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Integrating sustainability indicators into environmental impact assessment of a cattle manure biogas system in Jordan

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ABSTRACT

Anaerobic digestion (AD) integrated with combined heat and power (CHP) can improve agricultural waste management through renewable energy generation, emission mitigation, and resource recovery. However, conventional environmental impact assessments (EIAs) often overlook interactions among environmental performance, resource circularity, and operational sustainability. This study presents an integrated EIA framework for a full-scale cattle manure AD–CHP system in Jordan, combining operational monitoring, greenhouse gas (GHG) accounting, resource recovery indicators, water management assessment, and uncertainty considerations. The assessment was conducted using one stabilized operating year of monitoring data covering feedstock characteristics, biogas quality, energy production, water flows, digestate properties, and operational parameters. The system boundary was defined as gate-to-gate, including manure reception, anaerobic digestion, gas cleaning, CHP operation, digestate handling, and water reuse. Within this defined boundary, the AD–CHP system provided an estimated net GHG mitigation of approximately 38,800 tonnes CO_2-equivalent per year relative to unmanaged cattle manure storage, accounting for methane capture, residual losses, and project-system emissions considered within the assessment boundary. Electricity displacement was evaluated separately as a co-benefit and was not included in the core manure-management GHG mitigation balance. The system generated approximately 7,253 MWh/year of net electricity export, reduced freshwater demand by 55% (80,300 m^3/year), and enabled recovery of approximately 180 tonnes/year nitrogen, 55 tonnes/year P_2O_5, and 60 tonnes/year K_2O nutrient equivalents. The proposed framework demonstrates how integrated EIA approaches can support comprehensive evaluation of AD–CHP sustainability performance while emphasizing transparent boundaries, monitoring, and uncertainty characterization.

Keywords: environmental impact assessment; anaerobic digestion; biogas; waste-to-energy; circular economy; sustainability indicators; climate mitigation.

INTRODUCTION

Environmental impact assessment (EIA) is evolving from a conventional regulatory procedure focused primarily on predicting and mitigating environmental impacts into a broader sustainability-oriented decision-support framework that evaluates long-term environmental performance and supports strategic decision-making (Bond et al., 2025; Mulligan, 2026). This transformation reflects the increasing need for methodologies capable of addressing complex sustainability

challenges by integrating environmental indicators, life-cycle perspectives, resource efficiency considerations, and adaptive management strategies within decision-making processes (Kumar et al., 2025; Marcinkowski & Harężа, 2025). Recent developments further emphasize the importance of combining environmental evaluation with broader knowledge systems, stakeholder perspectives, and qualitative dimensions to improve the effectiveness of impact assessment practices (Walker et al., 2025; Schrijvers et al., 2026).

Contemporary assessment approaches increasingly incorporate sustainability performance, circularity potential, and climate mitigation considerations rather than focusing solely on adverse impacts (Walker et al., 2025; Schrijvers et al., 2026). Integrating life-cycle thinking and circular economy indicators enables evaluation of resource flows, recovery potential, and environmental trade-offs associated with complex systems (Kumar et al., 2025; Toniolo et al., 2025). These integrated approaches are particularly relevant for waste-to-energy systems, where renewable energy generation must be assessed together with resource efficiency, operational requirements, and potential environmental risks (Marcinkowski & Harężа, 2025; Wang et al., 2025).

Livestock manure management represents a significant environmental challenge due to greenhouse gas emissions, odor generation, nutrient losses, and potential soil and water contamination when waste is improperly managed (Wang et al., 2025; Wainer et al., 2025). Anaerobic digestion (AD) provides an important waste-to-energy pathway by converting organic waste into biogas while producing digestate suitable for nutrient recovery and agricultural use (Özdemir, 2025; Wang et al., 2025). Through methane capture and renewable energy production, manure-based AD systems can reduce emissions associated with uncontrolled decomposition and contribute to circular agricultural systems (Wainer et al., 2025; Purushothaman et al., 2025).

However, the sustainability performance of AD systems depends on multiple factors, including feedstock characteristics, transportation requirements, energy consumption, methane recovery efficiency, digestate management, and emission-control practices (Özdemir, 2025; Wang et al., 2025). Potential impacts related to methane leakage, hydrogen sulfide emissions, odor generation, ammonia emissions, wastewater management, and occupational safety require systematic assessment and continuous monitoring (Wainer et al., 2025; Mulligan, 2026). Therefore, integrated EIA frameworks are needed to ensure that renewable energy benefits are achieved while avoiding the transfer of environmental burdens to other receptors.

The need for integrated sustainability assessment is particularly important in arid and semi-arid regions, where water scarcity, ecosystem vulnerability, and increasing agricultural pressures require innovative resource-management solutions (European Environment Agency, 2025; Purushothaman et al., 2025). Jordan provides a particularly relevant case because severe water scarcity is coupled with high energy requirements for water abstraction, treatment, and distribution, reinforcing the importance of integrated water–energy and resource-efficiency strategies (Alwidyan et al., 2026; Ministry of Water and Irrigation, 2023). Developing cattle manure biogas systems in this context provides an opportunity to transform agricultural waste into renewable energy and recovered nutrients while supporting circular economy objectives. In addition to water scarcity, the Zarqa River Basin is subject to localized environmental pressures from industrial and agricultural activities, with elevated hazardous-metal concentrations reported in soils near affected areas and potential implications for groundwater quality (Ahmad, 2025b).

Despite advances in anaerobic digestion research, limited studies have evaluated manure-based biogas facilities through an integrated EIA perspective combining environmental risk assessment, sustainability indicators, circular economy performance, and long-term monitoring requirements. Existing studies frequently focus on individual aspects such as technical performance, energy production, or life-cycle impacts, while fewer studies address how these components can be integrated into a comprehensive EIA framework suitable for waste-to-energy systems operating in environmentally sensitive regions (Kumar et al., 2025; Schrijvers et al., 2026).

Therefore, this study aims to advance integrated EIA approaches for sustainable waste-to-energy systems through the assessment of a cattle manure biogas plant in Jordan. The study evaluates environmental impacts, sustainability benefits, and management requirements associated with anaerobic digestion-based energy recovery, including greenhouse gas mitigation, air emissions, water-resource protection, nutrient recovery, biodiversity considerations, occupational

health risks, and environmental monitoring strategies. By integrating EIA principles with circular economy concepts, life-cycle thinking, and sustainability indicators, this research provides a practical framework for evaluating renewable waste-management systems in Jordan and comparable water-limited regions.

MATERIALS AND METHODS

Regulatory framing, assessment scope, and methodological approach

The assessment framework integrated conventional environmental impact assessment (EIA) procedures with sustainability indicators, life-cycle thinking, circular economy principles, and adaptive management to evaluate environmental performance and resource recovery within the AD–CHP system. This approach incorporates technical environmental prediction with broader sustainability dimensions (Walker et al., 2025) and enables consideration of adverse impacts, resource recovery, climate mitigation, and long-term sustainability performance (Kumar et al., 2025; Marcinkowski & Haręża, 2025).

The EIA followed a structured pathway comprising project-scope definition, baseline environmental characterization, impact-pathway identification, significance evaluation, mitigation assessment, and monitoring verification. Monitoring results and operational feedback were incorporated into adaptive environmental management (Pope et al., 2013; Sánchez & Mitchell, 2017). The facility was therefore evaluated as an integrated environmental system encompassing waste management, renewable energy generation, greenhouse gas mitigation, water resources, nutrient recovery, and operational risks.

