KeAi
CHINESE ROOTS
GLOBAL IMPACT

Available online at www.sciencedirect.com

ScienceDirect

Advances in Climate Change Research xxx (xxxx) xxx

www.keaipublishing.com/en/journals/accr/

Research

Evaluating national methane control action plan: Measure-specific impacts and sectoral pathways across northern China

Yin-He DENG[a], Yun SHU[a,*], Hong SUN[b], Shu-Le LIU[a], Lin-Lin MA[a]

[a] *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China*
[b] *School of Transportation Engineering, Dalian Jiaotong University, Dalian 116028, China*

Received 12 May 2026; revised 19 July 2026; accepted 18 August 2026

Abstract

As countries worldwide accelerate efforts to reduce anthropogenic methane emissions, national methane action plans have become a key policy instrument for achieving climate targets. However, quantitative, measure-specific evaluations of these policies remain scarce. To address this gap, we use China's 2023 Methane Emissions Control Action Plan as a representative case to evaluate the effectiveness of 13 key mitigation measures across the energy, waste, and agricultural sectors in 17 northern provinces. Employing the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model methane framework and scenario analysis, we find that the full implementation of these measures could yield a 21% reduction in regional methane emissions by 2050 relative to 2020 levels. Five critical technical levers—ventilation air methane (VAM) oxidation and utilization, landfill gas management, pre-mining drainage, leak detection and repair programs, and waste recycling—collectively account for 93% of the total mitigation potential. However, the efficacy of specific mitigation measures exhibits notably provincial heterogeneity. Energy-intensive hubs, such as Shanxi, Shaanxi, Inner Mongolia, benefit predominantly from coal mining methane related interventions (VAM oxidation and pre-mining drainage), whereas landfill gas management and waste recycling are pivotal are pivotal for economically developed and densely populated regions like Beijing and Shandong. By identifying province-tailored mitigation portfolios, our findings provide high-resolution guidance for optimizing methane governance in China and offer a replicable evaluation framework for other nations striving to achieve ambitious climate targets.

Keywords: Methane emissions; Mitigation potential; Action plan; Regional heterogeneity

1. Introduction

Methane is responsible for approximately one-third of current anthropogenic warming and has become one of the most effective near-term climate mitigation targets because of its relatively short atmospheric lifetime. Beyond its climatic impact, methane serves as a primary precursor to ground-level ozone, which poses significant risks to human health, agriculture and ecosystems (UNEP, 2025a). Atmospheric methane concentrations have escalated rapidly in recent decades, with 2020 marking the highest growth rate in the 37-year record of the National Oceanic and Atmospheric Administration (Lan et al., 2022). These surges are largely attributed to intensified human-caused emissions (Jackson et al., 2020).

China remains a pivotal player in global methane mitigation, with its emissions totaling 60.64 Mt (with land use, land-use change, and forestry) in 2021—nearly one-fifth of the global total (NCCCSIC, 2024; UNEP, 2025a). Coal mining stands as the dominant source within the national profile. Consequently, curbing methane emissions in China

* Corresponding author.
E-mail address: shuyun@craes.org.cn (SHU Y.).
Peer review under responsibility of National Climate Centre (China Meteorological Administration)

https://doi.org/10.1016/j.accre.2026.08.012

Please cite this article as: DENG, Y.-H., et al., Evaluating national methane control action plan: Measure-specific impacts and sectoral pathways across northern China, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2026.08.012

is not only essential for achieving global climate stabilization but also indispensable for the country's domestic decarbonization targets, namely reaching carbon peak by 2030 and carbon neutrality by 2060 (Gan et al., 2026; Xu et al., 2025). Recent studies have substantially advanced the quantification of methane mitigation potentials through integrated assessment models, emphasizing the importance of technology-specific mitigation pathways and uncertainty characterization (Khanna et al., 2024). China integrated methane into climate policy via the 12th−14th Five-Year Plans and 2025 NDC, with a 7%−10% economy-wide cut by 2035 (MEEPRC, 2016, 2025; SCPRC, 2012, 2021). Sectoral action moved from energy gas recovery to agricultural waste use (MAPRC, 2015; MIITPRC, 2016; NDRCPRC, 2014).

A watershed moment occurred in 2023 with the release of the Methane Emissions Control Action Plan (hereafter, the Action Plan). As China's first comprehensive and ambitious national strategy dedicated to methane, the Action Plan prioritizes the deployment of advanced emission control technologies across the energy, waste, and agriculture sectors, and enhancement of monitoring, reporting and verification (MRV) systems (SCPRC, 2023). Thirteen key actions and 29 concrete measures were put forward covering various aspects of methane control, including ventilation air methane (VAM) oxidation and utilization, pre-mining drainage, landfill gas management, leak detection and repair (LDAR) programs, and waste recycling measures. Comparison of China's official methane inventory in the past reporting submitted to the United Nations Framework Convention on Climate Change shows that methane emission levels were broadly stable from 2018 to 2021, underscoring the urgency for a consistent downward trajectory. Evaluating the effectiveness of the Action Plan thus provides critical insights for future climate mitigation pathways.

A number of studies have sought to quantify China's methane emission source contribution and abatement potentials. National bottom-up assessments have consistently identified coal mining and agriculture as the sectors with the highest mitigation capacity through 2050 (Khanna et al., 2024; Lin et al., 2019). Similarly, studies by Teng et al. (2019) and the EPA (2019) emphasize that coal mining represents the single largest mitigation opportunity for both 2030 and 2050. Lan et al. (2022) evaluated pathways of non-CO_2 emission mitigation in China to 2050, and identified a cost-effective reduction potential of 35% for methane. Although recent studies have substantially improved estimates of methane emissions and mitigation potentials, they primarily evaluate hypothetical technology scenarios or sector-wide mitigation pathways rather than the implementation of actual national methane policies. Consequently, a critical scientific challenge remains: how can qualitative policy measures be translated into quantitative, technology-specific interventions that can be evaluated using integrated assessment models?

Moreover, the effectiveness of national methane policies depends not only on the technical performance of individual measures but also on regional differences in emission sources, infrastructure, industrial structure, and resource endowment (Duan et al., 2023). These disparities lead to divergent spatial responses to policy interventions. For instance, the consolidation of coal mines has triggered contrasting spatial trends—rising emissions in northern hubs like Shaanxi and Inner Mongolia, while declining in southwestern regions (Gao et al., 2021). Likewise, the efficacy of intensive livestock rearing and feed-switching varies dramatically between the North China Plain and the Northeast (Zhang et al., 2022). Existing national-scale assessments generally overlook this spatial heterogeneity, limiting their ability to identify region-specific mitigation priorities and to support evidence-based policy implementation.

To bridge these critical research gaps, this study utilizes northern China as a case study, employing the methane framework of the greenhouse gas and air pollution interactions and synergies (GAINS) model (Höglund-Isaksson, 2012; Höglund-Isaksson et al., 2020) to quantitatively evaluate the impacts of the Action Plan's measures. Specifically, this study aims to address three critical scientific questions: 1) how specific sectoral mitigation measures under the Action Plan quantitatively alter regional methane emission trajectories across structurally diverse provinces in northern China; 2) what the heterogeneous emission reduction potentials are under varying resource endowments; and 3) how localized policies can be optimized to balance stringent low-methane transitions with regional energy security. The results offer not only precise recommendations for northern China but also broader insights for other regions grappling with notable structural and resource diversity in their transition toward low-methane development.

