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Integrating life cycle assessment into biogas policy and practice: a systematic review and pathways for sustainable anaerobic digestion in Uganda

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ABSTRACT

Anaerobic digestion turns organic waste into biogas energy and Life Cycle Assessment (LCA) offers a standardised way to evaluate its environmental impacts across the full system. Global AD – LCA studies (2014–2025) written in English excluding non-LCA, non-AD, non-English, irrelevant policy were systematically reviewed until 29 July 2025 to inform policy for Uganda. Searches of Scopus, Web of Science, Google Scholar, and PubMed, plus targeted grey-literature screening, identified 124 studies though screening, full text assessment and citation mining out which 49 AD-LCA studies were analysed in depth. Most evidence came from Europe (61%), Asia (24%), and none originated from Uganda or sub-Saharan Africa. Methodologically, 88% used cradle-to-grave boundaries and 84% used attributional LCA, with climate-change impacts most frequently reported; few studies addressed Uganda's abundant feedstocks or alignment with national development goals. Risk of bias was low in 45 studies, moderate in 2, and high in 2. A five-phase roadmap was proposed to address the context gaps including capacity development, adoption of open-access LCA tools, generation of local data, integration into regulatory and planning frameworks, and circular-economy applications. Limitations include English/time restrictions, heterogeneity precluding meta-analysis, and lack of prospective registration. This review was not registered and was funded by TWAS and DFG.

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Life cycle assessment (LCA); anaerobic digestion; biogas; Uganda; sustainable energy policy; circular bioeconomy

1. Introduction

Agricultural waste, generated from crop production, livestock farming, and agro-processing, poses a mounting sustainability challenge, particularly in the face of global environmental change. Globally, agriculture produces around 1300 million tonnes of waste annually, a figure expected to increase due to rising food demand (Amran et al. 2021). These waste streams include a variety of residues, such as banana peels, bagasse, manure, rice husks, and fish industry by-products (Nsubuga, Banadda, and Kiggundu 2019). If unmanaged, they contribute to serious environmental and public health problems like methane emissions, water pollution, and disease transmission (Awogbemi and Kallon 2022).

In Uganda, agricultural waste is predominantly disposed of through open dumping and landfilling (Ghosh et al. 2016), practices that exacerbate methane emissions, contaminate water sources, and strain local governance systems (Manisalidis et al. 2020). These unsustainable approaches not only threaten environmental health but also compromise the resilience of rural food and energy systems. With the added pressures of climate change and urban population growth, Uganda urgently needs sustainable, context-specific waste management solutions that can be scaled across diverse agro-ecological zones.

Anaerobic digestion (AD) has emerged as a promising waste-to-energy technology aligned with circular bioeconomy principles. It decomposes organic waste in oxygen-free environments to produce biogas and nutrient-rich digestate (Mishra et al. 2021). Studies have shown that feedstocks such as banana peels are viable inputs for AD systems (Khan et al. 2016). In low-income countries like Uganda, shifting from landfill to AD could

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significantly reduce methane emissions, given that unmanaged landfills account for up to 90% of such emissions (Mishra et al. 2021).

The performance of AD systems depends on several variables including feedstock properties, pretreatment methods, and reactor design (Kumar et al. 2021). Innovations such as steam explosion pretreatment improve biogas yields from lignocellulosic biomass (Hülsemann et al. 2023). Typically, biogas from AD contains 40–55% methane, offering substantial potential for replacing fossil fuels and reducing greenhouse gas emissions by up to 80% (Sahota et al. 2018). The digestate by-product also holds agronomic value, offering a sustainable alternative to synthetic fertilisers while improving soil health and reducing weed seed viability (Masebinu et al. 2019; Zhou et al. 2020).

Further, AD is increasingly being explored for broader waste-valorisation opportunities, including phosphorus recovery and the treatment of unconventional biomass such as *Jatropha* residues and grassland cuttings, feedstocks that not only enhance biogas potential but also contribute to biodiversity conservation (Brandhorst et al. 2024; Khan et al. 2021). These developments highlight AD's potential as more than a biogas generator, positioning it as a multifaceted solution for waste remediation, nutrient cycling, and circular resource management (Kumar Khanal et al. 2021). To fully realise the climate, environmental, and health benefits of AD, a robust assessment of its life cycle performance is essential. Life Cycle Assessment (LCA) is a science-based methodology that quantifies environmental impacts from resource extraction through to end-of-life, capturing emissions, energy use, and resource flows across the full process chain (Aziz, Hanafiah, and Gheewala 2019). LCA enables policymakers and researchers to evaluate and compare waste treatment options, identify environmental hotspots, and guide system improvements based on empirical evidence (Smebye et al. 2017).

To enhance conceptual clarity, this study explicitly introduces Life Cycle Impact Assessment (LCIA), the phase of LCA in which inventory flows such as emissions, resource use, and energy inputs are translated into potential environmental impacts using scientifically established characterisation models. LCIA enables the quantification of key impact categories, including global warming potential, eutrophication, acidification, and resource depletion, thereby strengthening the methodological foundation for evaluating the environmental performance of anaerobic digestion systems. Ensuring the environmental sustainability of AD, especially in developing-country contexts, requires robust performance evaluation through Life Cycle Assessment (LCA), which provides a comprehensive method for quantifying environmental impacts across a system's entire life cycle (Aziz, Hanafiah, and Gheewala 2019), enabling comparison of waste-treatment options and identification of improvement areas (Smebye et al. 2017). However, LCA remains largely underutilised in Uganda's biogas sector, with no existing studies assessing AD systems within the national context. This study addresses that gap by reviewing global LCA literature on AD, identifying methodological challenges, and proposing policy-relevant strategies tailored to Uganda's feedstock resources and energy-planning frameworks.

2. Study methodology

A focused research question We formulated to define the study's scope, core concepts, and geographical emphasis: *How has Life Cycle Assessment (LCA) been applied to anaerobic digestion (AD) for biogas production globally, and what lessons are actionable for Uganda's policy and practice?* The review targeted methodological advancements and real-world implementations of LCA in AD as a sustainable agricultural waste management strategy.

A systematic search was conducted in Scopus, Web of Science, Google Scholar, and PubMed. The final database search was conducted on 29 July 2025. Search terms combined concepts of anaerobic digestion/biogas with LCA and sustainability, using Boolean operators to maximise retrieval (MacFarlane, Russell-Rose, and Shokraneh 2022). The complete Scopus search string is provided in [Appendix A](#), with analogous strategies adapted to the other databases. To capture relevant grey literature, we also screened institutional repositories and government portals (forexampleenergy and environment agencies) for policy reports pertinent to renewable energy and AD-LCA.

Eligible records included peer-reviewed, English-language studies published between 2014 and 2025 that applied life cycle assessment (LCA) to anaerobic digestion (AD) – based biogas systems and reported clearly defined system boundaries and impact categories, as well as relevant government or agency reports on renewable energy/AD-LCA. Records were excluded if they were duplicates; did not focus on AD-based

biogas or did not employ LCA (Appendix B); were non-English; or were government policy documents unrelated to renewable energy.

Data were extracted by two independent reviewers; disagreements were resolved by a third reviewer. Captured variables included country/context, study aim, functional unit, system boundary, feedstock type(s), software/databases, LCIA method and LCA type (attributional vs. consequential), impact categories, allocation/co-product handling, and the GWP time horizon. All results compatible with each predefined outcome domain were sought; when studies reported multiple measures, time points, or parallel analyses, prespecified decision rules were applied to maximise comparability: (i) LCIA method, ReCiPe midpoint preferred; if unavailable, CML; otherwise ILCD/IMPACT2002+, with no cross-method conversions attempted; (ii) impact categories, all reported were extracted, with priority to GWP100 (CO₂-eq), followed by acidification, eutrophication, and photochemical ozone formation; (iii) functional unit, all recorded as stated, with preference for energy-based units (per kWh/MJ), then mass-based (per tonne), then volume-based (per Nm³) for cross-study summaries; (iv) system boundary, where multiple scenarios were presented, cradle-to-grave was preferred; and (v) time horizon, 100-year GWP preferred; if only 20-year was available, it was extracted and flagged. Records were organised in structured tables and managed in Mendeley for traceability (Williams and Woods 2024). When key data were missing or unclear, corresponding authors were contacted; unresolved items were not reported.

Data were sought for variables beyond primary outcomes, including study identifiers (first author, year, country/region) and technology configuration (digester class, scale, co-digestion, pre/post-treatments, biogas end-use, digestate management). No meta-analysis was done, narrative synthesis was used to avoid overstating comparability across disparate functional units, boundaries, and LCIA methods and AD processes were assumed to be at steady state.