A gate-to-gate operational boundary was adopted, with external processes considered only where site-specific information was available. Environmental receptors included air quality, climate change, water resources, soil and land resources, biodiversity, occupational health and safety, and community impacts. Sustainability indicators included greenhouse gas mitigation, methane management, renewable electricity generation, water consumption and reuse, digestate quality, nutrient recovery, and operational risk control (Schrijvers et al., 2026; Purushothaman et al., 2025).

Monitoring covered one stabilized operating year using fixed sampling and metering locations for annual environmental, energy, and mass-balance calculations. Measurements included feedstock characteristics, biogas composition, process-water quality, digestate properties, energy performance, and operational parameters.

Study boundary, system description, and integrated assessment framework

The system boundary was defined to represent the cattle manure AD facility as an integrated waste-to-energy system in which waste treatment, renewable energy production, greenhouse gas mitigation, and resource recovery occur simultaneously. Boundary definition followed established environmental assessment and life-cycle principles (ISO 14040, 2006; Guinée et al., 2011).

The core assessment was gate-to-gate. Selected comparative indicators, particularly methane avoidance and renewable energy displacement, were evaluated against defined baseline scenarios solely to quantify improvements relative to conventional manure management and were not intended to constitute a complete cradle-to-grave life-cycle assessment.

The assessed pathway included manure collection and preparation, anaerobic digestion, biogas treatment, CHP generation, internal energy consumption, process-water management, and digestate separation and storage. External transportation, upstream livestock production, infrastructure and equipment manufacturing, downstream agricultural impacts of digestate application, and full avoided mineral-fertilizer production were excluded because they were outside the operational boundary or lacked sufficient site-specific data (Battini et al., 2016; Purushothaman et al., 2025). Included and excluded processes and their environmental relevance are summarized in Table 1.

Excluded processes and limitations

The integrated framework extends conventional EIA by incorporating resource flows, energy recovery, greenhouse gas mitigation, and circular economy indicators, while applying life-cycle principles to interconnected environmental burdens and benefits (ISO, 2006; Guinée et al., 2011). Performance was assessed through climate mitigation, air emissions, water-resource protection, waste conversion, nutrient recovery,

Table 1. System boundary and included/excluded processes of the AD–CHP environmental impact assessment framework

Assessment component	Included processes	Environmental relevance
Manure collection and reception	Cattle manure delivery, reception, handling, and preparation before digestion	Defines the waste input pathway and baseline manure-management conditions
Anaerobic digestion process	Feedstock degradation, biogas generation, digester operation, and process monitoring	Evaluates conversion of organic waste into renewable energy and reduction of uncontrolled decomposition
Biogas collection and treatment	Biogas storage, gas cleaning, methane monitoring, hydrogen sulfide control, and gas conditioning	Determines methane recovery efficiency, air-quality performance, and operational safety
Combined heat and power (CHP) generation	Biogas combustion, electricity generation, and energy export	Quantifies renewable energy production and avoided conventional electricity demand
Process-water management	Water consumption, internal recycling, reuse pathways, and freshwater demand reduction	Evaluates water-resource efficiency under water-limited conditions
Digestate management	Digestate separation, stabilization, nutrient recovery, and potential agricultural utilization	Assesses circular nutrient recovery and potential fertilizer substitution contribution
Environmental monitoring	Air emissions, greenhouse gases, water indicators, operational parameters, and safety indicators	Provides verification of environmental performance and adaptive management
Occupational and community assessment	Worker exposure risks, odor concerns, safety management, and community-related impacts	Integrates human health and social receptors into EIA evaluation
Excluded processes and limitations		
Excluded element	**Reason for exclusion**	
Manure transportation outside facility boundary	Not included within the operational assessment boundary	
Upstream livestock production emissions	Outside the defined project system boundary	
Manufacturing of infrastructure and equipment	Not included in the operational-phase assessment	
Downstream agricultural impacts of digestate application	Requires site-specific agricultural data and long-term monitoring	
Full replacement of mineral fertilizer production	Nutrient recovery potential assessed; full substitution benefits require additional LCA	

and operational risk management. Climate performance included methane avoidance, controlled biogas utilization, and energy substitution, whereas circularity included manure conversion, renewable energy production, and nutrient recovery from digestate (Poeschl et al., 2012; Wang et al., 2025).

Figure 1 presents the integrated EIA framework linking system inputs and processes with environmental impacts, sustainability indicators, mitigation, monitoring, and adaptive management. Operational measurements rather than theoretical assumptions alone were used for environmental and mass-balance calculations. The framework illustrates the progression from system inputs and operational processes through impact and sustainability assessment to mitigation, monitoring, and adaptive-management feedback, thereby linking impact prediction with continuous environmental performance improvement.

Figure 2 presents the operational boundary and associated material, energy, water, and monitoring flows. The diagram highlights the gate-to-gate assessment boundary and the internal links among manure treatment, biogas generation, CHP energy recovery, process-water reuse, and digestate nutrient recovery.

Baseline environmental characterization and impact indicators

Baseline characterization established reference conditions and measurable indicators for evaluating project-related environmental changes, receptor sensitivity, impact magnitude, and mitigation requirements (Glasson & Therivel, 2019). Sustainability considerations were incorporated by assessing environmental pressures together with resource recovery, climate mitigation, and circular economy performance (Pope et al., 2013; Kumar et al., 2025).

Environmental receptors were selected using a cause–pathway–receptor approach and included atmospheric emissions, greenhouse gas mitigation, water resources, soil and nutrient management, biodiversity, occupational health and safety, and community impacts (Sánchez & Mitchell, 2017).

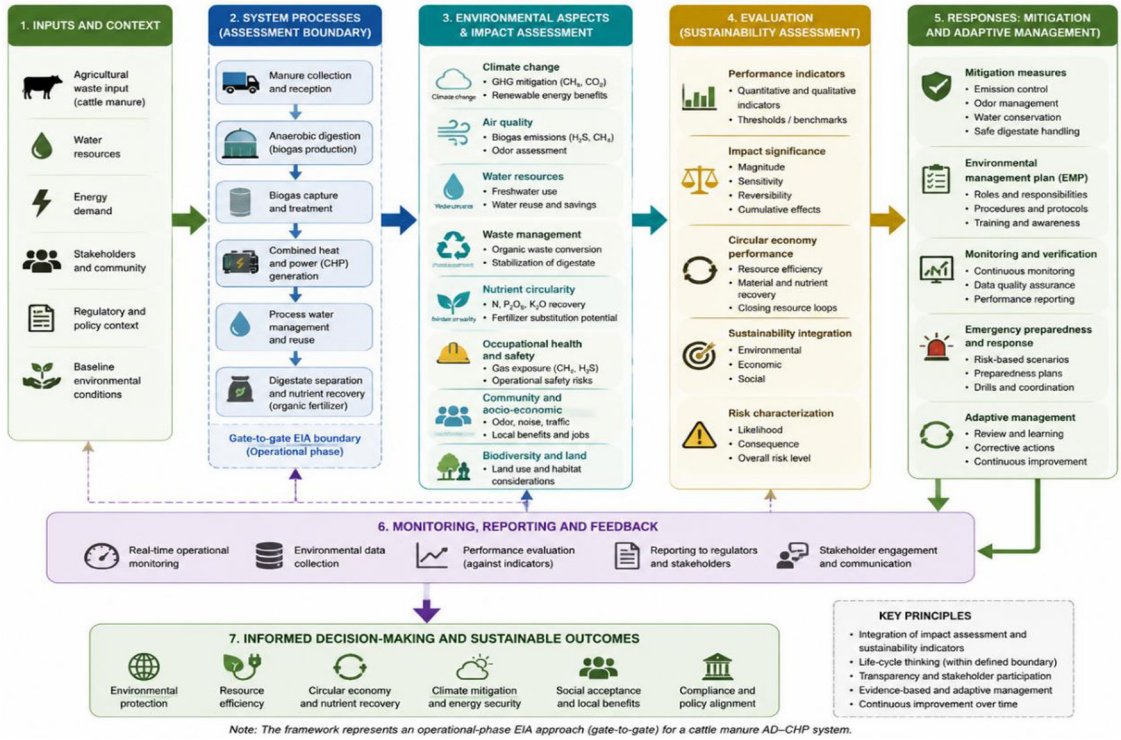

Figure 1. Integrated next-generation EIA framework for the cattle manure AD–CHP system