2. Materials and methods

Our methodology follows a three-fold approach: First, we develop an updated multi-sectoral inventory for 17 provinces across northern China for the 2020 base year, alongside a baseline projection through 2050. Second, we integrate a dedicated policy scenario based on a comprehensive review of the Action Plan into the GAINS model to simulate measure-specific impacts at the provincial scale. Third, we map the spatial distribution of these impacts to identify targeted, regionally appropriate policy actions. This study focuses on 17 northern Chinese provinces: Anhui, Beijing, Gansu, Hebei, Heilongjiang, Henan, Inner Mongolia, Jiangsu, Jilin, Liaoning, Ningxia, Qinghai, Shaanxi, Shandong, Shanxi, Tianjin, and Xinjiang. These regions encompass approximately 373 million hm^2, representing nearly 40% of China's total land area (NBS, 2021a). We employed the methane framework of the GAINS IV East Asia model to analyze anthropogenic methane emissions across eight sectors: coal mining, abandoned coal mines, oil and gas systems, solid waste, wastewater, livestock, rice cultivation, and agricultural waste burning (Details shown in Table A2). Furthermore, we evaluated the mitigation potential and effectiveness of various technologies by comparing two future pathways: the Base Case and the Action Plan scenarios.

2.1. Model description

The GAINS IV East Asia model (http://gains.iiasa.ac.at/gains/EAN/index.login logout =), developed by International Institute for Applied Systems Analysis (IIASA), is a regional version of the GAINS model. It facilitates multi-sectoral analyses of GHG (e.g., methane) and air pollutants at both provincial and national scales across East Asia. Methane emissions are estimated using a technology-based bottom-up methodology (Amann et al., 2011; Höglund-Isaksson, 2012), as detailed in Appendix Section A2. For each source, emissions are calculated as a function of activity data, unabated emission factors, and the removal efficiencies of applied control technologies. Emission factors were synthesized from China's national GHG inventories, the Intergovernmental Panel on Climate Change Guidelines, and updated literature estimates, detailed descriptions are provided in Höglund-Isaksson, 2012; Höglund-Isaksson et al., 2020.

2.2. Base case scenario

The Base Case scenario adopts the structural assumptions of the 'ECLIPSE_V6c_CLE_base' default scenario within GAINS (Shu et al., 2022). It integrates macro-economic and energy projections from the World Energy Outlook 2018 Current Policy Scenario (WEO-2018-CPS) (IEA, 2019) and agricultural projections from the Food and Agriculture Organization of the United Nations and International Fertilizer Association (FAO, 2023). For China, this scenario follows the energy trajectory outlined in the 13th Five-Year Plan (NDRCPRC, 2016) which assumes a gradual phase-out of coal use from 2020 to 2050 (Fig. A2). The deployment of emission controls is based on expert judgment from the IIASA AIR group, considering regulatory, market, and infrastructural constraints (Höglund-Isaksson et al., 2020).

To ensure the model accurately reproduces provincial methane emissions for 2020, activity data and technology penetration rates were recalibrated using localized statistical yearbooks. The detailed recalibration methodology is provided in Appendix Section A3 and Tables A3–A15. Post-2020 activity levels and technology adoption rates were then projected by scaling these base-year realities with the growth rates from the original 'ECLIPSE_V6b_CLE_base' scenario, thereby generating a revised baseline that reflects the continuation of current policies.

2.3. Action plan scenario

Starting from the Base Case scenario, the Action Plan scenario simulates methane reductions achieved through the implementation of 29 specific end-of-pipe control measures outlined in the 2023 Methane Emissions Control Action Plan. Based on an extensive review of policy documents, technical reports, and expert surveys, we modified the technology application rates within the model. A summary of these policy parameters is provided in Table A1 and detailed by sector below.

2.3.1. Coal mining

Despite the projected decline of coal in China's energy mix, coal mining remains a critical methane source, particularly in production hubs such as Shanxi and Inner Mongolia. Current abatement primarily relies on gas drainage and low-concentration utilization. In alignment with the Action Plan's mandate for enhanced extraction and comprehensive utilization, our scenario incorporates the accelerated deployment of VAM oxidation and pre-mining drainage. Consistent with the Roadmap for the Development of Methane Control Technology in China (Liang and Jin, 2024), the application rate of these dual technologies is projected to scale from 0% to 45% in 2020 to 80% by 2050.

2.3.2. Oil and gas system

Methane emissions in this sector occur throughout the lifecycle of oil (extraction, transport, refining) and natural gas (extraction, transmission, distribution). While recovery and utilization of associated petroleum gas in oil fields had already achieved a 95% application rate by 2020, the Action Plan mandates a systemic expansion of LDAR protocols. Our scenario reflects this shift through differentiated penetration rates; for instance, LDAR adoption in gas distribution is projected to rise from 0% in 2020 to 80% by 2050, while gas field recovery rates are maintained at 95% (Tian, 2020).

2.3.3. Solid waste

Methane emissions from solid waste result from the anaerobic decomposition of biodegradable organic matter. In accordance with the Action Plan, this study incorporates strategies for landfill diversion and resource recovery. Furthermore, the scenario includes the remediation of existing landfills to optimize fugitive methane capture via enhanced landfill gas recovery systems. To account for composition-dependent technical effects, we assigned distinct adoption rates: anaerobic digestion (AD) and composting serve as primary treatments for food waste (32% adoption by 2050), while recycling is the dominant pathway for paper, textile, and wood waste (70%–80% by 2050). Overall, reliance on landfilling is projected to decline as the sector shifts toward sustainable waste hierarchies (Wang et al., 2023).

2.3.4. Wastewater

Wastewater emissions arise from the organic degradation in municipal and industrial streams. Following the Action Plan's priority on biogas recovery, we parameterized a transition from conventional aerobic treatment toward low-emission infrastructure. Under the Action Plan scenario, centralized aerobic systems are systematically replaced by anaerobic secondary/tertiary systems with integrated gas recovery. For domestic wastewater, the adoption of centralized anaerobic secondary/tertiary treatment with gas recovery is projected to increase to 30% by 2050.

2.3.5. Livestock

Livestock emissions stem from enteric fermentation (in ruminants) and manure management. To mitigate enteric emissions, nutritional interventions, such as substituting roughage with concentrates and implementing precision feeding, are prioritized. Regarding manure management, methane abatement is achieved through the deployment of anaerobic digestion (AD) biogas systems. To align with the Action Plan's modernization mandates, adoption rates for feed improvements and AD systems are projected to reach 70% and 75%, respectively, by 2050 (Lin, 2012), while biotechnological solutions like genetic engineering are expected to show more gradual market penetration (Xu et al., 2019).

2.3.6. Rice cultivation

Methane from rice cultivation results from organic decomposition in flooded paddies. Abatement is achieved through a multi-pronged approach: water-saving irrigation (e.g., intermittent irrigation), optimized fertilizer management, and the use of low-methanogenic rice cultivars. Complying with the Action Plan, we integrated a strategy combining low-methane hybrids with sulfate-containing fertilizers in intermittently flooded areas, with adoption projected to reach 40% by 2050 (Lin, 2012). Additionally, the scenario incorporates a critical transition toward intermittent aeration in traditionally continuously flooded fields.

3. Results

In 2020, anthropogenic methane emissions from seventeen northern provinces of China were quantified at 34.335 Mt. The sectoral emission trajectories for these provinces under the Base Case scenario (2020−2050) are illustrated in Fig. 1. Given that the majority of methane emissions occur when the coal is mined (Kang et al., 2024), coal mining sector emerged as the most notable contributors among the eight categories, representing 56% of the regional total, respectively. Livestock and solid waste also exerted some influence, occupying 13% and 12% of total emissions, respectively. The oil and gas, rice cultivation and abandoned coal mines sectors contributed 8%, 4% and 4%, respectively, while agricultural waste burning only contributed 1%.

Due to pronounced regional disparities in economic development, energy structures, and demographic status (Duan et al., 2023), methane emission levels vary widely across the seventeen provinces. Inner Mongolia and Shanxi were identified as the two largest provincial emitters in 2020, with outputs nearly 26 times higher than those of Tianjin—the lowest emissions. Moreover, sectoral contributions to methane emissions also vary greatly by region. In energy-intensive provinces such as Shanxi, Shaanxi, Inner Mongolia, Ningxia, and Xinjiang (Table A3), coal mining activities constituted the core of anthropogenic methane emissions, accounting for 85%, 79%, 77%, 66% and 58% of their respective provincial totals. In contrast, emissions in Qinghai, Gansu and Jilin originated mainly from livestock, due to their relatively extensive cattle populations (Table A13), representing 70%, 46% and 32% of the provincial totals, respectively.