Since no formal risk-of-bias tool exists for LCA studies, principles from the Joanna Briggs Institute (JBI) critical appraisal approach were adopted (Porritt, Gomersall, and Lockwood 2014) and evaluated each study across the reporting/design domains captured in our extraction: country/context, functional unit, system boundary, feedstock, software/databases, LCIA method and LCA type, and impact categories. Based on performance across these domains, studies were classified as low (all/most domains clearly reported and justified), moderate (one-two domains partially reported), or high (multiple domains unclear/not reported) risk of methodological bias. Results are presented in Table A3 (Appendix).

Given heterogeneity in objectives, boundaries, and metrics, we conducted a narrative/thematic synthesis rather than a meta-analysis, aggregating patterns by geography, functional units, system boundaries, LCIA methods, software, and impact categories. A formal statistical assessment of reporting bias was not conducted due to methodological heterogeneity. We qualitatively considered publication bias by noting under-represented regions. Certainty of evidence was not graded using GRADE or similar frameworks because the review objective was descriptive/methodological rather than effect-size estimation.

2.1. The selection process

The selection process of the studies is summarised in the PRISMA 2020 flow diagram (Figure 1). Searches of Scopus, Web of Science, Google Scholar, and PubMed (final search 29 July 2025) identified 155 records. After removing 25 records before screening (forexample duplicates/irrelevance/language), 135 records were screened by title/abstract and all proceeded to full-text assessment (n = 130). At full-text, 15 studies were excluded for not meeting the biogas-focused LCA criteria (Table A2). Citation (reference) mining contributed 9 additional records. In total, 124 studies were included in the qualitative synthesis (115 from databases +9 from citation searching), of which 49 AD-LCA studies were analysed in detail for country/context, study aims, system boundaries, functional units, feedstocks, software/databases, LCIA method and LCA type, and impact. The selection process is summarised in the PRISMA 2020 flow diagram (Figure 1).

3. Risk of bias assessment

Risk of bias assessment indicated that, of the 49 studies assessed, 92% of the studies were judged low risk of methodological bias, while 4 % were moderate and another 4 % were high risk (Figure 2, Appendix C, Table A3). This profile indicates generally strong reporting and transparency across the evidence base. The small subset rated moderate/high typically showed gaps such as incomplete description of functional units or

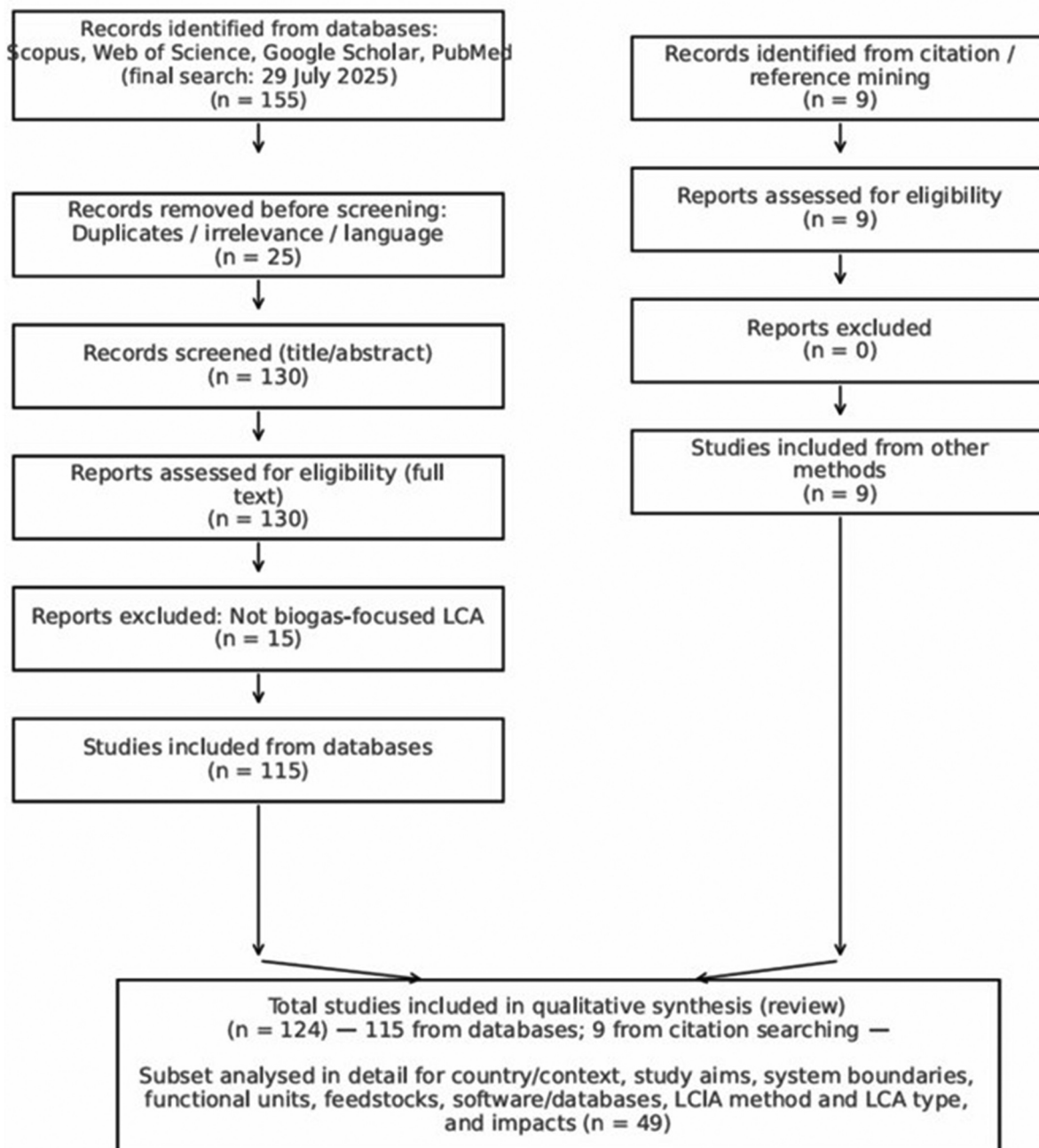


Figure 1. A flowchart for the selection process.

system boundaries, limited detail on LCIA methods/data sources, or unclear treatment of co-products and sensitivity/uncertainty analyses. Overall, the synthesis is unlikely to be driven by high-bias studies, though the noted shortcomings in a few papers should be considered when interpreting comparative findings.

3.1. Life cycle assessment of anaerobic digestion systems

Anaerobic digestion (AD) (Figure 3) is increasingly recognised worldwide as a sustainable and multifunctional technology for managing organic waste and producing renewable energy (Wang et al. 2023). Through microbial activity in oxygen-free environments, AD transforms agricultural residues, animal manure, food waste, and municipal solid waste into biogas and digestate (Zamri et al. 2021). This process not only reduces the volume and environmental burden of organic waste but also generates biogas for electricity, heat, or biomethane production,

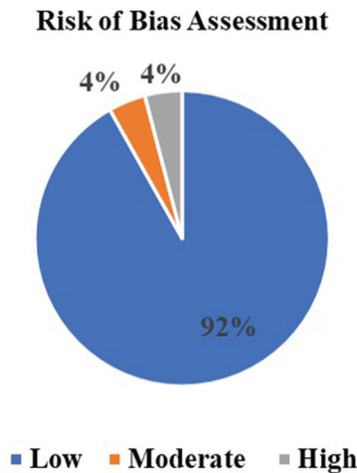


Figure 2. Risk of bias assessment for the LCA studies considered.