Air-quality indicators included methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH3), odor potential, and combustion emissions. Methane and H_2S were emphasized because of their relevance to climate effects, odor, operational safety, and biogas performance. Methane capture and energy recovery can reduce emissions associated with conventional manure management (Gerber et al., 2013; Intergovernmental Panel on Climate Change (IPCC), 2019),

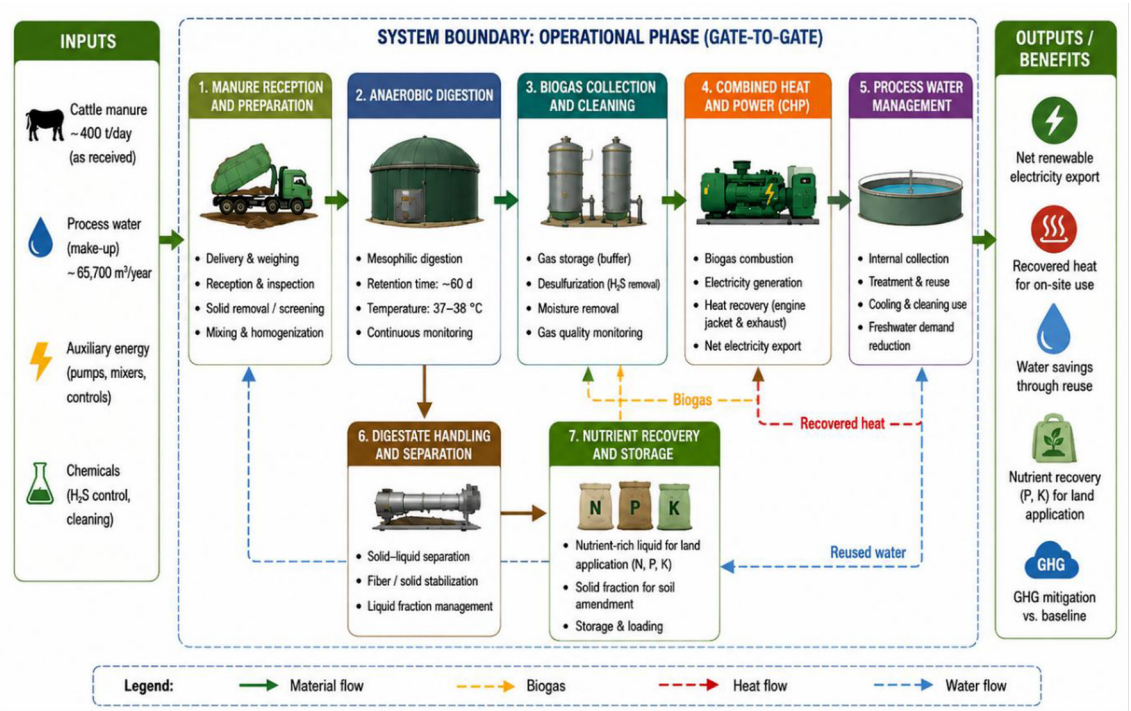

Figure 2. System boundary and material–energy flow diagram of the full-scale AD–CHP facility

while AD performance depends on gas collection efficiency, leakage prevention, biogas utilization, and emission control (Hijazi et al., 2016).

Climate indicators included methane avoidance, renewable electricity generation, conventional energy displacement, and CO_2-equivalent reductions (IPCC, 2019), while considering the effects of manure characteristics, management practices, energy substitution, and system boundaries (Battini et al., 2016; Wang et al., 2025).

Water indicators included freshwater consumption, process-water requirements, wastewater generation, and internal reuse, with particular relevance to Jordan's water scarcity. Water recycling and digestate management were evaluated for both resource-efficiency benefits and potential secondary environmental risks (Hijazi et al., 2016; Wang et al., 2025).

Soil and nutrient indicators included digestate characteristics, nutrient-recovery potential, and associated management requirements. Nutrient recovery may reduce dependence on synthetic fertilizers, although nutrient losses, contamination, and inappropriate application require control. This consideration is particularly relevant in the Zarqa region, where anthropogenic activities have been associated with elevated soil-metal contamination and potential groundwater migration risks (Ahmad, 2025b). Integrating circularity and life-cycle indicators supports evaluation of these resource-recovery pathways and trade-offs (Kumar et al., 2025; Schrijvers et al., 2026).

Biodiversity, occupational health, and community considerations included land-use interactions, ecological sensitivity, odor, noise, exposure to hazardous gases, and methane- and H_2S-related operational risks (Walker et al., 2025). Quantitative indicators were combined with qualitative criteria including receptor sensitivity, duration, reversibility, and mitigation effectiveness. The complete environmental indicator framework and corresponding measurement parameters are summarized in Table 2.

Greenhouse gas accounting and boundary definition

The GHG balance was calculated as the difference between baseline manure-management emissions and project-case emissions within the gate-to-gate boundary. The baseline represented methane emissions from unmanaged manure storage using IPCC-based parameters, while project emissions included methane losses associated

Table 2. Environmental indicators, measurement parameters, and assessment methods applied in the integrated EIA framework

Environmental dimension	Indicator	Measurement/assessment parameter	Assessment purpose
Climate change	Greenhouse gas mitigation	CO_2-equivalent reduction compared with unmanaged manure baseline	Quantifies methane avoidance and renewable energy climate benefits
Methane management	Biogas recovery performance	CH_4 concentration, gas flow, methane capture pathway	Evaluates effectiveness of methane control
Renewable energy performance	Energy recovery	Electricity generation and net electricity export (MWh/year)	Assesses renewable energy contribution
Air quality	Biogas emissions	CH_4, CO_2, H_2S, O_2, moisture, gas quality parameters	Evaluates emission control and operational stability
Odor management	Odor risk indicators	Manure handling, digestion conditions, digestate management practices	Assesses potential community nuisance impacts
Water resources	Water efficiency	Freshwater consumption, process-water recycling, annual water savings	Evaluates resource conservation performance
Waste management	Organic waste conversion	Manure input, digestion efficiency, waste stabilization	Determines effectiveness of waste-to-resource conversion
Nutrient circularity	Nutrient recovery	Nitrogen, phosphorus pentoxide, potassium oxide recovery	Evaluates circular bioeconomy contribution
Soil and agricultural resources	Digestate quality	Nutrient content and management requirements	Assesses potential agricultural value and risks
Occupational health	Safety indicators	Methane, H_2S exposure potential, operational hazards	Evaluates worker protection requirements
Social sustainability	Community impacts	Odor, safety perception, environmental improvements	Evaluates social acceptance and stakeholder relevance
Uncertainty management	Data reliability	Monitoring variability, assumptions, sensitivity parameters	Evaluates confidence of environmental conclusions

with digestion, storage, and facility operation. Grid-electricity displacement was reported separately as a sensitivity/co-benefit term to avoid double counting as per Equation. 1:

$$\Delta GHG = GHG_{baseline} - GHG_{project} \quad (1)$$

where: $GHG_{baseline}$ = emissions from unmanaged manure storage (counterfactual scenario), $GHG_{project}$ = emissions associated with AD–CHP operation within the defined boundary.