For the metropolitan hubs of Beijing and Tianjin, the primary methane emission contributors were solid waste and the oil and gas sector; this is primarily attributed to Beijing's high population density and Tianjin's status as a leading crude oil producer (36.31 Mt) in China (Table A4), contributing 69% and 75% to their provincial totals, respectively. In other provinces, emission sources were more diversified. For example, solid waste, livestock, coal mining, and oil and gas system contributed 34%, 25%, 18% and 13% of Hebei's emissions, respectively. Owing to its extensive cultivation area (Table A14), rice cultivation represented the dominant source of methane emissions in Heilongjiang province (27% of the provincial total), succeeded by the livestock (20%), coal mining (16%), and oil and gas (15%) sectors. In Anhui, Henan and Shandong, coal mining consistently accounted for approximately one-third of the provincial totals. These were followed by rice cultivation (23%) in Anhui, livestock (22%) in Henan and solid waste (24%) in Shandong.

Under the Base Case scenario, total methane emissions across the seventeen provinces are projected to undergo minor fluctuations between 2020 and 2050, peaking at 37.622 Mt in 2040 before slightly declining to 36.858 Mt by 2050. This temporal trend reflects a counterbalance between two dominant forces. On one hand, emissions from the solid waste sector are rising, driven by increased urbanization rate and rising gross domestic product (GDP) (Fig. A3). On the other hand, emissions from the coal mining sector are declining, reflecting the transition from coal to natural gas and renewable energy mandated by China's clean air and carbon reduction policies (Fig. A2). In addition, emissions from the oil and gas and livestock sectors also exhibit an increase, propelled by projected growth in the demand for natural gas and meat products (Fig. A4).

Spatially, methane emissions by 2050 in Beijing, Jiangsu, Qinghai, Tianjin, Hebei, Jilin, Gansu, Heilongjiang, and Henan are expected to increase monotonically by 9%−92% relative to 2020 levels. These increments are predominantly dictated by solid waste in Beijing, Hebei, Heilongjiang, Henan, and Jiangsu provinces (Tables A5−A9); livestock in Gansu, Jilin and Qinghai (Fig. A5); and oil and gas activities in Tianjin (Fig. A6), respectively. Conversely, Shanxi and Shaanxi are projected to exhibit a

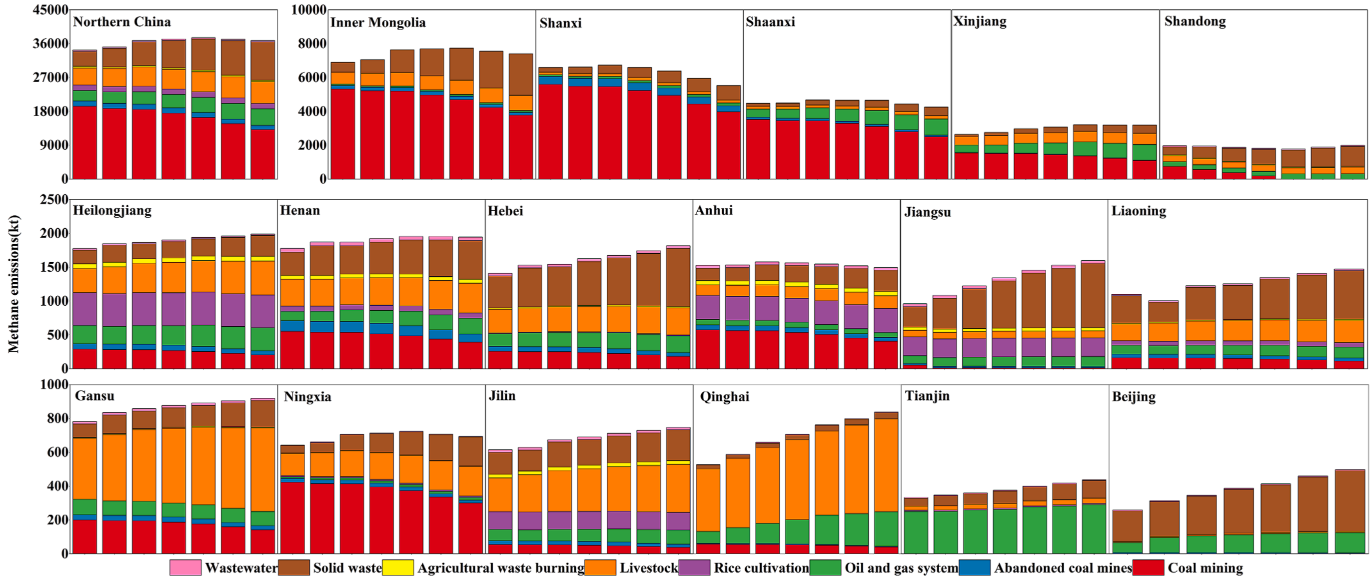

Fig. 1. Sectoral methane emissions for northern Chinese provinces in the Base case scenario during 2020−2050.

marginal upward trend until 2030, followed by a steady decline through 2050, largely driven by the contraction of coal mining activities (Fig. A7). While methane emissions in other provinces are projected to remain relatively stable, their temporal evolutions differ. For example, Shandong is expected to see a slight decline until 2040 followed by a subsequent rebound by 2050, whereas Henan, Inner Mongolia, Ningxia and Xinjiang will likely experience modest growth until 2040 before reaching a plateau.

Under the Action Plan scenario, total methane emissions in northern China are projected to commence a downward trajectory post-2020, reaching 27.112 Mt by 2050, notwithstanding a marginal resurgence between 2025 and 2030. Fig. 2 shows the temporal evolution of sectoral methane reduction potentials under the Action Plan scenario relative to the Base Case. By 2050, the implementation of technical mitigation measures is estimated to yield an emission reduction of 9.747 Mt. This corresponds to a 26% decrease from the baseline and a 21% reduction relative to 2020 levels; however, this remains below the global methane mitigation target of over 50% by 2050 (relative to 2020) proposed in the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC, 2022). This variation is not an underestimation of technological potential, but rather a reflection of the real-world policy boundary conditions inherent in our provincial-level modeling. Unlike the global aggregate estimates, our results integrate site-specific constraints such as local regulatory friction and infrastructure compatibility. These factors serve as dampeners on rapid emission reduction, leading to a more conservative estimation. Within this framework, coal mining constitutes the majority of the abatement potential, contributing to more than half of the total reductions. Nevertheless, its contribution to total methane abatement is projected to decline from 69% in 2025 to 56% in 2050, a shift primarily attributable to the structural contraction of coal production as China transitions toward a low-carbon energy mix (Zhao et al., 2024). Concurrently, the technical abatement potentials for the oil and gas sector and the livestock sector will dimmish from 24% to 6% in 2025 to 14% and 3% in 2050, respectively.

In the solid waste sector, the mitigation potential is expected to expand from −2% in 2025 to 25% by 2050. This gradual trajectory is dictated by the first-order decay kinetics of organic matter in landfills, which postpones the mitigation effects by an assumed ten years for food waste and twenty years for paper, wood, and textile waste (Höglund-Isaksson et al., 2020). Notably, a transient increase in methane emissions is observed during the initial stages of the Action Plan. This phenomenon is fundamentally attributable to a temporal superposition within the GAINS model between time-lagged legacy emissions from historical landfills and instantaneous fugitive leakage from newly deployed treatment facilities, such as anaerobic digestion and composting plants. Meanwhile, technical abatement potentials for rice cultivation and wastewater sectors are expected to remain stable within a range of 0.5%−2%.