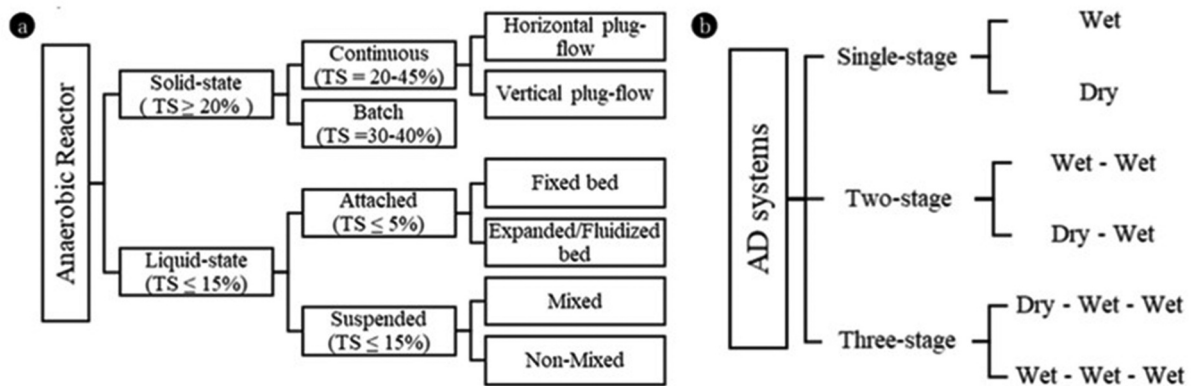


Figure 3. A) classification of digesters; b) classification of AD systems (Van et al. 2020).

and digestate for use as a biofertilizer, enhancing nutrient recycling and reducing reliance on synthetic fertilisers. These combined benefits support climate change mitigation, energy security, and circular bioeconomy goals. AD systems are classified as wet or dry based on total solids content, which influences reactor design, process efficiency, and economic viability (Van et al. 2020). However, their environmental sustainability is not guaranteed by default. Performance depends on feedstock characteristics, operational efficiency, energy utilisation, and the management of co-products like digestate (Parolin, McAlloone, and Pigosso 2024). As a result, comprehensive environmental evaluations are needed to ensure AD systems align with Sustainable Development Goals (SDGs), particularly SDG 7, 11, 12, and 13 (Piadeh et al. 2024).

To conduct such evaluations, Life Cycle Assessment (LCA) (Figure 4) serves as a robust and internationally standardised tool governed by ISO 14040 and 14,044. LCA assesses the environmental sustainability of products and systems across their entire life cycle, from raw material extraction to disposal (Rimano et al. 2019). It consists of four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Pacana et al. 2023).

This structured methodology enables transparent and reproducible assessments, supporting informed decision-making. Unlike traditional tools that assess only isolated stages or emissions, LCA takes a cradle-to-grave approach, capturing environmental flows across upstream and downstream stages such as energy and material inputs, production, use, and waste management. This approach minimises the risk of burden shifting and facilitates a holistic understanding of AD systems' environmental performance, making it an essential framework for evaluating and optimising their sustainability (Figure 4).

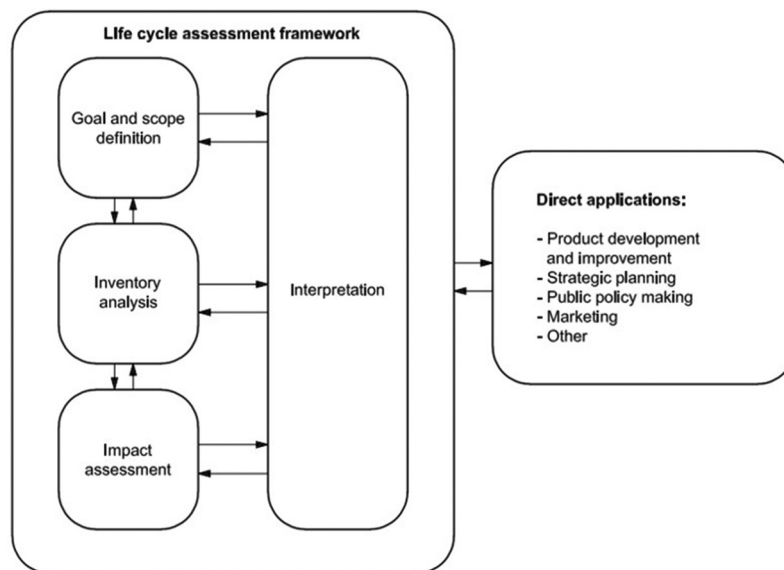


Figure 4. Phases in a life cycle assessment (Pacana et al. 2023).

3.2. Importance of life cycle assessment in anaerobic digestion systems

Life Cycle Assessment (LCA) offers a comprehensive approach to evaluating the environmental performance of anaerobic digestion (AD) systems by accounting for resource inputs and emissions throughout the system's life cycle (Piadeh et al. 2024). Typical inputs include electricity and thermal energy for feedstock preparation, pumping, mixing, and biogas upgrading; water for dilution and cleaning; and chemical additives such as pH buffers or trace nutrients to enhance microbial activity (Jameel et al. 2024). These inputs can vary significantly depending on the AD system's scale, feedstock characteristics, and intended end-uses of the biogas and digestate. Equally critical are emissions that occur at various stages, such as fugitive methane leaks during biogas collection and use, which, if uncontrolled, can undermine the climate benefits of AD due to methane's high global warming potential (Mundra and Lockley 2024). Other emissions include CO₂ from combustion or upgrading, ammonia volatilisation from digestate storage, and nitrous oxide emissions from land application, all contributing to acidification, eutrophication, and air pollution (Huf et al. 2023). LCA enables a systematic quantification of these flows, providing a transparent basis for comparing AD with conventional waste and energy pathways.

In addition to tracking environmental burdens, LCA captures the positive impacts of AD systems, such as fossil fuel displacement through biogas energy, reduced reliance on synthetic fertilisers via nutrient-rich digestate, and diversion of organic waste from landfills, which mitigates uncontrolled methane emissions and potential groundwater contamination (Huf et al. 2023). These avoided impacts are modelled using system expansion or substitution methods, showcasing AD's potential contribution to a circular, low-carbon economy. One of LCA's major advantages is its ability to identify environmental hotspots, specific stages or operations with disproportionately high impacts, such as feedstock transport, energy use in biogas compression, or poorly managed digestate application (Acosta-Alba, Chia, and Andrieu 2019). Identifying these hotspots allows for targeted interventions, including renewable energy integration, gas-tight digestate storage, and optimised land application techniques. Thus, LCA transcends impact quantification by offering insights that inform better system design, operational strategies, and supportive policies. It equips policy-makers, researchers, developers, and farmers with the information needed to make informed decisions that enhance the sustainability and socio-economic value of anaerobic digestion systems.

3.3. Global Trends in life cycle assessment of anaerobic digestion

3.3.1. Geographical distribution

The geographical analysis of 49 reviewed LCA studies on anaerobic digestion (AD) reveals a stark regional imbalance, with Europe leading (25 studies), followed by Asia (18), and minimal representation from

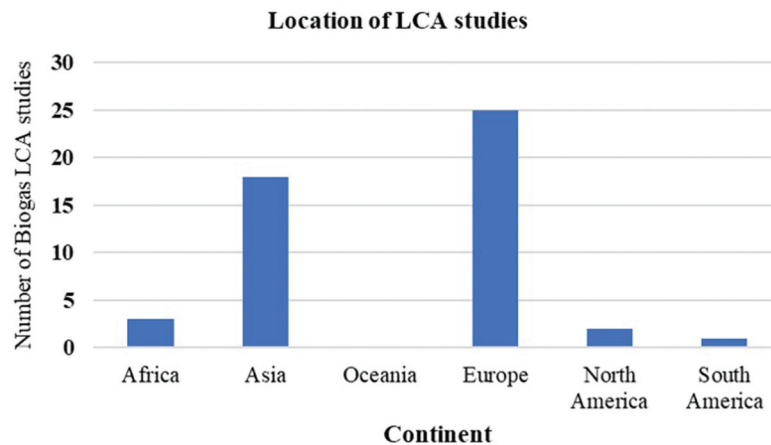


Figure 5. Continental distribution of the biogas LCA studies analysed.

Africa, the Americas, and Oceania (Figure 5, Table A1). European dominance is attributed to robust environmental policies and investment in circular economy initiatives, particularly in countries like Germany, Sweden, and the Netherlands (Aziz, Hanafiah, and Gheewala 2019; Igliński et al. 2024). Asia's rising contributions from China, India, and Southeast Asian nations reflect growing investment in renewable energy and organic waste management. The high volume of organic waste in these densely populated regions further justifies academic and policy attention to LCA in biogas development. Africa is significantly underrepresented, with only three studies identified, two from Egypt and one from Zimbabwe, and none from Uganda. This gap has persisted despite the continent's vast potential for biogas adoption in rural and off-grid communities. The limited number of African studies can be attributed to constraints such as lack of LCA expertise, underinvestment in environmental research, and a focus on technology adoption over environmental performance evaluation (Muthivhi et al. 2024).

North and South America are similarly underrepresented, with only two and one studies respectively. This may be explained by a stronger focus on other renewable energy sources like solar, wind, and bioethanol, which have historically received more policy and research support (Igliński et al. 2024). The abundance of fossil fuel resources in North America, especially the United States, has also diminished the urgency for biogas development (Nevzorova and Kutcherov 2019), and fewer large-scale biogas projects exist to justify LCA investment. Oceania, particularly Australia and New Zealand, had no identified studies. This likely results from a regional emphasis on solar, wind, and hydropower, with biogas technologies receiving limited policy and academic attention (Li et al. 2020).

