis moves beyond emissions accounting to deliver decision-relevant evidence on where near-term methane reductions can be achieved most effectively.

Jordan's methane is structurally waste-dominated, so the fastest and most reliable national progress comes from prioritizing solid-waste interventions rather than distributing effort evenly across sectors. A central contribution of this study is an improved, decision-ready methane inventory that adds uncertainty treatment and clearer source disaggregation, strengthening the credibility and usefulness of national reporting and planning. The analysis indicates that Jordan can achieve substantial methane reductions using interventions/suggestions already reflected or supported in national strategies, with scenario differences driven mainly by implementation readiness, financing, institutional capacity, and sustained operations rather than technological feasibility. In practice, landfills emerge as the highest-confidence, lowest-regret target because proven controls—gas capture/flaring/energy recovery, engineered landfill practices, and organics diversion—can deliver durable reductions and strong co-benefits (air quality, odor control, energy recovery, and reduced future landfill demand).

By contrast, wastewater mitigation is important but harder to scale nationally because it depends on stable O&M capability, reliable sludge handling, and bankable PPP/regulatory arrangements. Agriculture offers many scalable, low-cost actions, but each is incremental and requires broad adoption and enforcement to accumulate meaningful reductions; small biogas systems and improved manure management can also provide livelihood and energy co-benefits. Energy-sector reductions align well with Jordan's strengths in solar and electrification, but depend on long-term regulatory stability, grid readiness, and affordable financing; hydrogen is the most uncertain option and should be approached cautiously due to infrastructure burdens and potential indirect climate/air-chemistry impacts from leakage. Finally, transport measures contribute only minor methane reductions, so they should not be framed as the core methane strategy.

Rapid, verifiable methane reductions in Jordan are achievable by prioritizing implementation-ready measures already embedded in national waste, agriculture, and energy plans, with success depending more on timely execution, coordination, and sustained investment than on new technologies. The study emphasizes sequencing high-impact near-term actions while scaling structural measures for lasting benefits, strengthening cost-effectiveness, alignment with the Global Methane Pledge, and the credibility of national implementation and reporting.

**Data Availability**   The data used in this study are available through the LEAP software model which is delivered to be under the ownership of Jordan Ministry of Environment. A comprehensive profile for Jordan has been established for the baseline year of 2022.

## Declarations

**Ethics Approval and Consent to Participate**   Not applicable.

**Consent for Publication**   Not applicable.

**Competing interest**   The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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