From a sub-national perspective, technical abatement potentials exhibit high regional heterogeneity. Energy-intensive provinces, including Shanxi, Inner Mongolia and Shaanxi, demonstrate the most substantial relative reduction capacities. Conversely, remarkably lower potentials are found for regions where livestock-related sources predominate, such as Gansu, Qinghai and Jilin. Sectoral contributions to these reductions also vary markedly across provinces. For example, by 2050, coal mining is expected to be the primary driver in Inner Mongolia, Shanxi, Ningxia, and Shaanxi, accounting for more than 72% of provincial reductions. The solid waste sector is projected to contribute 64%−89% of the total abatement in Jiangsu, Beijing, Shandong and Liaoning,

Please cite this article as: DENG, Y.-H., et al., Evaluating national methane control action plan: Measure-specific impacts and sectoral pathways across northern China, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2026.08.012

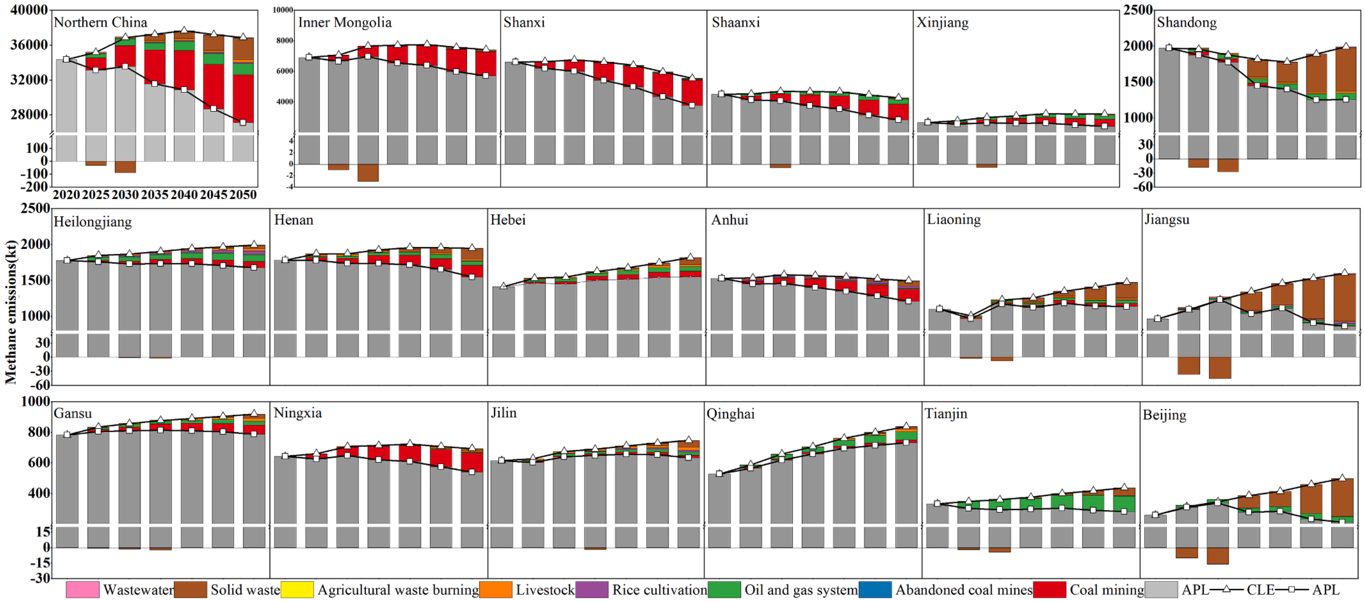

Fig. 2. Methane reduction potential by sector from 2020 to 2050 calculated by comparing action plan scenario with base case scenario.

despite a localized emission uptick during the early timeframe, while the oil and gas sector represents 52%−65% of the potential in Tianjin and Qinghai.

Among the 13 mitigation measures evaluated in the Action Plan scenario, five key strategies, namely VAM oxidation and utilization, landfill gas management, pre-mining drainage, LDAR programs, and waste recycling, are identified as the primary drivers of emission control, together accounting for 92% of the total regional methane abatement. However, the efficacy of specific mitigation measures exhibits remarkable provincial heterogeneity. Fig. 3 illustrates the methane reductions of 13 measures across the seventeen provinces by 2050 under the Action Plan scenario compared to the Base Case scenario. In energy-intensive provinces such as Shanxi, Inner Mongolia, and Ningxia, VAM oxidation and utilization, followed by pre-mining drainage, emerge as the most effective interventions, yielding over 83% of their respective provincial emission reductions. In Xinjiang and Shaanxi, LDAR programs in the oil and gas sector also contribute substantial abatements, necessitated by their extensive hydrocarbon production (Table A4).

Similarly, Tianjin, Qinghai, and Heilongjiang derive significant benefits from LDAR implementation, primarily because major national oil fields, such as Bohai, Dagang, Daqing and Qinghai, are situated within these regions (Luo et al., 2025). In Hebei, leak control within the gas distribution network contributes 19% of the provincial mitigation potential. In economically developed and densely populated provinces like Beijing, Shandong, and Jiangsu, three groups of waste sector measures, comprising landfill gas management, waste recycling and incineration, collectively accounts for over 89% of the provincial reduction potential. Furthermore, in Heilongjiang, Anhui, and Jilin, characterized by expansive cultivation areas (Table A14), irrigation and fertilization management demonstrate relatively high efficacy. In pastoral regions where livestock emissions predominate, feed management and manure treatment are relatively important, contributing 22%, 20%, and 16% to the total reductions in Qinghai, Jilin, and Gansu, respectively.

4. Discussion

4.1. Evaluation and improvement of methane emission estimates

Fig. 4 benchmarks our 2020 methane estimates for northern China against two widely used bottom-up inventories (EDGARv8.0 and CEDSv2025) and top-down satellite-based inversions (Zhang et al., 2022). To ensure comparability, methane sources in the bottom-up inventories were harmonized into four primary sectors: energy, agriculture, waste, and others, with the specific sectoral mapping detailed in Table A16. At the regional level, our aggregate estimates for northern China exhibit high concordance with the bottom-up inventories, showing only a marginal deviation of 3% from CEDSv2025 (Hoesly et al., 2018) and 4% from EDGARv8.0 (Crippa et al., 2024), despite moderate inter-sectoral variations. However, substantial provincial discrepancies reveal important methodological differences and highlight the improvements achieved in this study.

First, our estimates for frontier and energy-intensive provinces, namely Xinjiang, Qinghai, and Heilongjiang, are notably higher than those in CEDSv2025 (by 63%−194%) and EDGARv8.0 (by 66%−127%). This divergence is primarily driven by the energy and agricultural sectors. For energy, our bottom-up recalibration captures the localized intensification of fugitive emissions

Please cite this article as: DENG, Y.-H., et al., Evaluating national methane control action plan: Measure-specific impacts and sectoral pathways across northern China, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2026.08.012