The absence of Uganda in the global LCA literature reviewed highlights an urgent need for context-specific studies that incorporate local waste streams, technologies, and environmental conditions. This would help bridge the knowledge gap and support evidence-based decision-making for sustainable biogas implementation in Uganda.

3.3.2. Functional units

The reviewed studies reveal considerable diversity in the selection of functional units (FUs), including mass-based, energy-based, volume-based, and service-based metrics (Figure 6, Table A1). This variation reflects differences in study objectives, system boundaries, and biogas technologies, and has a significant impact on the comparability and interpretation of LCA results, an observation consistent with (Aziz, Hanafiah, and Gheewala 2019).

Mass-based FUs (e.g. per MWh of energy, per MJ of biogas) were the most frequently used (19 studies), followed closely by Energy-based FUs (18 studies), such as per tonne of feedstock or manure (Wang et al. 2016). Volume-based FUs (8 studies) and service-based FUs (1 studies) were less common. Three studies did not specify their FUs at all, undermining transparency and limiting comparability (Figure 6).

Mass-based FUs are especially relevant for waste treatment evaluations where impacts are tied to the quantity of feedstock processed. However, variability in feedstock properties (e.g. moisture content, biodegradability) can distort comparisons across studies unless normalisation (e.g. dry matter or volatile solids) is applied (Karthikeyan,

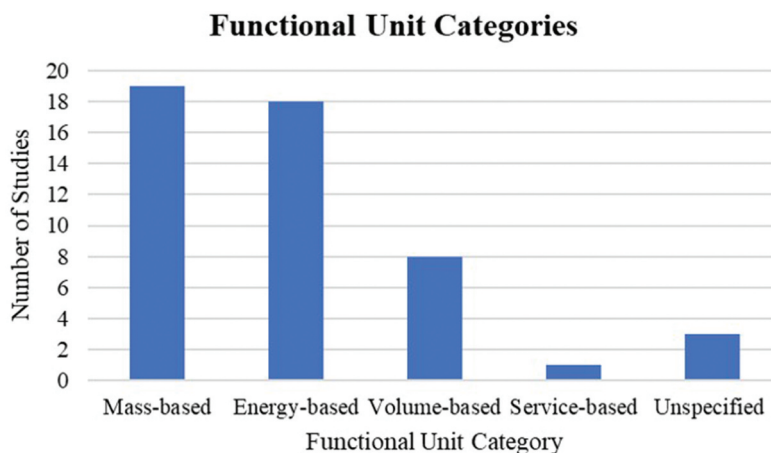


Figure 6. Categorisation of functional units used in the reviewed biogas LCA literature.

Bandulasena, and Radu 2024). Similarly, energy-based FUs are critical in assessing biogas systems as renewable energy solutions, allowing for energy return on investment (EROI) and emissions per energy unit (Fusi et al. 2016). Volume-based units, such as per Nm³ of biogas (Florio et al. 2019), are useful for assessing gas quality and grid injection potential, while service-based units (e.g. per kilometre of bus transport) offer insight into end-use applications, such as urban mobility or cooking energy (Lyng and Brekke 2019).

While the global diversity in FU choice highlights the adaptability of LCA, it also reveals a challenge for developing countries like Uganda, where context-specific guidance on FU selection is lacking. For Uganda, mass-based FUs may be appropriate for studies focused on agricultural waste treatment, while energy-based FUs would suit analyses targeting energy access and rural electrification goals. However, integrating service-based FUs, e.g. cost per litre of milk cooled or meals cooked using biogas, could greatly enhance the policy relevance and community-level impact assessment of biogas systems.

To ensure meaningful comparison and relevance, future Ugandan LCA studies should prioritise clearly defined and context-appropriate functional units, ideally standardised across projects. This would enhance the utility of LCA in evidence-based policy development, improve data comparability, and support the design of efficient, scalable, and locally adapted anaerobic digestion systems.

3.3.3. System boundary

The system boundary defines the processes, inputs, and outputs included in an LCA study and plays a crucial role in shaping the results and their interpretation (Li et al. 2014). Among the 49 reviewed studies, the vast majority (43 studies, or 88%) adopted a cradle-to-grave system boundary, while only 6 studies (12%) used a cradle-to-gate approach (Figure 7, Table A1). This marks a shift from earlier trends noted by Aziz, Hanafiah, and Gheewala (2019), who found that most biogas LCA studies between 2006 and 2018 used cradle-to-gate boundaries. The increased adoption of cradle-to-grave boundaries in recent years reflects a broader commitment to evaluating the entire environmental footprint of biogas systems, from feedstock collection through to final product use or disposal.

Cradle-to-grave assessments allow for the inclusion of downstream processes such as biogas combustion, digestate application, and emissions avoided through fossil fuel substitution (Montegiove et al. 2024). This broader system scope enhances the credibility of LCA results and enables policymakers to assess the full climate and environmental benefits of anaerobic digestion.

However, cradle-to-gate studies, while narrower in scope, are often used when data limitations exist or when studies aim to optimise specific internal processes such as feedstock pretreatment or digester design. These boundaries can be appropriate for early-stage research or process benchmarking, but they risk omitting key benefits, such as avoided fertiliser use or emissions reductions, if used in isolation (Wang et al. 2025).

For Uganda, where data collection and analytical capacity for full cradle-to-grave assessments may be limited, there is a need to strike a balance between feasibility and completeness. In the short term, cradle-to-gate assessments can be used to initiate LCA research, especially for system design, feedstock prioritisation,

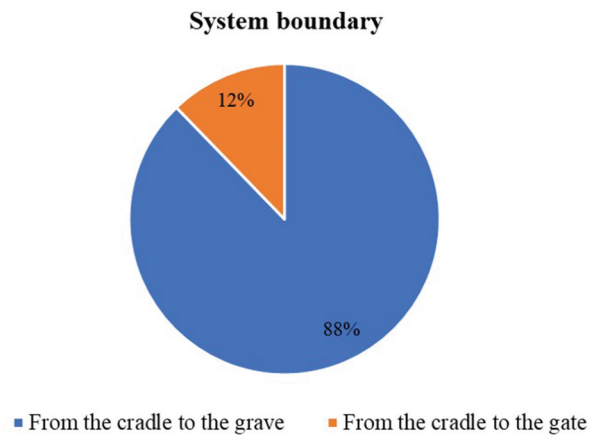


Figure 7. System boundaries distribution.

or economic feasibility studies. However, to fully inform evidence-based policy and investment decisions, cradle-to-grave boundaries should be adopted where possible, especially in studies aimed at evaluating the sustainability performance of AD systems for rural energy and waste management.

3.3.4. Type of LCA

The analysis shows that out of the 49 life cycle assessment (LCA) studies reviewed on anaerobic digestion technologies for biogas production, 41 studies (84%) employed an attributional approach, while only 8 studies (16%) used a consequential perspective (Figure 8, Table A1). This trend aligns with findings by (Gaffey, Collins, and Styles 2024), who similarly observed that attributional LCA is more widely adopted in environmental research. The preference for attributional LCA stems from its simpler implementation, reliance on average datasets, and the availability of well-established frameworks and tools (Schaubroeck et al. 2021). These factors make it particularly suitable for evaluating existing systems and conducting comparative studies, especially in academic contexts where access to marginal or market-based data is limited.

From a Ugandan perspective, this imbalance presents both a challenge and an opportunity. While attributional LCA provides important insights into the current environmental performance of biogas systems, consequential LCA is better suited to inform context-specific decisions and future-oriented strategies. For instance, it can support the design of hybrid biogas-solar systems for milk cooling in off-grid areas, or evaluate the implications of scaling up digesters in rural communities. The absence of consequential LCA studies in Uganda highlights a critical gap in the country's capacity to conduct forward-looking sustainability assessments, underscoring the need to strengthen local expertise, improve data availability on indigenous feedstocks and energy systems, and foster collaborative research efforts that support scenario-based decision-making.

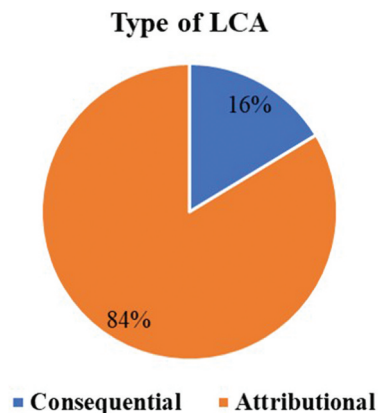


Figure 8. Type of LCA considered by different studies reviewed.