Baseline methane emissions were estimated using methane conversion factors and methane-generation parameters, whereas project emissions considered methane capture efficiency, fugitive methane losses, and residual digestate-storage emissions. Detailed system-boundary treatment and GHG parameterization are provided in Supplementary Section S3 and Table S3.

Data collection, monitoring strategy, and quality assurance/quality control (QA/QC)

Data collection combined continuous operational measurements, periodic laboratory analyses, and facility records to characterize material flows, emissions, resource consumption, and environmental performance and to verify predicted impacts through operational observations (Glasson & Therivel, 2019; Sánchez & Mitchell, 2017). Detailed analytical procedures, instrument validation, detection-limit treatment, and data-quality procedures are provided in Supplementary Section S2.

Primary data were obtained during stabilized full-scale AD–CHP operation, excluding commissioning and transitional periods. Monitoring included feedstock characteristics, biogas composition, digestate properties, process-water parameters, energy generation, and operational conditions, providing representative inventory data for environmental assessment (ISO 14044, 2006; Guinée et al., 2011).

Feedstock characterization included total solids (TS), volatile solids (VS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total ammonia nitrogen (TAN), total phosphorus (TP), pH, and carbon-to-nitrogen (C/N) ratio. These parameters were monitored because they affect biodegradability, methane generation, nutrient recovery, process stability, and digestate properties (Raposo et al., 2011; Wang et al., 2025).

Biogas monitoring included methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), hydrogen sulfide (H_2S), moisture content, and gas-flow rate at the digester outlet, raw-biogas collection system, gas-cleaning stage, and CHP inlet. These measurements supported evaluation of gas quality, treatment efficiency, operational safety, emission control, greenhouse gas calculations, and energy performance (Poeschl et al., 2012; Holliger et al., 2016).

Process-water monitoring evaluated treatment effectiveness and internal reuse, while digestate characterization assessed nutrient recovery and environmental suitability, including nitrogen, phosphorus, organic matter, and potential contamination risks (Hijazi et al., 2016; Schrijvers et al., 2026). Energy monitoring included electricity generation, heat recovery, internal energy consumption, and operational efficiency (Kumar et al., 2025; Marcinkowski & Haręża, 2025).

QA/QC procedures included instrument calibration and verification, standardized sampling, laboratory quality controls, duplicate analyses where appropriate, and validation of operational records. Water and wastewater analyses followed recognized analytical procedures, and biogas measurements used calibrated equipment suitable for biogas applications. Fixed monitoring locations and defined measurement procedures supported annualized calculations and reproducibility. Monitoring locations, analytical methods, instruments, and QA/QC procedures are detailed in Supplementary Table S1.

Impact assessment methodology, significance evaluation, and mitigation framework

Measured environmental and operational indicators were translated into impact significance using criteria encompassing magnitude, sensitivity, duration, reversibility, and mitigation effectiveness (Glasson & Therivel, 2019; IAIA, 1999). Life-cycle thinking, circular economy performance, and sustainability indicators were incorporated to evaluate both environmental pressures and resource-recovery benefits (Bond et al., 2025; Kumar et al., 2025).

A cause–pathway–receptor approach linked manure reception and handling, digestion, biogas storage and utilization, CHP operation, digestate management, and wastewater handling with atmospheric emissions, greenhouse gas releases, resource consumption, nutrient losses, and

occupational exposure risks (Pope et al., 2013; Sánchez & Mitchell, 2017).

Impact significance was assessed according to magnitude, spatial extent, duration, frequency, reversibility, probability, and receptor sensitivity, distinguishing temporary and reversible impacts from persistent impacts requiring long-term intervention (Glasson & Therivel, 2019). Both adverse impacts and beneficial sustainability outcomes were considered. Climate assessment addressed methane capture, renewable energy generation, leakage, incomplete combustion, and uncontrolled biogas release (IPCC, 2019; Gerber et al., 2013), while controlled digestion and energy recovery were considered beneficial relative to uncontrolled manure decomposition and conventional energy demand (Wang et al., 2025).

Air-quality assessment considered H_2S, NH_3, odor, combustion emissions, exposure pathways, and control-system performance, with gas-tight operation, biogas cleaning, leak prevention, and monitoring forming key risk-control measures (Hijazi et al., 2016; Poeschl et al., 2012). Water, soil, and nutrient impacts were assessed through water consumption and reuse, wastewater management, digestate quality, nutrient recovery, nutrient losses, and contamination pathways (Schrijvers et al., 2026; Purushothaman et al., 2025).

Mitigation followed the hierarchy of avoidance, minimization, restoration, and compensation. Avoidance focused on preventing uncontrolled methane release through closed digestion and appropriate gas-management infrastructure. Minimization included H_2S removal, odor control, optimized feedstock management, wastewater treatment, and equipment maintenance, while digestate utilization and water recycling returned nutrients and resources to productive cycles (IAIA, 1999; Bond et al., 2025). Residual impacts were addressed through monitoring and adaptive management, linking impact prediction, mitigation, verification, corrective action, and continuous environmental improvement (Sánchez & Mitchell, 2017).

Uncertainty assessment, sensitivity analysis, and adaptive management framework

Uncertainty analysis addressed variability in feedstock composition, operating conditions, measurement accuracy, and calculation assumptions to distinguish observed performance from expected variability and potential deviations (Huijbregts et al., 2003; Lloyd & Ries, 2007).

Major uncertainty sources included manure characteristics, biogas production and methane concentration, analytical measurements, energy performance, and environmental calculation assumptions. Variability in total solids, volatile solids, nutrient composition, and biodegradability can affect methane yield and digestate characteristics (Raposo et al., 2011; Wang et al., 2025), while uncertainty in biogas flow and composition affects estimates of greenhouse gas mitigation and renewable energy production (Poeschl et al., 2012; Holliger et al., 2016).

Sensitivity analysis focused on methane recovery efficiency, biogas production rate, energy-conversion efficiency, emission-control performance, and digestate-management assumptions to identify parameters with the greatest influence on environmental outcomes and priorities for monitoring and mitigation (Lloyd & Ries, 2007). Alternative assumptions and scenarios were used to evaluate conclusion robustness (ISO 14044, 2006).

Data quality and representativeness were addressed by prioritizing measured full-scale operational data, defined sampling locations, analytical procedures, and operational measurements. Uncertainty propagation incorporated measurement variability, sampling uncertainty, and calculation assumptions.

Adaptive management linked monitoring and uncertainty assessment with corrective action and long-term environmental improvement (Sánchez & Mitchell, 2017). Predictive and spatial modeling approaches can further strengthen adaptive environmental management by identifying emerging environmental risks, supporting early intervention, and enabling management responses to be updated as new monitoring data become available (Ahmad, 2025a). Measures included adjusting feedstock management, optimizing digestion conditions, improving gas-cleaning efficiency and odor control, and modifying digestate-management strategies when monitoring identified performance deviations.