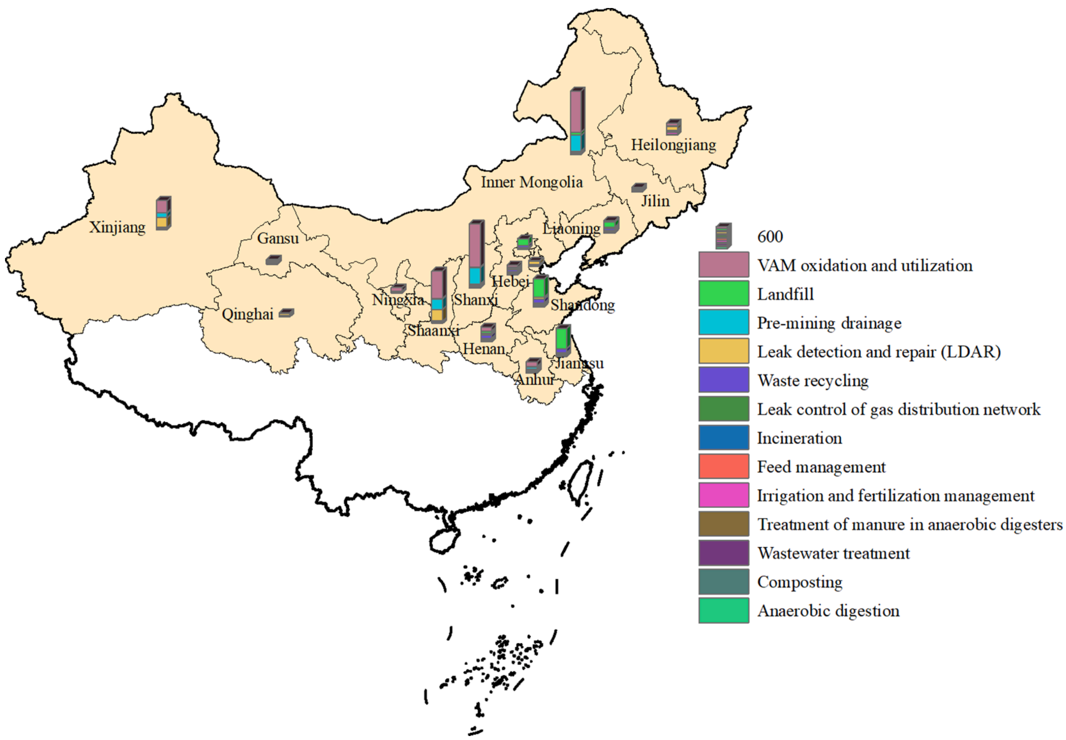

Fig. 3. Spatial distribution of dominant methane mitigation measures in 2050 under the POL scenario.

resulting from China's mine consolidation policy in the North and West—a structural shift corroborated by recent top-down evidences (Zhang et al., 2022). This improvement enables a more accurate representation of methane emission heterogeneity associated with China's evolving coal production structure and regional mining characteristics. In the agricultural sector, the higher estimates in these regions are linked to our refined livestock population accounting (Appendix Text A3). By applying the 2019 IPCC Refinement (Olga et al., 2019) to provincial-specific slaughter and stock data from the China Agricultural Statistical Yearbook (NBS, 2021b), our model better characterizes the enteric fermentation and manure management emissions from the large-scale pastoral systems prevalent in Xinjiang and Qinghai, which are often smoothed out in FAO-based national aggregates. Therefore, our provincial-scale livestock characterization provides a more realistic assessment of methane emissions from extensive pastoral systems compared with approaches relying on aggregated national statistics.

Conversely, in the highly populous and industrialized provinces such as Jiangsu and Shandong, our results are notably lower than those reported by CEDSv2025 (by 26%−60%) and EDGARv8.0 (by 18%−55%). This offset is predominantly attributable to spatial allocation artifacts within the waste sector. Global inventories like EDGARv8.0 rely on the Global Human Settlement Layer as a primary proxy, essentially assuming that methane emissions from waste are a linear function of population density and built-up surfaces (Crippa et al., 2024). In contrast, this study utilizes actual provincial-level statistics on municipal and industrial solid waste collection and transport volumes (MEEPRC, 2021). This treatment-based approach reflects China's waste management transition, specifically the rapid adoption of waste-to-energy incineration and centralized treatment, which decouples methane emissions from population growth. This treatment-based allocation represents a key improvement over population-proxy methods by better capturing the impacts of China's rapid transition in waste management practices.

Compared with the top-down observations from Zhang et al. (2022), our estimated methane emissions in northern China are 36% higher. This regional discrepancy is primarily attributable to the methodological differences between bottom-up inventories and satellite-based inversions. Specifically, this study explicitly accounts for methane leakage from abandoned coal mines, a source that remains challenging for greenhouse gases observing satellite or surface networks to detect with high precision. Furthermore, while top-down observations directly reflect the real-time efficacy of methane drainage and recovery at large energy bases, bottom-up frameworks may still rely on emission factors that do not fully capture the latest operational efficiencies or policy-driven mitigation gains (Gao et al., 2021). In addition, it should be noted that the top-down observational estimates used for comparison represent observation-constrained total methane emissions, which include both anthropogenic and natural sources.

Please cite this article as: DENG, Y.-H., et al., Evaluating national methane control action plan: Measure-specific impacts and sectoral pathways across northern China, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2026.08.012

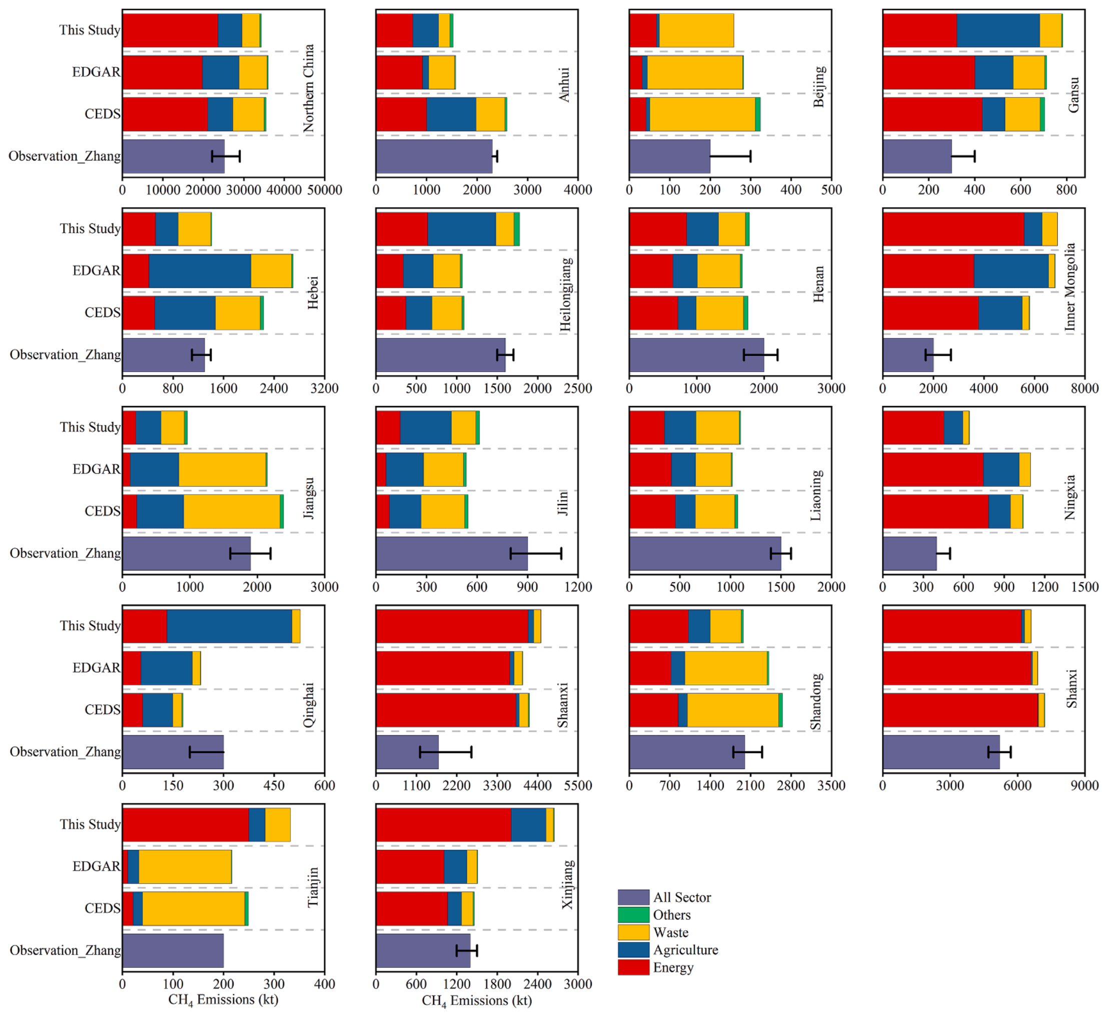

Fig. 4. Comparison of emission results from this study with other recent estimates.