The dominance of attributional LCA in biogas research constrains the ability to fully capture the sustainability potential of anaerobic digestion in Uganda. Increasing the use of consequential LCA would significantly enhance decision-making and evidence-based planning, particularly in advancing the country's clean energy goals, promoting waste valorisation, and supporting rural development

3.3.5. Software used

Among the 49 biogas LCA studies reviewed, SimaPro emerged as the most commonly used software, featured in 29 studies (Figure 9, Table A1). Its dominance can be attributed to its established reputation in academic research, integration with widely used databases such as ecoinvent and Agri-Footprint, and its user-friendly interface for managing life cycle inventories (Thomsen et al. 2017). This widespread adoption promotes standardisation in methodological approaches and enables cross-study comparability, especially when similar databases and LCIA methods are used (Abawalo, Pikoń, and Landrat 2025).

Gabi, used in 8 studies, is typically preferred by researchers working closely with industry due to its compatibility with product carbon footprint (PCF) protocols and strong support for energy system modelling (Yuguda et al. 2020). However, both SimaPro and Gabi are proprietary tools with high licencing fees, which may pose significant barriers to adoption in low- and middle-income countries.

Only 3 studies reported using OpenLCA, an open-source platform that is growing in capability but still limited by database access, documentation, and technical support (Silva et al. 2017). Despite these challenges, OpenLCA offers an important opportunity for expanding LCA capacity in resource-constrained settings. Its gradual uptake suggests a growing interest in more accessible, community-driven LCA solutions.

Notably, 9 studies did not disclose the software used. This lack of transparency hinders reproducibility and undermines efforts to validate or build upon previous research, especially in policy or industry applications where consistent methods are crucial.

For Uganda, where institutional access to commercial LCA software is limited, the reliance on proprietary platforms presents a challenge. Building national LCA capacity will require investment in training, database development, and support for open-source tools like OpenLCA, which can provide a cost-effective entry point for universities, research institutes, and government agencies. Furthermore, promoting transparency in software reporting and developing Uganda-specific inventory datasets will enhance the reliability and applicability of LCA studies for local biogas systems.

3.3.6. Impact categories

The distribution of impact categories used in the 49 reviewed LCA studies on biogas systems reveals a strong preference for midpoint impact indicators (84%), with only 14% combining midpoint and endpoint categories, and just 2% using endpoint categories alone (Figure 10, Table A1). This finding is consistent with earlier research by Aziz, Hanafiah, and Gheewala (2019). Midpoint categories, such as global warming

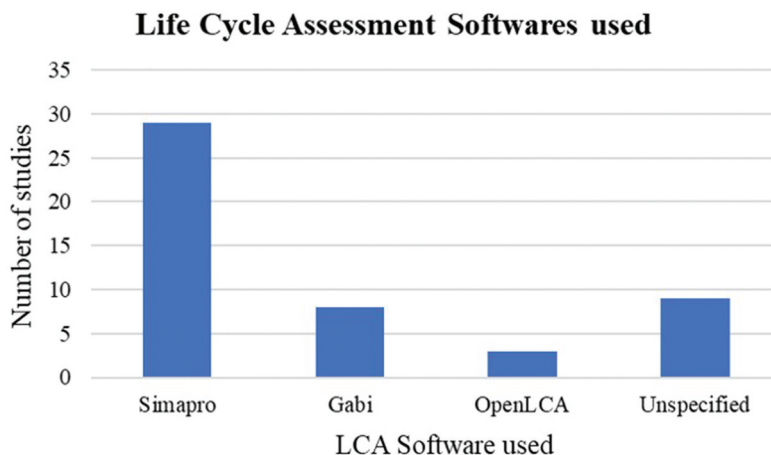


Figure 9. Life cycle assessment software used in the reviewed biogas studies.

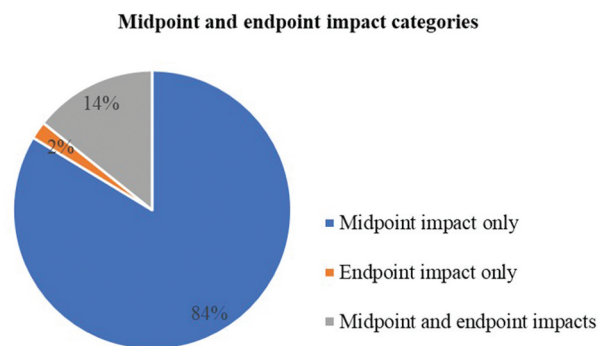


Figure 10. Distribution of mean and endpoint impact categories.

potential, acidification, eutrophication, and ozone depletion, assess impacts at an intermediate stage of the cause-effect chain and are widely adopted due to their scientific robustness, lower uncertainty, and strong data availability (Denac and Ošlovnik 2025).

While midpoint indicators dominate due to their technical clarity and reproducibility (Mikosch et al. 2022), endpoint indicators offer additional value by translating environmental impacts into damage to human health, ecosystems, and resource availability, a more decision-oriented perspective (Hardaker et al. 2022). However, their limited use in biogas LCAs reflects concerns about greater model complexity, uncertainty, and subjective value choices.

The small but growing share of studies (14%) using both midpoint and endpoint categories reflects an emerging effort to bridge technical detail and societal relevance. This dual approach supports more informed and balanced sustainability assessments, especially for policy and technology adoption contexts (Lago-Oliveira, Moreira, and González-García 2025).

For Uganda, this distinction is highly relevant. Given the country's limited access to localised life cycle inventory data, technical capacity, and software tools, midpoint categories are a more practical starting point for LCA development. Their lower data demands and established methodologies make them suitable for early-stage assessments of anaerobic digestion systems. However, the exclusive use of midpoint indicators may limit the policy relevance and communication power of LCA results, particularly when engaging non-technical stakeholders such as local governments, NGOs, or community leaders.

3.3.7. Life cycle impact assessment (LCIA) method

The data on the Life Cycle Impact Assessment (LCIA) methods used in the biogas studies analysed reveal important trends in terms of methodological preferences and transparency in environmental assessment. Among the 49 studies analysed, ReCiPe proved to be the most widely used LCIA method, used in 25 studies, followed by CML in 11 studies (Figure 11, Table A1). The remaining methods, Eco-indicator 99 (H), IMPACT2002+ and ILCD 2011, were only used in a small number of studies each, while 9 studies did not specify the LCIA method used.

The choice of Life Cycle Impact Assessment (LCIA) methods plays a crucial role in shaping the interpretation, comparability, and policy relevance of LCA studies. Among the 49 biogas LCA studies reviewed, ReCiPe was the most frequently used method (24 studies, 49%), followed by CML (13 studies, 27%) (Figure 11). Less commonly used methods included Eco-indicator 99 (H), IMPACT2002+, and ILCD 2011, each appearing in only 1–2 studies. Notably, 8 studies (16%) did not report their LCIA method, raising concerns about transparency and reproducibility. ReCiPe's popularity stems from its dual-layer structure, allowing both midpoint (problem-oriented) and endpoint (damage-oriented) assessments (Rybczewska-Błazejowska and Jezierski 2024). This makes it well-suited for both technical comparisons and high-level decision-making, particularly in contexts where results need to be communicated to a range of stakeholders. Its seamless integration with SimaPro and ongoing updates (De Wolf et al. 2023). CML, by contrast, is a midpoint-only method that offers methodological transparency and scientific rigour. It remains a favoured option for studies that aim to avoid subjective assumptions associated with endpoint modelling. While less used, Eco-indicator 99, IMPACT2002+, and ILCD 2011 offer valuable perspectives, especially for

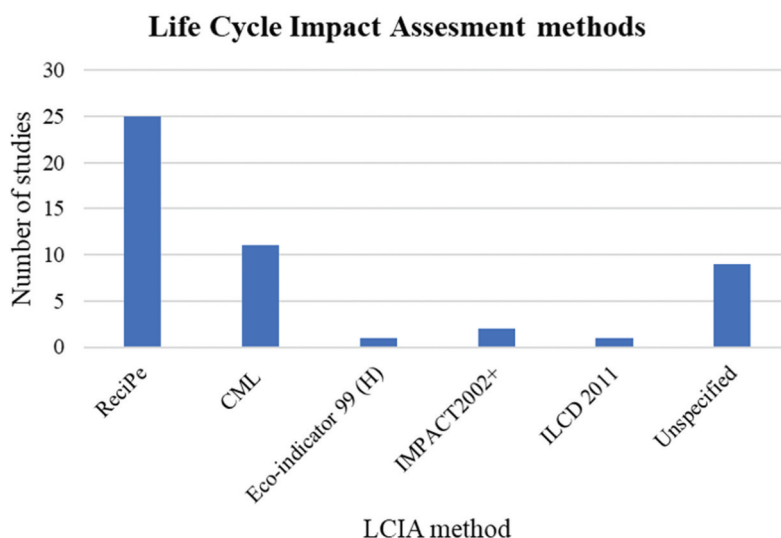


Figure 11. Impact assessment methods (LCIA) in reviewed biogas studies.

translating environmental impacts into human and ecosystem damage, but are often limited by software support, regional relevance, or user familiarity (Rybczewska-Błażejowska and Jezierski 2024).