RESULTS AND DISCUSSION

Environmental baseline and operational performance of the AD–CHP system

The environmental baseline and operational performance assessment was based on one year of measurement-derived data from a full-scale

cattle manure anaerobic digestion (AD) system integrated with biogas cleaning, combined heat and power (CHP) generation, process-water reuse, and digestate recovery. The facility processed approximately 400 tonnes of cattle manure per day under mesophilic conditions (approximately 37–38 °C), with manure reception, anaerobic digestion, biogas collection and cleaning, CHP generation, process-water recirculation, and digestate recovery forming the principal operational components. Detailed feedstock characterization and source-derived operating values are provided in Supplementary Table S4.1. The classification of measured plant outputs, calculated indicators, and model-derived counterfactual estimates is provided in Supplementary Section S5.

The monitored system demonstrated that manure-based AD provides environmental functions beyond electricity generation. Net renewable electricity export reached 7,253 MWh/year, while methane concentrations in biogas were approximately 54–56% CH_4. Feedstock characteristics, including total solids, volatile solids, chemical oxygen demand, nitrogen compounds, phosphorus, pH, and carbon-to-nitrogen ratio, provided the basis for interpreting digestion stability and environmental performance because substrate variability directly affects methane generation and digestate characteristics (Raposo et al., 2011; Wang et al., 2025). Biogas monitoring further confirmed the importance of methane recovery and emission control for energy recovery, equipment reliability, worker safety, and atmospheric emissions (Hijazi et al., 2016; Poeschl et al., 2012).

The system provided an estimated net GHG mitigation of approximately 38,800 tonnes CO_2-equivalent/year relative to unmanaged manure storage. Closed-loop process-water recirculation reduced freshwater demand by approximately 55%, equivalent to about 80,300 m³/year, while digestate recovery provided estimated annual nutrient credits of approximately 180 tonnes of nitrogen, 55 tonnes of phosphorus pentoxide, and 60 tonnes of potassium oxide. Collectively, these indicators demonstrate integrated sustainability performance across climate mitigation, water conservation, and nutrient-resource recovery. The main operational and sustainability indicators are summarized in Table 3.

Greenhouse gas mitigation, methane management, and climate impact assessment

The climate assessment compared the AD–CHP system with unmanaged manure storage, where anaerobic decomposition produces methane without controlled recovery. Methane capture,

Table 3. Summary of operational performance and sustainability indicators of the cattle manure AD–CHP system

Sustainability indicator	Performance value	Environmental significance
Daily cattle manure processing capacity	~400 tonnes /day	Demonstrates full-scale waste-management capacity
Anaerobic digestion operating condition	Mesophilic operation (~37–38 °C)	Supports stable biological conversion conditions
Methane concentration in biogas	Approximately 54–56% CH_4	Indicates suitability for renewable energy recovery
Renewable electricity export	7,253 MWh/year	Represents renewable energy generation and fossil-energy displacement potential
Greenhouse gas mitigation	≈38,800 tonnes CO_2-equivalent/year	Demonstrates net climate benefit from methane management within the defined assessment boundary
Freshwater demand reduction	≈55% reduction	Demonstrates improved water-use efficiency
Annual freshwater saving	≈80,300 m³/year	Reduces pressure on freshwater resources in Jordan
Nitrogen recovery	≈180 tonnes /year	Supports nutrient circularity and contribution to fertilizer substitution
Phosphorus recovery (as P_2O_5)	≈55 tonnes /year	Recovers valuable agricultural nutrients
Potassium recovery (as K_2O)	≈60 tonnes /year	Enhances digestate resource value
Primary environmental benefits	Climate mitigation, energy recovery, water conservation, nutrient recycling	Demonstrates multifunctional sustainability performance
Main residual risks	Methane leakage, H_2S emissions, odor, digestate management, operational variability	Defines monitoring and mitigation priorities

controlled biogas utilization, and substitution of conventional energy therefore represent the principal climate-mitigation pathways (IPCC, 2019; Gerber et al., 2013). Within the defined assessment boundary, the facility achieved an estimated net GHG mitigation of approximately 38,800 tonnes CO_2-equivalent/year relative to unmanaged manure storage. Figure 3 illustrates the transition from uncontrolled manure-management emissions toward methane capture, controlled biogas utilization, renewable electricity generation, and avoided emission pathways.

The produced biogas contained approximately 54–56% methane, supporting energy recovery through CHP after appropriate cleaning and conditioning. Controlled methane utilization reduces direct atmospheric release, while the net electricity export of 7,253 MWh/year provides an additional energy-substitution co-benefit (Hijazi et al., 2016; Wang et al., 2025). Thus, climate benefits arise from methane management together with renewable energy recovery rather than electricity generation alone.

Maintaining these benefits depends on effective control of fugitive methane leakage, incomplete gas capture, digestate-storage emissions, and operational inefficiencies. Continuous monitoring of methane concentration, gas flow, storage conditions, and CHP performance is therefore required because uncertainties in gas capture and measurement can materially affect estimated climate performance (Poeschl et al., 2012; Holliger et al., 2016). By integrating waste management, energy recovery, and methane mitigation, the system also demonstrates the contribution of circular resource management to climate objectives (Bond et al., 2025; Mulligan, 2026).

The reported mitigation value should be interpreted within the defined gate-to-gate boundary rather than as a complete cradle-to-grave carbon footprint. External manure transportation, digestate field-application emissions, future electricity-grid changes, and regional management practices may alter overall life-cycle performance. Detailed methane-pathway assumptions, baseline comparisons, and GHG mass-balance calculations are provided in Supplementary Table S4.2, with associated calculation parameters summarized in Supplementary Table S6.

Water conservation, process-water reuse, and resource efficiency assessment

Water conservation was evaluated using operational water demand, internal process-water reuse, and freshwater requirements, recognizing water efficiency as an important sustainability indicator within integrated AD systems (Bond et al., 2025; Mulligan, 2026). Internal recycling and reuse reduced freshwater demand by approximately 55%, corresponding to an annual saving of approximately 80,300 m³/year.

This reduction is particularly important in Jordan, where severe water scarcity is compounded by the substantial energy requirements associated with water abstraction, treatment, and distribution (European Environment Agency, 2025; Alwidyan et al., 2026; Ministry of Water and