4.2. Policy implications

In 2023, China promulgated its first comprehensive Methane Emission Control Action Plan, marking a pivotal step in the national strategy for synchronized climate mitigation and adaptation. This study quantified the trajectory of methane mitigation across Northern China from 2020 to 2050, validating the efficacy of the Action Plan through a measure-by-measure assessment. Five critical measures—VAM oxidation and utilization, landfill gas management, pre-mining drainage, LDAR programs, and waste recycling—emerge as the primary drivers of regional emission reductions.

The implementation of these measures will catalyze a profound structural shift in the regional emission profile. Fig. 5 illustrates the changes in emission percentages across source sectors from 2020 to 2050 under the Action Plan scenario. Although coal mining's relative share of regional emissions is projected to decline from 56% in 2020 to 28% by 2050, it remains the dominant abatement priority. In energy-intensive provinces such as Shanxi, Inner Mongolia, and Ningxia, VAM utilization and pre-mining drainage are expected to contribute over 83% of provincial reductions by 2050 (Fig. 3). A key regulatory backbone for this transition is the revised mandatory standard (MEEPRC, 2024), which notably tightens the permissible methane release threshold from 30% to 8% by volume concentration. Furthermore, as emissions from abandoned coal mines can persist for decades post-closure (Ocko et al., 2021), their relative contribution in Shanxi and Shaanxi is anticipated to rise by about 3%. This necessitates the urgent integration of abandoned mine monitoring and closure protocols into provincial policy framework to prevent long-term fugitive leakage (Kang et al., 2024).

By 2050, the solid waste sector is projected to undergo a significant expansion in its emission share, rising from 12% to 29% under the Action Plan scenario, ultimately become the largest single sectoral source. Substantial mitigation potentials are concentrated in economically advanced and densely populated regions like Beijing, Shandong, and Jiangsu. In these provinces, landfill gas management, waste recycling and incineration measures account for 89% of the total reduction capacity (Fig. 3). However, the realization of this potential is constrained by legacy disposal bur-

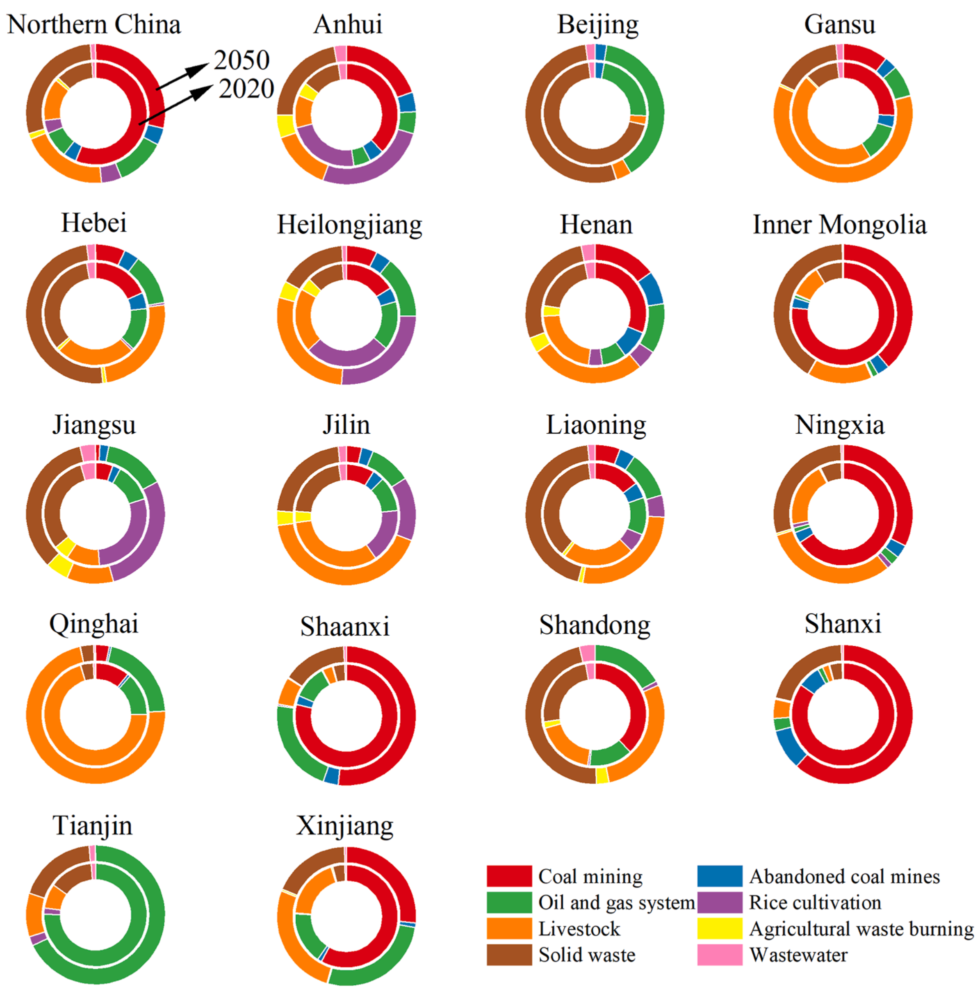

Fig. 5. Changes in emission percentages across source sectors from 2020 to 2050 under the action plan scenario.

dens—the historic accumulation of organic waste in poorly managed landfills. Given the decadal persistence of legacy waste emissions and the potential for instantaneous fugitive leakage from new infrastructure (Fig. 2), early action is paramount. Policies must prioritize high-efficiency gas capture systems and pre-disposal diversion strategies to unlock long-term 'negative-emission' benefits in the waste sector (Powell et al., 2016; Yusuf et al., 2012). Moreover, in order to avoid methane surge driven by the temporal overlap of emissions from legacy landfills and newly commissioned waste-treatment facilities, accelerated remediation of high-emitting landfills, and startup-phase fugitive emission control are required.

Methane policies for livestock sector remain comparatively less stringent, reflecting a complex nexus between climate goals, food security, and rural livelihoods (UNEP, 2025a). Consequently, the agricultural share of regional emissions is expected to increase from 13% to 20% by 2050. Our results indicate that feed management (to suppress enteric fermentation) and manure treatment offer relatively large reduction potentials (16%−22%) in pastoral regions such as Qinghai, Jilin, and Gansu (Fig. 3). And the reduction potentials for feed management is larger than that for manure treatment. Notably, mechanical feed processing (e.g., pulverizing and ammoniating) presents a highly scalable and cost-effective solution for large-scale livestock operations in Northwest China (Yu et al., 2018). Simultaneously, the oil and gas sector's contribution is projected to grow to 12% by 2050, driven by the surging demand for natural gas as a bridge fuel in China's clean air and carbon neutrality pathways. In provinces like Tianjin and Heilongjiang, LDAR programs must be prioritized through frequent monitoring and stringent equipment standards to mitigate the inevitable infrastructure-led emission growth (Lei et al., 2021).

Ultimately, achieving China's methane reduction goals will require a multi-level governance framework that translates national commitments into region-specific, quantitative mitigation pathways. Our provincial analysis provides a scientific basis for differentiated strategies, highlighting energy-sector interventions in Shanxi and Xinjiang, while identifying agricultural mitigation as the greatest opportunity in Qinghai and Gansu. Although several provinces have introduced methane-related action plans (BMEEB, 2024; SDEE, 2022), most remain qualitative and lack measurable reduction targets. Moving beyond policy intent will therefore require standardized emission inventories, province-specific targets informed by regional mitigation potential, and a transparent MRV system to track implementation and periodically refine mitigation pathways. Such an integrated framework would enable China to shift from uniform policy mandates toward evidence-based, performance-oriented methane governance, thereby strengthening progress toward its 2035 greenhouse gas mitigation objectives and long-term carbon neutrality goals.