For Uganda, the selection of LCIA methods should consider several factors: data availability, software access, and capacity for interpretation and communication. Given current limitations in localised life cycle inventory data and expertise, midpoint-focused methods like CML or the midpoint tier of ReCiPe may offer a practical starting point. These methods rely on well-established characterisation factors and are compatible with both commercial (SimaPro) and open-source (OpenLCA) platforms. However, as Uganda seeks to scale up biogas technology through evidence-based policy, endpoint indicators, available in ReCiPe and IMPACT2002+, could be increasingly valuable for translating technical results into actionable insights for health, ecosystem, and resource-related decision-making. Moreover, the lack of LCIA method reporting in 16% of reviewed studies highlights a need for clearer reporting standards and capacity building, particularly in regions like Uganda where LCA is still emerging. Future LCA efforts should prioritise methodological transparency and promote training in widely accepted and policy-relevant LCIA methods.

3.4. An overview of biogas production and utilisation through anaerobic digestion in Uganda

In Uganda and many other developing countries, biogas is still viewed as a low-value, pro-poor renewable energy source (Clemens et al. 2018). Its use is mostly limited to small-scale operations by livestock-keeping households and institutions like the National Agricultural Research Organization (NARO). Despite its potential, the biogas sector remains underdeveloped and lacks the commercial viability necessary to compete in Uganda's broader energy landscape. However, the Uganda Renewable Energy Policy recognises the value of bioenergy and seeks to promote a liquid bioenergy market by incentivising private sector investment in biomethane production. With support from development partners, the government has encouraged biogas adoption among zero-grazing households, resulting in the installation of about 9500 digesters (Namugenyi and Scholderer 2024). Notable public investments include a 116 m³ biogas plant at the National Livestock Resources Research Institute (NaLIRRI) and a now-defunct facility at the National Water and Sewerage Corporation (NWSC). The NaLIRRI plant with a capacity of 116 m³ remains Uganda's largest and includes purification technology aimed at upgrading raw biogas to biomethane for commercial bottling, though technical capacity and packaging limitations have stalled this goal.

At the household level, biogas is primarily used unprocessed for cooking and lighting, yet much of the gas produced goes unused and is released into the atmosphere, contributing to energy loss and environmental concerns (Bluemling, Mol, and Tu 2013). This inefficiency is troubling, given Uganda's high and growing energy demand, which cannot be met by electricity or solar energy alone. The country has abundant feedstocks, animal manure, crop residues, and energy crops, amounting to over 1400 tonnes daily and

481,081 tonnes annually (Namugenyi and Scholderer 2024). This resource base presents a strong foundation for biogas expansion, but it remains underutilised due to a lack of process optimisation and market structure. The key barrier to sustainable growth lies in the government's limited enforcement of policies to ensure systematic feedstock collection, processing, and distribution. Addressing these policy and infrastructure gaps is essential for transforming biogas from a marginal energy source into a scalable, sustainable contributor to Uganda's renewable energy mix.

Climate-related impacts of biogas systems also warrant careful assessment, particularly methane leakage during digestion, storage, and end-use. Most international LCA studies typically apply IPCC-based Global Warming Potential (GWP) indicators, with GWP100 being the most commonly reported metric (McAuliffe et al. 2023). However, the IPCC defines GWP over different time horizons, most notably the 20-year (GWP20) and 100-year (GWP100) periods. GWP20 captures the short-term climate forcing of methane due to its high radiative efficiency and relatively short atmospheric lifetime, while GWP100 reflects longer-term climate effects (Mar et al. 2022). Given that methane is significantly more potent over a 20-year horizon than over 100 years, the choice of time horizon can substantially influence reported climate impacts, especially in anaerobic digestion systems where CH₄ emissions dominate (Werku, Bulto, and Geleto 2025). Distinguishing between GWP20 and GWP100 is therefore essential for understanding both near-term and long-term climate implications. For Uganda, where unintentional, uncontrolled, and often unnoticed leaks of methane gas that escape into the atmosphere during the production, handling, or use of biogas may vary widely due to differences in digester design, maintenance regimes, and biogas utilisation efficiency, future LCA studies should ideally report both GWP20 and GWP100. This dual reporting would provide a more comprehensive and transparent assessment of the climate performance of biogas systems across the different IPCC time horizons.

In addition to energy losses, environmental concerns such as odour emissions are emerging considerations for future biogas development. In Europe, odour complaints from feedstock handling, digestion tanks, and digestate storage have led to the development of specific regulatory measures, including odour threshold limits, mandated biofilters, covered digestate tanks, and community nuisance guidelines (Wiśniewska, Kulig, and Lelicińska-Serafin 2021). These policies reflect growing recognition that odours significantly influence public acceptance and long-term sustainability of biogas projects. In contrast, Uganda currently lacks explicit odour-related standards within its renewable energy, waste-management, or environmental regulatory frameworks. While odour emissions are not yet a major driver of public concern in Uganda, they have important implications for ammonia volatilisation, air quality, and community acceptance, issues that will become increasingly relevant as biogas adoption expands. Incorporating odour-related midpoint indicators (such as ammonia and volatile organic compound emissions) into future Ugandan LCA studies would therefore align national assessments with international best practice and support more socially acceptable, environmentally responsible biogas development.

3.5. Status of anaerobic digestion and biogas technology research in Uganda

Biogas production in Uganda has gained considerable traction as a sustainable response to persistent national challenges such as energy insecurity, unmanaged organic waste, and environmental degradation. Several studies have demonstrated the technical and socio-economic viability of biogas systems, particularly among rural and peri-urban households (Kabyanga et al. 2018), aligning closely with national priorities in clean energy access, rural development, and environmental conservation. Much of the existing research has focused on assessing raw material availability and evaluating the feasibility of biogas technologies, with several authors confirming the potential of biogas to support household- and community-level energy needs.

Research efforts have extensively examined the technical and economic dimensions of biogas production, including feedstock characterisation and consumer willingness to invest (Gumisiriza et al. 2019; Kabyanga et al. 2018). These studies have explored a variety of organic substrates, including livestock manure, crop residues, and agro-processing by-products, while assessing digester performance and financial viability. In parallel, others have examined feedstock optimisation strategies (Mutesasira et al. 2019), digestate valorisation pathways (Ogwang et al. 2021), and opportunities for enhanced energy recovery (Okullo 2018). Innovations in gas purification (Walozi, Nabuuma, and Sebity 2016) and strategies to increase methane yield (Nansubuga et al. 2015) further demonstrate a maturing research landscape addressing technical bottlenecks within Uganda's biogas sector.

Beyond agricultural residues, emerging studies have begun to recognise the growing role of municipal and market organic waste as a potential feedstock for anaerobic digestion. Uganda generates a wide range of biodegradable waste streams, banana peels, cassava waste, fruit and vegetable offcuts, and mixed food waste from urban markets, yet a significant proportion is still managed through open dumping or landfilling (Ssepunya et al. 2023). Such practices contribute to uncontrolled methane emissions, water contamination, and increased pressure on municipal waste-management systems.

Recent characterisation studies conducted in markets such as Nakasero, Kalerwe, Owino, and regional trading centres reveal that Uganda's food waste typically contains high-moisture, highly biodegradable fractions with moisture contents of 65–85%, high volatile-solids levels, and moderate C:N ratios (approximately 15–30:1) (Nsubuga et al. 2021; Olupot and Nayebare 2024). These compositional attributes make municipal organic waste an excellent candidate for biogas production. Seasonal variations are evident, with banana waste dominating during peak harvest periods, while cassava and sweet-potato residues become more abundant during dry-season trade. Although a national database on food-waste composition is lacking, available characterisation studies provide sufficiently robust values to inform preliminary LCA modelling and strengthen the contextual accuracy of environmental assessments.

In addition to energy production, biogas has been examined for its contributions to solid waste management, clean cooking, and public health (Mukasa-Tebandeke et al. 2019). Adoption dynamics and policy integration have also been explored (Namugenyi, Coenen, and Scholderer 2022; Tumusiime, Kirabira, and Musinguzi 2022) and broader regional insights (Namugenyi and Scholderer 2024) with studies highlighting barriers and enablers across Uganda and the broader East African region (Nyang, Nina, and Hussein 2020 (Mwirigi et al. 2014).); Despite this progress, a critical oversight remains: environmental sustainability has not been systematically assessed using Life Cycle Assessment (LCA), leaving a gap in understanding the full ecological implications of biogas technologies in the Ugandan context.