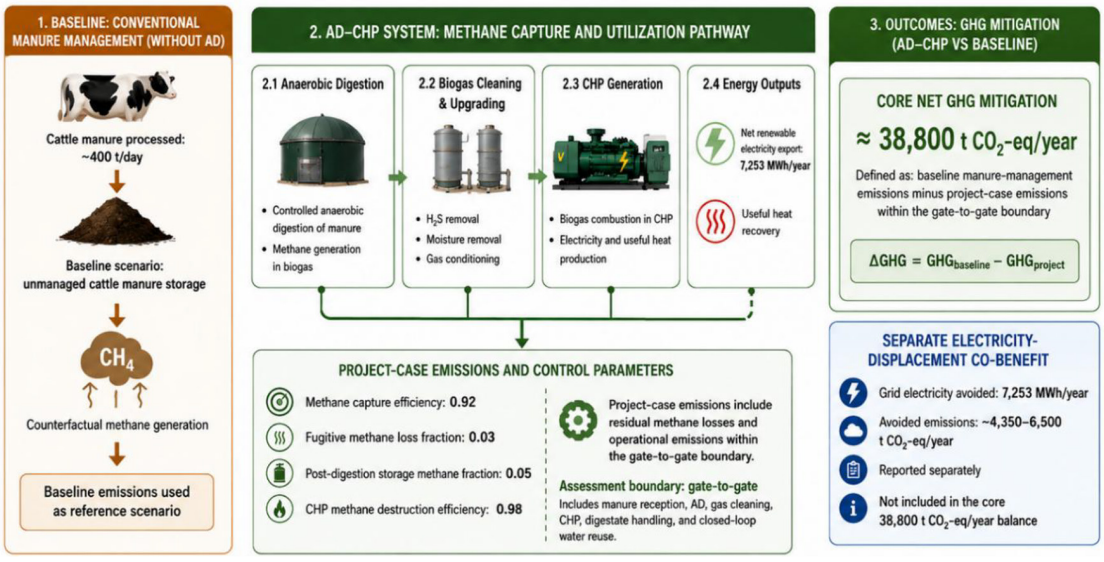

Figure 3. Methane management and greenhouse gas mitigation pathway of the AD–CHP system

Irrigation, 2023). Internal water circulation also supports circular economy principles by reducing dependence on primary freshwater resources and wastewater generation (Kumar et al., 2025; Schrijvers et al., 2026).

However, process-water reuse requires monitoring to prevent accumulation of contaminants, nutrients, or pathogens that could affect operational reliability or generate secondary environmental risks (Hijazi et al., 2016; Wang et al., 2025). Water performance must also be interpreted together with process efficiency, energy balance, and recovered-product management because these factors jointly influence the environmental performance of biogas systems (Hijazi et al., 2016; Wang et al., 2025). Long-term variability in feedstock characteristics, cleaning requirements, maintenance, and seasonal operating conditions further requires continued monitoring of freshwater consumption, recycled-water quality, and wastewater characteristics.

Nutrient recovery, digestate management, and circular bioeconomy performance

Digestate management provides a pathway for recovering nutrients from stabilized organic residues and extending the environmental benefits of AD beyond energy generation toward circular nutrient management (Purushothaman et al., 2025; Schrijvers et al., 2026). The facility generated estimated annual nutrient credits of approximately 180 tonnes of nitrogen (N), 55 tonnes of phosphorus pentoxide (P_2O_5), and 60 tonnes of potassium oxide (K_2O). These nutrients may partially substitute mineral fertilizers under appropriate agricultural and regulatory conditions. Detailed digestate delivery data, compliance parameters, and nutrient-recovery calculations are provided in Supplementary Table S7.

Anaerobic digestion provides a more controlled nutrient-recovery pathway than unmanaged manure storage, where nutrients may be lost through volatilization, runoff, or uncontrolled decomposition (Hijazi et al., 2016; Wang et al., 2025). Potential fertilizer substitution may also reduce environmental pressures associated with mineral-fertilizer production, although the magnitude of this benefit depends on actual downstream utilization (Battini et al., 2016; Kumar et al., 2025).

These benefits depend on appropriate digestate management. Uncontrolled storage or land application may generate ammonia emissions, nutrient leaching, groundwater contamination, or ecological impacts; therefore, digestate quality, nutrient content, application rates, and regulatory compliance require monitoring (IPCC, 2019; Wang et al., 2025). Integration of digestate recovery with renewable energy generation and water reuse demonstrates the multifunctional circular-resource role of the AD–CHP system (Bond et al., 2025; Mulligan, 2026).

Importantly, the reported nutrient credits represent potential resource-recovery benefits, not verified downstream environmental savings. Their actual benefits depend on soil conditions, crop requirements, transportation distance, application practices, and regulatory acceptance. This distinction is necessary to avoid overestimating the circular bioeconomy benefits of digestate utilization.

Air emissions, odor control, and environmental risk management

Air-emission assessment addressed residual risks from methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH3), odor compounds, and CHP combustion emissions associated with manure handling, digestion, biogas management, and energy generation (Glasson & Therivel, 2019; Bond et al., 2025). Biogas composition, including methane, carbon dioxide, oxygen, hydrogen sulfide, moisture, and gas flow, was monitored at critical process locations to evaluate environmental performance and operational safety (Holliger et al., 2016).

The measured methane concentration of approximately 54–56% CH_4 indicated stable gas quality suitable for CHP utilization. Within the gate-to-gate boundary, the AD–CHP system achieved an estimated net GHG mitigation of approximately 38,800 tonnes CO_2-equivalent/year relative to unmanaged manure storage after accounting for methane capture, residual losses, and project-system emissions. Electricity displacement was evaluated separately as a co-benefit and was not included in the core manure-management mitigation balance. Maintaining this benefit requires control of fugitive methane emissions from digesters, pipelines, storage units, and CHP systems (IPCC, 2019; Poeschl et al., 2012).

H_2S control is necessary because of its contribution to odor, equipment corrosion, and occupational risks; consequently, gas cleaning and monitoring are essential for safe and reliable operation (Hijazi et al., 2016; Holliger et al., 2016). Controlled digestion can also reduce odors associated

with unmanaged manure decomposition, although residual odor risks remain at manure reception, digestate storage, and during abnormal operating conditions. Enclosed handling, appropriate storage, rapid detection of disturbances, and communication mechanisms are therefore required (Wang et al., 2025; Sánchez & Mitchell, 2017).

Environmental risk management followed a prevention–reduction–verification approach involving gas-tight infrastructure, feedstock control, biogas cleaning, CHP optimization, odor management, equipment maintenance, and continuous monitoring. Monitoring results support corrective actions and adaptive management (Sánchez & Mitchell, 2017; Mulligan, 2026). Nevertheless, long-term emission performance remains subject to variations in feedstock, operating conditions, maintenance, and production scale, emphasizing the need for continued verification.

Occupational health, safety, and community impact assessment

Occupational and community impacts were incorporated as EIA receptors to evaluate worker protection, operational risks, and social acceptance alongside biophysical environmental effects (Glasson & Therivel, 2019; Bond et al., 2025). Major occupational hazards include methane accumulation, H_2S exposure, carbon dioxide accumulation, ammonia emissions, confined spaces, pressure systems, and mechanical equipment associated with pumps, digesters, gas systems, and CHP units (Holliger et al., 2016; Poeschl et al., 2012).

The approximately 54–56% methane content of the biogas provides renewable energy potential but also requires strict gas-management controls because of its flammability. Gas-tight digesters, pressure control, leak detection, ventilation, and safe CHP operation are therefore essential. H_2S additionally presents health, odor, and corrosion risks, supporting the need for gas cleaning, continuous gas-quality monitoring, and preventive maintenance (Holliger et al., 2016). Engineering controls were complemented by operator training, standard operating procedures, emergency-response plans, restricted access, and appropriate personal protective equipment (ISO 45001, 2018).

At the community level, controlled digestion can reduce odor, pests, uncontrolled methane emissions, and other nuisance associated with unmanaged manure storage (Wang et al., 2025; Sánchez & Mitchell, 2017). Residual concerns may include odors from manure reception and digestate handling, transportation, mechanical noise, visual effects, and perceived gas-related safety risks. Transparent monitoring, stakeholder communication, and responsive management are therefore important for long-term project performance (Walker et al., 2025). Community benefits include improved manure management, renewable electricity generation, potential agricultural support through nutrient recovery, and reduced environmental pressures from uncontrolled waste disposal (Mulligan, 2026).