While the 2023 Methane Emissions Control Action Plan provides an important policy foundation, our analysis projects only a 21% reduction in methane emissions by 2050, well below the 50% global reduction benchmark envisioned by the IPCC. Closing this ambition gap will require a transition from end-of-pipe mitigation toward transformative structural changes across major emitting sectors. Beyond conventional measures such as LDAR and VAM oxidation, accelerating renewable energy deployment and phasing out inefficient coal production will be essential to reduce methane emissions at their source (Teng et al., 2019). Moreover, our provincial-scale analysis indicates that the waste sector is likely to become China's largest methane source in densely populated provinces by 2050. Accordingly, mitigation efforts should extend beyond improving landfill gas recovery to advancing circular waste management through source separation, industrial-scale organic waste valorization, and agricultural residue reutilization (UNEP, 2025b). Collectively, these transitions are pivotal for shifting China's methane policy from incremental emission control toward the structural transformation of methane-intensive systems.

4.3. Uncertainties and limitations

This study is subject to several uncertainties and limitations that warrant cautious interpretation. The first source of uncertainty originates from the lack of detailed information regarding the quantification of specific measures under the Action Plan. While the plan delineates strategic priorities, such as intensifying coal mine methane recovery, expanding LDAR protocols, and optimizing livestock feed additives—it currently lacks time-bound quantitative targets for these measures. Consequently, the parameterization process within the GAINS framework may introduce deviations from actual emission trajectories. Furthermore, the selection of 2020 as the base year—three years prior to the Plan's promulgation—introduces a temporal misalignment that may inadvertently overestimate the near-term mitigation efficacy attributed solely to the new policy framework. Second, this assessment focuses exclusively on technical abatement measures, thereby potentially underestimating the holistic mitigation potential of the Action Plan. The exclusion of demand-side behavioral interventions, such as the reduction of food loss and waste or dietary shifts, represents a notable conservative bias (Smith et al., 2007). Such non-technical levers have been identified as high-impact strategies for methane mitigation but were beyond the analytical scope of the current model. Third, the omission of a comprehensive economic cost-benefit analysis limits the immediate utility of our findings for multisectoral strategy prioritization. Although methane abatement is frequently cited as more cost-effective than CO_2 mitigation (UNEPCCAC, 2021), the constraints of the publicly accessible GAINS interface precluded the construction of provincial-level marginal abatement cost curves. While the full GAINS framework, as demonstrated by Höglund-Isaksson et al. (2020), is capable of modeling complex technological evolution and cost dynamics, the current study relies on a streamlined version.

5. Conclusions

This study provides a comprehensive, province-level evaluation of China's 2023 Methane Emissions Control Action Plan across 17 northern provinces using the methane framework of GAINS model. Our results demonstrate that the full implementation of the Action Plan's technical measures could catalyze a 21% reduction in regional methane emissions by 2050 relative to the 2020 baseline. We identified five critical technical levers—VAM oxidation, landfill gas recovery, pre-mining drainage, LDAR programs, and waste recycling—which collectively account for 93% of the total mitigation potential. The findings highlight a pronounced spatio-sectoral heterogeneity in mitigation efficacy. In energy-intensive provinces such as Shanxi, Shaanxi, and Inner Mongolia, coal mine methane interventions (specifically VAM and pre-mining drainage) remain the most impactful strategies. Conversely, in economically developed and densely populated regions like Beijing and Shandong, the prioritization of landfill gas management and waste recycling yields the highest dividends. These results suggest that a 'one-size-fits-all' approach may be sub-optimal for national methane governance. In addition, the model framework's reliance on replicable data processing and standardized sectoral classification allows for its application in diverse regional contexts, providing a reliable alternative for data-scarce countries and supporting broader requirements for atmospheric modeling and integrated policy assessment. In summary, while the Action Plan establishes a robust framework for methane control, achieving China's long-term climate neutrality goals will require continuous technological innovation and regionally differentiated implementation strategies.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Yin-He Deng: Writing − original draft, Methodology, Conceptualization. **Yun Shu:** Writing − review & editing,

Please cite this article as: DENG, Y.-H., et al., Evaluating national methane control action plan: Measure-specific impacts and sectoral pathways across northern China, Advances in Climate Change Research, https://doi.org/10.1016/j.accre.2026.08.012

Validation, Conceptualization. **Hong Sun:** Investigation. **Shu-Le Liu:** Data curation. **Lin-Lin Ma:** Validation, Software.

Acknowledgments

This work was supported by the Jing–Jin–Ji Regional Integrated Environmental Improvement-National Science and Technology Major Project (2025ZD1202205) and Sino-Norwegian cooperation project CHINORCH$_4$ (CHN-2148, 22/0011).

Declaration of generative AI section

The authors used ChatGPT only for English language polishing. No generative AI tools were used for research design, data analysis, interpretation of results, or the generation of scientific content. The authors have reviewed the AI-assisted edits and take full responsibility for the final manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2026.08.012.

References

Amann, M., Bertok, I., Borken-Kleefeld, J., et al., 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model. Software 26, 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012.

BMEEB (Beijing Municipal Ecology and Environment Bureau), 2024. Notice on Issuing the Beijing Municipal Methane Emission Control Action Plan. https://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/zfxxgk43/fdzdgknr2/zcfb/2024bzcwj/743687125/index.html (1 January 2026).

Crippa, M., Guizzardi, D., Pagani, F., et al., 2024. Insights into the spatial distribution of global, national, and subnational greenhouse gas emissions in the Emissions Database for Global Atmospheric Research (EDGAR v8.0). Earth Syst. Sci. Data 16, 2811–2830. https://doi.org/10.5194/essd-16-2811-2024.

Duan, Y., Gao, Y., Zhao, J., et al., 2023. Agricultural methane emissions in China: inventories, driving forces and mitigation strategies. Environ. Sci. Technol. 57, 13292–13303. https://doi.org/10.1021/acs.est.3c04209.

EPA (Environmental Protection Agency), 2019. Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation Potential: 2015–2050. Washington, DC.

FAO (Food and Agriculture Organization), 2023. Food and Agriculture Organization Statistics. https://www.destatis.de/EN/Themes/Countries-Regions/International-Statistics/DataSources/45_01_FAO_Data.html (1 January 2026).

Gan, T., Ali, T., Liu, W., et al., 2026. Assessing climate and transition risks to China's agriculture under 1.5 and 2.0 °C global warming scenarios. Adv. Clim. Change Res. 17, 411–420. https://doi.org/10.1016/j.accre.2025.12.011.

Gao, J., Guan, C., Zhang, B., et al., 2021. Decreasing methane emissions from China's coal mining with rebounded coal production. Environ. Res. Lett. 16, 124037–124047. https://doi.org/10.1088/1748-9326/ac38d8.

Hoesly, R.M., Smith, S.J., Feng, L., et al., 2018. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geosci. Model Dev. 11, 369–408. https://doi.org/10.5194/gmd-11-369-2018.

Höglund-Isaksson, L., 2012. Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs. Atmos. Chem. Phys. 12, 9079–9096. https://doi.org/10.5194/acp-12-9079-2012.

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., et al., 2020. Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe: results from the GAINS model. Environ. Res. Commun. 2, 25004–25025.

IEA (International Energy Agency), 2019. World Energy Outlook 2018. Directorate of Sustainability, Technology and Outlooks, Paris, France.

IPCC (Intergovernmental Panel on Climate Change), 2022. Sixth Assessment Report Working Group III, Climate Change 2022: Mitigation of Climate Change. Cambridge University Press, Cambridge and New York.

Jackson, R.B., Saunois, M., Bousquet, P., et al., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environ. Res. Lett. 15, 071002. https://doi.org/10.1088/1748-9326/ab9ed2.

Kang, Y., Tian, P., Li, J., et al., 2024. Methane mitigation potentials and related costs of China's coal mines. Fundam. Res. 4, 1688–1695. https://doi.org/10.1016/j.fmre.2023.09.012.

Khanna, N., Lin, J., Liu, X., et al., 2024. An assessment of China's methane mitigation potential and costs and uncertainties through 2060. Nat. Commun. 15, 1–13. https://doi.org/10.1038/s41467-024-54038-y.