LCA offers a rigorous framework for quantifying the environmental footprint of biogas systems, including emissions, resource use, and ecosystem impacts across their entire life cycle (Liu, Zhu, and Tian 2024). Applying LCA can uncover trade-offs and guide better decision-making on feedstock use, technology selection, and energy application. This is especially relevant as Uganda pursues its National Development Plan III, Nationally Determined Contributions (NDCs), and SDGs, particularly SDGs 7 (clean energy), 12 (sustainable consumption and production), and 13 (climate action). As biogas systems grow more complex, with multiple by-products and end uses, comprehensive environmental assessments are essential for optimising sustainability outcomes.

While most studies have focused on livestock manure and crop residues, other waste streams like municipal biowaste and agro-industrial residues (e.g. fruit pulp and juice waste) remain underexplored. These feedstocks are becoming more available due to urbanisation and agro-processing growth but have yet to be fully assessed for their biogas potential and environmental trade-offs. Incorporating such diverse feedstocks into Uganda's biogas research agenda and evaluating them through LCA could significantly enhance the country's efforts to build a resilient, low-carbon, and circular bioeconomy.

3.6. The need for life cycle assessment in anaerobic digestion systems in Uganda

While Uganda has made commendable strides in promoting renewable energy, including biogas from anaerobic digestion, current policy frameworks remain heavily focused on technical and economic aspects, with limited attention to environmental sustainability. The Uganda Renewable Energy Policy (MEMD 2023) acknowledges the role of biomass alternatives but lacks provisions for incorporating Life Cycle Assessment (LCA) in project planning and evaluation. This omission constrains the ability to assess critical trade-offs such as greenhouse gas emissions from digester construction or methane leakage, thereby limiting the effectiveness of environmental governance. Integrating LCA into existing regulatory mechanisms like the Environmental Impact Assessment (EIA) framework would align Uganda's strategies with international best practices, as demonstrated in countries where LCA has informed bioenergy policy and technology selection (Tagne et al. 2021).

Despite its potential, the adoption of LCA in Uganda faces key challenges, including limited local data, low technical capacity, and insufficient stakeholder awareness. Addressing these gaps will require investment in training, institutional coordination, and the development of Uganda-specific life cycle inventory (LCI) databases and tools. Embedding LCA into academic programmes, government planning, and

regulatory systems, particularly through institutions like National Environmental Management Authority (NEMA), can institutionalise evidence-based decision-making. This would enable Uganda to transition from donor-dependent biogas projects to a more resilient, scalable, and accountable sector. Ultimately, LCA offers a transformative opportunity to strengthen environmental accountability, support sustainable development goals, and build a data-driven circular bioeconomy tailored to Uganda's context.

3.7. Biogas potential in relation to Uganda's national energy demand

Uganda's national energy mix is overwhelmingly dominated by solid biomass, which accounts for an estimated 89% of total primary energy consumption, largely in the form of firewood and charcoal (Bamwesigye et al. 2020). Electricity is contributing only 1.4 percent to the national energy balance while oil products, which are mainly used for vehicles and thermal power plants, account for the remaining 9.5% (Muwangu et al. 2021). Natural gas consumption is less than 1%, as Uganda does not currently have an operational domestic natural gas sector or distribution network. This heavy reliance on biomass and petroleum poses environmental, economic, and public health challenges, including deforestation, household air pollution, and vulnerability to global fuel price fluctuations.

Against this backdrop, biogas presents a promising but currently underutilised renewable energy resource. Theoretical estimates based on Uganda's organic waste streams, including livestock manure, crop residues, agro-industrial by-products, and municipal organic waste, suggest a national biogas generation potential of approximately 20–30 PJ per year (Owusu and Nabadda 2017). While this energy output is substantial, it remains insufficient to replace Uganda's total annual energy consumption which is 772 PJ (Muwangu et al. 2021).

However, biogas holds significant potential to transform specific, high-impact segments of Uganda's energy landscape. In household and institutional cooking, biogas can directly displace charcoal and firewood, fuels responsible for severe deforestation, biomass scarcity, and household air pollution. In agro-processing, biogas can substitute firewood, electricity, or diesel for thermal applications such as drying, pasteurisation, and heating. In off-grid rural communities, biogas-based electricity generation can support productive uses such as milk cooling, lighting, and small-scale mechanisation. These targeted applications demonstrate that while biogas may not satisfy Uganda's overall energy demand, it can play a strategic role in reducing pressure on forests, expanding clean-energy access, and enhancing energy security.

Given the growing volumes of municipal organic waste and agro-industrial residues arising from urbanisation and increased food-processing activities, the contribution of biogas to Uganda's energy system is expected to rise. Integrating biogas into Uganda's broader renewable-energy planning, supported by robust Life Cycle Assessment (LCA) frameworks, can therefore help advance the country towards a cleaner, more diversified, and resilient energy future.

3.8. Phased integration of LCA into Uganda's biogas policy framework

Integrating Life Cycle Assessment (LCA) into Uganda's biogas sector requires a structured, phased, and context-specific approach that builds national capacity, develops local datasets, and embeds life-cycle thinking within policy and regulatory frameworks. The proposed roadmap therefore presents a strategic five-phase progression that guides Uganda from basic LCA awareness to advanced, policy-relevant modelling and circular bioeconomy innovation (Figure 12). This approach aligns with, and complements, the objectives of the Uganda Renewable Energy Policy (MEMD 2023), which prioritises access to modern biomass energy and the promotion of environmentally responsible technologies. To operationalise this transition, the roadmap begins with the creation of a National Biogas LCA Task Force to coordinate capacity building, research harmonisation, and policy development, as recommended by LCA integration frameworks globally (Curran et al. 2018). Although the phases appear sequential, they are also mutually reinforcing, with continuous feedback loops that enable learning, refinement, and institutional strengthening as local capacity and data quality improve. A conceptual diagram (Figure 12) has been included to illustrate the relationships and transitions between the phases, addressing the reviewer's request for a visual representation of how the steps interconnect and support one another.

Phase 1 focuses on building foundational national capacity for conducting LCAs, addressing Uganda's current limitation of having only a small number of LCA-trained researchers and virtually no practitioners within public

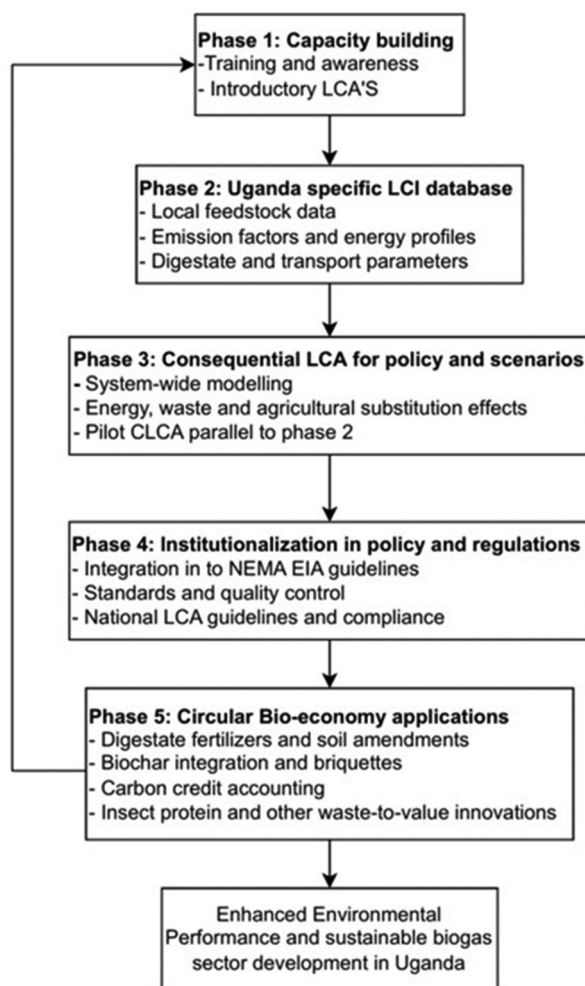


Figure 12. A stepwise approach to embedding life cycle assessment within Uganda's policy framework.

institutions or the biogas industry (Figure 12). This lack of technical expertise constrains the country's ability to produce credible environmental assessments for biogas systems. To close this gap, targeted training programmes that introduce stakeholders to LCA principles, attributional modelling, and open-source tools such as OpenLCA are essential. These introductory applications should prioritise commonly available Ugandan feedstocks, including cattle manure, poultry litter, banana residues, cassava peels, and municipal market waste, to generate basic midpoint assessments and produce Uganda's first baseline environmental performance datasets (Gumisiriza et al. 2017). By conducting simple LCAs using readily accessible local data, Phase 1 will build technical confidence among government officials, researchers, and private-sector actors while laying the analytical foundation required for more advanced LCA work in subsequent phases.