Integrated sustainability assessment and comparison with conventional manure management pathways

Conventional manure management represents a largely linear pathway in which manure storage or disposal can generate methane emissions, odors, nutrient losses, and soil- and water-quality pressures with limited resource recovery. In contrast, the assessed AD–CHP system integrates waste stabilization, renewable energy production, climate mitigation, water conservation, and nutrient recovery within a circular waste-to-energy pathway (Bond et al., 2025; Mulligan, 2026). Figure 4 summarizes the integrated sustainability performance across climate, energy, water, nutrient-recovery, and resource-efficiency indicators.

Compared with unmanaged manure storage, the facility provided an estimated net GHG mitigation of approximately 38,800 tonnes CO_2-equivalent/year and exported approximately 7,253 MWh/year of renewable electricity, demonstrating the combined waste-management and energy-recovery functions of AD (Hijazi et al., 2016; Wang et al., 2025). Freshwater demand was reduced by approximately 55%, corresponding to approximately 80,300 m³/year, an important benefit within Jordan's water-limited context (European Environment Agency, 2025; Kumar et al., 2025). Digestate recovery provided approximately 180 tonnes of nitrogen, 55 tonnes of P_2O_5, and 60 tonnes of K_2O annually, creating potential for improved nutrient cycling and partial mineral-fertilizer substitution (Purushothaman et al., 2025; Schrijvers et al., 2026).

Digestate management further resulted in approximately 28,000 m³/year of liquid digestate and 4,500 tonnes/year of separated solids being delivered for reuse, with 95% of assessed batches meeting metals and specification requirements (Supplementary Table S7).

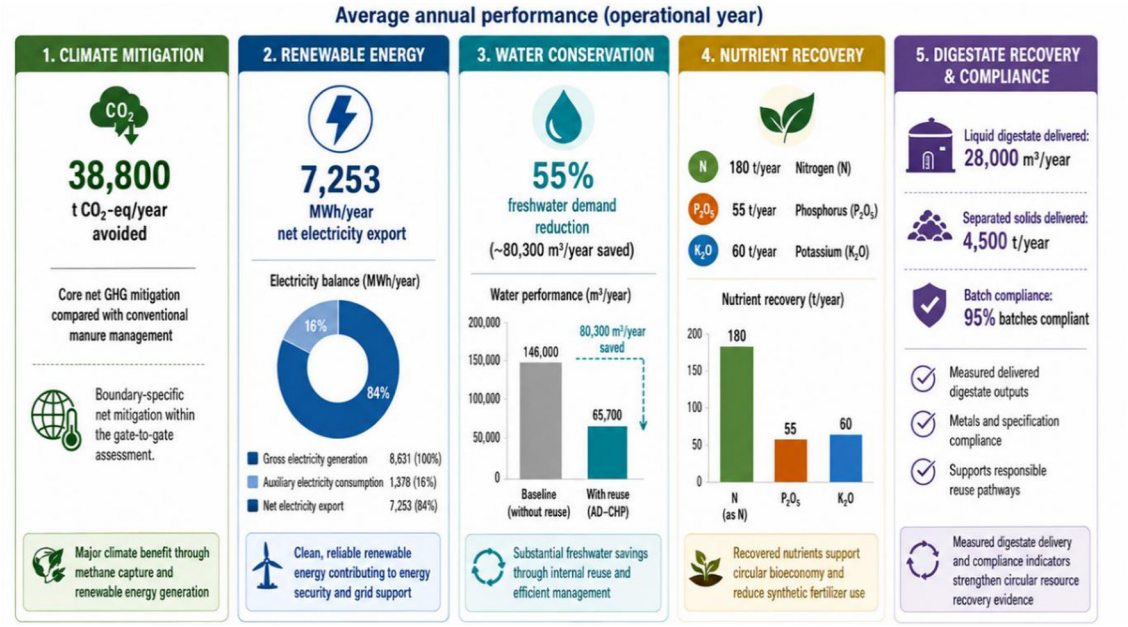

Figure 4. Integrated sustainability performance dashboard of the full-scale AD–CHP system based on climate, energy, water, nutrient recovery, and measured digestate/compliance indicators

Despite these benefits, AD–CHP does not eliminate environmental pressures. Residual risks include fugitive methane emissions, digestate handling, gas-cleaning efficiency, operational energy requirements, and downstream nutrient management; therefore, environmental performance depends on continuous monitoring, maintenance, leakage prevention, and appropriate operating practices (Hijazi et al., 2016; Wang et al., 2025).

The assessment also demonstrates that these environmental benefits are interconnected: methane capture supports both climate mitigation and improved manure management; digestate recovery combines nutrient recycling with reduced disposal requirements; water recycling reduces freshwater pressure while improving process efficiency; and renewable electricity increases the resource value of manure treatment. This interdependence supports integrated assessment approaches combining life-cycle thinking, circularity indicators, and EIA principles rather than evaluating individual impacts independently (Kumar et al., 2025; Schrijvers et al., 2026).

Overall, the comparison indicates a transition from disposal-oriented manure management toward a multifunctional environmental-management system that converts environmental pressures into measurable resource-recovery opportunities. This supports the evolution of EIA from identifying project-generated impacts toward evaluating how projects can reduce existing pressures and contribute to sustainable development (Bond et al., 2025; Walker et al., 2025).

CONCLUSIONS

This study demonstrates that integrating sustainability indicators, life-cycle thinking, circular economy principles, operational monitoring, and adaptive management can extend conventional Environmental Impact Assessment (EIA) into a more comprehensive decision-support framework for waste-to-energy systems. Within the defined gate-to-gate boundary, the full-scale cattle manure AD–CHP system provided an estimated net GHG mitigation of approximately 38,800 tonnes CO_2-equivalent/year relative to unmanaged manure storage, while generating approximately 7,253 MWh/year of net renewable electricity. Process-water reuse reduced freshwater demand by approximately 55% (80,300 m³/year), and digestate recovery provided approximately 180 tonnes/year of nitrogen, 55 tonnes/year of P_2O_5, and 60 tonnes/year of K_2O. These results demonstrate that manure-based anaerobic digestion functions as a multifunctional resource-management pathway integrating methane mitigation, renewable energy generation, water conservation, and nutrient recovery rather than solely as an electricity-generation technology.

The findings support next-generation EIA approaches that evaluate both environmental risks and measurable sustainability benefits, including climate mitigation, resource efficiency, circularity, and resource recovery. Operational monitoring and adaptive management are particularly important for verifying long-term performance and controlling residual risks such as methane leakage, air emissions, digestate management, and operational variability. For Jordan and other water-limited regions, integrating climate, water, energy, and nutrient indicators provides a practical basis for evaluating waste-to-energy systems where resource efficiency and environmental protection are closely interconnected.

The conclusions should nevertheless be interpreted within the defined assessment boundary. Future research should extend the analysis through comprehensive life-cycle assessment incorporating transportation, infrastructure requirements, digestate application pathways, and avoided fertilizer production. Longer-term operational datasets, improved uncertainty characterization, and comparative assessment of alternative waste-to-energy configurations under different climatic and operational conditions are also required to strengthen the generalizability of the proposed framework.