Lan, X., Thoning, K.W., Dlugokencky, E.J., 2022. Trends in globally-averaged CH_4, N_2O, and SF_6 Determined from NOAA Global Monitoring Laboratory Measurements. https://doi.org/10.15138/P8XG-AA10.

Lei, T., Guan, D., Shan, Y., et al., 2021. Adaptive CO_2 emissions mitigation strategies of global oil refineries in all age groups. One Earth 4, 1114–1126.

Liang, Y., Jin, H., 2024. Roadmap for the Development of Methane Control Technology in China, Second. Science Press, Beijing (Chinese).

Lin, E., 2012. Technology options for reducing agricultural methane emissions. J. Ecol. Rural Environ. 9, 9–12 (Chinese).

Lin, J., Khanna, N., Liu, X., et al., 2019. China's non-CO_2 greenhouse gas emissions: future trajectories and mitigation options and potential. Sci. Rep. 9, 16095. https://doi.org/10.1038/s41598-019-52653-0.

Luo, J., Wang, H., Li, H., et al., 2025. Structural shifts in China's oil and gas CH_4 emissions with implications for mitigation efforts. Nat. Commun. 16, 2926. https://doi.org/10.1038/s41467-025-58237-z.

MAPRC (Ministry of Agriculture of the People's Republic of China), 2015. Action Plan for Zero-growth in Chemical Fertilizer Use by 2020. http://www.moa.gov.cn/nybgb/2015/san/201711/t20171129_5923401.htm. (Accessed 1 January 2026).

MEEPRC (Ministry of Ecology and Environment of the People's Republic of China), 2016. Notice of the State Council on Issuing the Work Plan for Greenhouse Gas Emission Control During the 13th Five-Year Plan Period. https://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/201904/t20190419_700360.shtml. (Accessed 1 January 2026).

MEEPRC (Ministry of Ecology and Environment of the People's Republic of China), 2021. China Statistical Yearbook on Environment 2021 (Beijing).

MEEPRC (Ministry of Ecology and Environment of the People's Republic of China), 2024. Emission Standard of Coalbed Methane/Coal Mine Gas (GB21522-2024). China Environment Publishing Group, Beijing.

MEEPRC (Ministry of Ecology and Environment of the People's Republic of China), 2025. China's National Autonomous Contribution Report for 2035 (Beijing).

MIITPRC (Ministry of Industry and Information Technology of the People's Republic of China), 2016. Industry Green Development Plan (2016–2020). https://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057267/n3057272/c5118197/part/5118220.pdf. (Accessed 1 January 2026).

NBS (National Bureau of Statistics), 2021a. China Statistical Yearbook 2021 (Beijing).

NBS (National Bureau of Statistics), 2021b. China Agricultural Statistical Yearbook 2021 (Beijing).

NCCCSIC (National Center for Climate Change Strategy and International Cooperation), 2024. The People's Republic of China First Biennial Transparency Report on Climate Change (Beijing).

NDRCPRC (National Development and Reform Commission the People's Republic of China), 2014. Guiding Opinions on Promoting Safe and Green Development, Clean and High-efficiency Utilization of Coal. https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html. (Accessed 1 January 2026).

NDRCPRC (National Development and Reform Commission the People's Republic of China), 2016. Notice on issuing the "13th Five-Year Plan" for Energy Development. https://www.ndrc.gov.cn/xxgk/zcfb/tz/201701/t20170117_962873.html. (Accessed 1 January 2026).

Ocko, I.B., Sun, T., Shindell, D., et al., 2021. Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. Environ. Res. Lett. 16, 054042. https://doi.org/10.1088/1748-9326/abf9c8.

Olga, G., Adrian, L., Hongmin, D., et al., 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas inventories. Intergovernmental Panel on Climate Change, Switzerland.

Powell, J.T., Townsend, T.G., Zimmerman, J.B., 2016. Estimates of solid waste disposal rates and reduction targets for landfill gas emissions. Nat. Clim. Change 6, 162−165. https://doi.org/10.1038/nclimate2804.

SCPRC (The State Council of the People's Republic of China), 2012. Notice of the State Council on Issuing the Work Plan for Greenhouse Gas Emission Control During the 12th Five-Year Plan Period. https://www.gov.cn/zhengce/zhengceku/2012-01/13/content_1294.htm. (Accessed 1 January 2026).

SCPRC, 2021. The 14th five-year Plan for Economic and Social Development of the People's Republic of China and the Long-range Objectives through the Year 2035. https://www.gov.cn/xinwen/2021-0313/content_5592681.htm. (Accessed 1 January 2026).

SCPRC, 2023. Notice of the State Council on Issuing the Methane Emissions Control Action Plan. https://www.gov.cn/zhengce/zhengceku/202311/content_6914109.htm. (Accessed 1 January 2026).

SDEE (Shanxi Department of Ecology and Environment), 2022. Addressing Climate Change and Promoting Green and Low-carbon Transformation in Shanxi Province. https://sthjt.shaanxi.gov.cn/sy/hjyw/202512/t20251226_3599724.html. (Accessed 1 January 2026).

Shu, Y., Hu, J., Zhang, S., et al., 2022. Analysis of the air pollution reduction and climate change mitigation effects of the Three-Year Action Plan for Blue Skies on the "2+26" Cities in China. J. Environ. Manag. 317, 115455. https://doi.org/10.1016/j.jenvman.2022.115455.

Smith, P., Martino, D., Cai, Z., et al., 2007. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363, 789−813. https://doi.org/10.1098/rstb.2007.2184.

Teng, F., Su, X., Wang, X., 2019. Can China peak its non-CO_2 GHG emissions before 2030 by implementing its nationally determined contribution? Environ. Sci. Technol. 53, 12168−12176. https://doi.org/10.1021/acs.est.9b04162.

Tian, S., 2020. Use of low-temperature separation method in light hydrocarbon recovery from oilfield associated gas. Technol. Mark. 27, 115−116 (Chinese).

UNEP (United Nations Environment Programme), 2025a. Global Methane Status Report. Paris, France.

UNEP, 2025b. Global Methane Status Report 2025. Paris, France.

UNEPCCAC (United Nations Environment Programme and Climate and Clean Air Coalition), 2021. Global Methane Assessment-Benefits and Costs of Mitigating Methane Emissions. Paris, France.

Wang, K., Dong, R., Luo, J., 2023. China Biogas Industry's Contribution to Carbon Peak and Carbon Neutrality. Tsinghua University Press, Beijing (Chinese).

Xu, P., Liao, Y., Zheng, Y., et al., 2019. Northward shift of historical methane emission hotspots from the livestock sector in China and assessment of potential mitigation options. Agric. For. Meteorol. 272−273, 1−11. https://doi.org/10.1016/j.agrformet.2019.03.022.

Xu, Y., Li, K., Zhang, X., et al., 2025. Climate change adaptation technology development of key socioeconomic sectors and ecosystem in China. Adv. Clim. Change Res. 16, 666−673. https://doi.org/10.1016/j.accre.2025.07.006.

Yu, J., Peng, S., Chang, J., et al., 2018. Inventory of methane emissions from livestock in China from 1980 to 2013. Atmos. Environ. 184, 69−76. https://doi.org/10.1016/j.atmosenv.2018.04.029.

Yusuf, R.O., Noor, Z.Z., Abba, A.H., et al., 2012. Methane emission by sectors: a comprehensive review of emission sources and mitigation methods. Renew. Sustain. Energy Rev. 16, 5059−5070. https://doi.org/10.1016/j.rser.2012.04.008.

Zhang, Y., Fang, S., Chen, J., et al., 2022. Observed changes in China's methane emissions linked to policy drivers. Proc. Natl. Acad. Sci. 119, e2202742119. https://doi.org/10.1073/pnas.2202742119.

Zhao, M., Tian, X., Wang, Y., et al., 2024. Slowdown in China's methane emission growth. Natl. Sci. Rev. 11. https://doi.org/10.1093/nsr/nwae223 nwae223.