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REFERENCES

1. Ahmad, O. A. (2025a). Predicting future contamination spread using 3D modeling: A case study of lead, cadmium, and arsenic contamination. *Journal of Ecological Engineering, 26*(5), 347–357. https://doi.org/10.12911/22998993/201750
2. Ahmad, O. A. (2025b). The effect of anthropogenic activities on soil quality (Shafa Badran watercourse) in the Al Zarqa River Basin. *Journal of Ecological Engineering, 26*(3), 108–118. https://doi.org/10.12911/22998993/199570
3. Alwidyan, M. I., Jaradat, A. I., Ahmad, O. A., & Al Assaf, A. (2026). Optimizing water and energy efficiency in Jordan: Challenges, opportunities, and sustainable solutions for the future. *Jordan Journal of Mechanical and Industrial Engineering, 20*(1), 97–113. https://doi.org/10.59038/jjmie/200109
4. Battini, F., Agostini, A., Tabaglio, V., & Amaducci, S. (2016). Environmental impacts of different dairy farming systems in the Po Valley. *Journal of Cleaner Production, 112*, 91–102. https://doi.org/10.1016/j.jclepro.2015.09.062
5. Bond, A., Morrison-Saunders, A., & Sinclair, A. J. (2025). Sustainability assessment: The state of the art in 2026. *Impact Assessment and Project Appraisal*. https://doi.org/10.1080/14615517.2025.2593204
6. European Environment Agency. (2025). *Assessing the climate mitigation potential of circular economy* (EEA Briefing 19/2025). https://doi.org/10.2800/2803942
7. Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., & Tempio, G. (2013). *Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations.
8. Glasson, J., & Therivel, R. (2019). *Introduction to Environmental Impact Assessment* (5th ed.). Routledge.
9. Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology, 45*(1), 90–96. https://doi.org/10.1021/es101316v
10. Hijazi, O., Munro, S., Zerhusen, B., & Effenberger, M. (2016). Review of life cycle assessment for biogas production in Europe. *Renewable and Sustainable Energy Reviews, 54*, 1291–1300. https://doi.org/10.1016/j.rser.2015.10.013
11. Holliger, C., Alves, M., Andrade, D., Angelidaki, I., Astals, S., Baier, U., Bougrier, C., Buffière, P., Carballa, M., De Wilde, V., Ebertseder, F., Fernández, B., Ficara, E., Fotidis, I., Frigon, J. C., De Laclos, H. F., Ghasimi, D. S. M., Hack, G., Hartel, M., … Wierinck, I. (2016). Towards a standardized anaerobic digestion process monitoring protocol based on a large survey among full-scale plants. *Water Science and Technology, 74*(11), 2515–2522. https://doi.org/10.2166/wst.2016.336
12. Huijbregts, M. A., Gilijamse, W., Ragas, A. M., & Reijnders, L. (2003). Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling. *Environmental science & technology*, *37*(11), 2600–2608. https://doi.org/10.1021/es020971

13. Intergovernmental Panel on Climate Change. (2019). *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories*.
14. International Association for Impact Assessment & Institute for Environmental Assessment. (1999). *Principles of environmental impact assessment best practice*.
15. International Organization for Standardization. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*.
16. International Organization for Standardization. (2006). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*.
17. International Organization for Standardization. (2018). *ISO 45001: Occupational health and safety management systems—Requirements with guidance for use*.
18. Kumar, A., Grimstad, S. M. F., & Fet, A. M. (2025). Better together: A review of approaches for the integration of life cycle and circularity assessment. *Circular Economy and Sustainability*, *5*, 5699–5725. https://doi.org/10.1007/s43615-025-00699-w
19. Lloyd, S. M., & Ries, R. (2007). Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: A survey of quantitative approaches. *Journal of Industrial Ecology, 11*(1), 161–179. https://doi.org/10.1162/jiec.2007.1136
20. Marcinkowski, A., & Haręża, P. (2025). Integration of life cycle sustainability assessment indicators in different energy sectors. *Economics and Environment, 91*(4), 799. https://doi.org/10.34659/eis.2024.91.4.799
21. Ministry of Water and Irrigation. (2023). *National Water Strategy 2023–2040*. Hashemite Kingdom of Jordan.
22. Mulligan, C. N. (2026). Sustainability impact assessment tools and frameworks. *Frontiers in Environmental Engineering*, *4*, 1677492. https://doi.org/10.3389/fenve.2025.1677492
23. Özdemir, A. (2025). Determination the environmental performance of biogas production from cattle manure via life cycle assessment. *Black Sea Journal of Engineering and Science*. https://doi.org/10.31466/kfbd.1604880
24. Poeschl, M., Ward, S., & Owende, P. (2012). Environmental impacts of biogas deployment—Part I: Life cycle inventory for evaluation of production process emissions to air. *Journal of Cleaner Production, 24*, 168–183. https://doi.org/10.1016/j.jclepro.2011.10.039
25. Pope, J., Bond, A., Morrison-Saunders, A., & Retief, F. (2013). Advancing the theory and practice of impact assessment: Setting the research agenda. *Environmental Impact Assessment Review, 41*, 1–9.
26. Purushothaman, R., Alamelu, R., Selvabaskar, S., & Sudha, M. (2025). Theories, techniques and strategies of sustainable circular economy: A systematic literature review. *Discover Sustainability*, *6*, 297. https://doi.org/10.1007/s43621-025-01161-5
27. Raposo, F., De la Rubia, M. A., Fernández-Cegrí, V., & Borja, R. (2011). Anaerobic digestion of solid organic substrates in batch mode: An overview relating to methane yields and experimental procedures. *Renewable and Sustainable Energy Reviews, 16*(1), 861–877. https://doi.org/10.1016/j.rser.2011.09.008
28. Sánchez, L. E., & Mitchell, R. E. (2017). Conceptualizing impact assessment as a learning process. *Environmental Impact Assessment Review, 62*, 195–204. https://doi.org/10.1016/j.eiar.2016.06.001
29. Schrijvers, D., Schaubroeck, T., Vidinha, M., Saidani, M., Charpentier Poncelet, A., Amaral, M., Entrena Barbero, E., Gallego Fernández, M., Rydberg, T., & Adibi, N. (2026). Interim tandems of life cycle assessment methods and circularity indicators—Elaboration for the circular bio-economy. *Frontiers in Sustainability, 7*, 1766353. https://doi.org/10.3389/frsus.2026.1766353
30. Toniolo, S., Pierli, G., Bravi, L., Liberatore, L., & Murmura, F. (2025). Digital technologies and circularity: Trade-offs in the development of life cycle assessment. *The International Journal of Life Cycle Assessment, 30*, 2537–2557. https://doi.org/10.1007/s11367-025-02436-9
31. Wainer, A., Love, D. C., Kim, B. F., Harding, J., Lyu, Q., Williams, D. L., Heaney, C. D., Hobbs, B. F., & Nachman, K. E. (2025). Deconstructing the livestock manure digester and biogas controversy. *Current Environmental Health Reports, 12*, 43. https://doi.org/10.1007/s40572-025-00512-8
32. Walker, H., Bond, A., Sinclair, A. J., Diduck, A. P., Pope, J., Retief, F., & Morrison-Saunders, A. (2025). Understanding the role qualitative methods can play in next generation impact assessment. *Environmental Impact Assessment Review, 112*, 107780. https://doi.org/10.1016/j.eiar.2024.107780
33. Wang, X., Wang, J., Duan, C., Wang, X., & Liang, D. (2025). Systematic review on the life cycle assessment of manure-based anaerobic digestion system. *Sustainability*, *17*(19), 8926. https://doi.org/10.3390/su17198926