Phase 2 (Figure 12) focuses on developing a Uganda-specific Life Cycle Inventory (LCI) database to enhance the contextual relevance and accuracy of LCA studies by capturing local data on feedstock characteristics, energy inputs, emissions, and transport systems (Liu, Zhu, and Tian 2024). This need is especially critical given that LCAs conducted with European or generic global datasets cannot reliably represent Uganda's biogas sector, as they overlook the country's unique climatic conditions, feedstock compositions, energy mix, and waste-management practices. For instance, manure characteristics vary significantly across Uganda's diverse livestock production systems, municipal market waste composition shifts seasonally and regionally, and the national electricity grid is dominated by hydropower rather than fossil fuels, as assumed in many international datasets. Digestate handling also varies widely, with some households applying it directly to fields and others disposing of it in drains, causing uncontrolled methane and ammonia emissions. Developing an LCI database that reflects these realities is therefore essential not only for accurate modelling but also for supporting Uganda's National Energy Policy

objective of improving data quality for energy planning and policy formulation. By establishing a robust LCI foundation, Phase 2 enables the country to transition towards more advanced and policy-relevant LCA methodologies in subsequent phases.

Phase 3 shifts the roadmap towards the application of consequential Life Cycle Assessment (CLCA), a methodology that enables Uganda to model system-wide and long-term impacts of biogas expansion across the energy, agriculture, and waste-management sectors (Figure 12). CLCA provides the analytical foundation for evaluating how biogas adoption may influence market behaviour, land-use patterns, resource flows, and greenhouse gas emissions, thereby supporting national policy priorities outlined in the Uganda Energy Policy Review (MEMD 2023) and Electricity Connections Policy (MEMD 2018), both of which seek to expand access to clean, modern, and affordable energy sources. Through scenario modelling, CLCA can assess, for example, the potential substitution of firewood or charcoal with biogas for cooking, the integration of biogas into off-grid rural electrification schemes, the displacement of diesel-powered milk cooling systems in off-grid cattle corridors such as Kyankwanzi district, or the replacement of imported synthetic fertilisers through increased digestate use. Although the reviewer raised the question of whether Uganda could advance directly to this phase, CLCA requires a robust empirical foundation and technical expertise that are currently limited. Phases 1 and 2 therefore serve as essential precursors by building national capacity and generating reliable local datasets. Nonetheless, pilot CLCA studies can run concurrently with Phase 2, helping stakeholders build experience, refine modelling approaches, and generate early policy-relevant insights while the national LCI database is still under development (Katelhön, Bardow, and Suh 2016).

Phase 4 involves the institutionalisation of LCA within Uganda's environmental and energy governance systems, ensuring that life-cycle thinking becomes a mandatory component of planning, approving, and evaluating biogas projects (Figure 12). Once sufficient technical capacity and reliable local data are established through earlier phases, LCA can be formally integrated into the National Environment Management Authority (NEMA) Environmental Impact Assessment (EIA) guidelines, the Ministry of Energy and Mineral Development's renewable energy planning processes, and national standards governing biogas system design, leak detection, and digestate quality. Embedding LCA within these regulatory frameworks strengthens Uganda's commitment to environmental protection, low-carbon development, and evidence-based decision-making. It ensures that medium- and large-scale biogas investments are assessed using transparent, scientifically grounded criteria and facilitates systematic evaluation of biogas-related climate mitigation measures, thereby supporting Uganda's Nationally Determined Contributions (NDCs). Institutionalisation ultimately makes LCA an enduring element of Uganda's regulatory architecture and ensures the long-term sustainability and accountability of biogas sector development.

Phase 5 extends the application of LCA into Uganda's emerging circular bioeconomy by evaluating innovative pathways for resource recovery, waste valorisation, and renewable product development (Figure 12). As national interest grows in nutrient recycling, organic fertiliser production, carbon-credit mechanisms, and other waste-to-value technologies, LCA becomes essential for guiding investment decisions and selecting environmentally and economically optimal options. Uganda has considerable potential to develop circular biogas-linked innovations, including digestate-based organic fertilisers, biochar – digestate blends for soil enhancement, insect-based protein production using digestate solids, and briquettes derived from biogas residues for institutional cooking. These opportunities align closely with Uganda's Green Growth Development Strategy (2017/18–2030/31) (NPA 2017), which emphasises resource efficiency, sustainable agriculture, and low-carbon development. By applying LCA to these innovations, stakeholders can compare their environmental performance, assess climate mitigation potential, and ensure that emerging technologies contribute meaningfully to national sustainability goals. Embedding LCA within circular economy planning also helps Uganda transition from fragmented, donor-driven biogas initiatives to a coordinated, data-informed, and environmentally responsible bioenergy sector. The success of this phase, like the entire roadmap, depends on sustained collaboration among engineers, environmental scientists, agricultural practitioners, policymakers, and local communities to ensure that sustainability assessments remain both technically rigorous and contextually relevant.

Taken together, these five interconnected phases provide a coherent and actionable roadmap for integrating LCA into Uganda's biogas sector. They respond directly to Uganda's current constraints, limited capacity, lack of local data, weak regulatory frameworks, and underdeveloped circular economy markets, while offering a systematic pathway towards evidence-based policymaking and sustainable scaling of biogas technologies.

3.9. Limitations of the review

Although we searched four databases and screened grey literature (2014–2025), restricting to English may have excluded relevant regional work. Heterogeneity in goals, functional units, boundaries, and LCIA methods precluded meta-analysis. No validated LCA-specific risk-of-bias tool exists; our adapted JBI approach focuses on reporting transparency and may underrate unreported practices. Several included studies incompletely described allocation/co-product handling or data sources, limiting comparability. Finally, the review was not prospectively registered, which may introduce minor protocol flexibility.

4. Conclusion

Anaerobic digestion (AD) presents a viable solution to Uganda's intertwined challenges of energy insecurity, organic waste mismanagement, and environmental degradation. With over 481,000 tonnes of biomass feedstock produced annually, Uganda holds substantial untapped potential for sustainable biogas production. However, the absence of comprehensive Life Cycle Assessment (LCA) studies within the country has created a critical gap in understanding the true environmental performance of over 9500 installed biogas digesters. This lack of localised sustainability data hampers the ability to make informed decisions, optimise system designs, and develop context-specific, climate-resilient bioenergy solutions.

A global review of 49 LCA studies highlights growing methodological rigour, particularly the use of cradle-to-grave boundaries and attributional approaches. Yet, the dominance of European research and minimal representation from Africa, none from Uganda, reflects a significant imbalance in the global knowledge base. Locally abundant feedstocks like banana peels, cassava waste, and market refuse remain underexplored, while the limited application of endpoint impact categories restricts policy relevance in low-income settings. To bridge these gaps, a phased roadmap is proposed, emphasising local capacity building, open-access tools, a Uganda-specific life cycle inventory, and policy integration. Embedding LCA into Uganda's energy and waste strategies will promote smarter investments, enhance environmental accountability, and position the country as a leader in circular bioenergy innovation across sub-Saharan Africa.

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Data availability statement

The data obtained is mainly from previous literature and reports, and only some part of the data in 3.2 is analysed based on the literature data by authors of this paper. All data can be shared, and there is no ethical, privacy or security concerns.

Declaration of generative AI and AI-assisted technologies in writing process

During the preparation of this manuscript, the authors used ChatGPT (GPT-5.1 model) tool in order to improve language and readability of the manuscript. After using the tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendices

Appendix A: search string for Scopus

TITLE-ABS-KEY('anaerobic digestion' OR 'AD' OR 'biogas')
 AND ('life cycle assessment' OR 'LCA' OR 'life-cycle analysis' OR 'environmental assessment' OR 'carbon footprint'
 OR 'GHG emissions')
 AND ('sustainability' OR 'environmental impact' OR 'circular bioeconomy' OR 'waste management' OR 'renewable
 energy')
 AND ('agricultural waste' OR 'livestock manure' OR 'organic waste' OR 'crop residues' OR 'municipal solid waste')
 AND (LIMIT-TO(LANGUAGE, 'English'))
 AND (LIMIT-TO(DOCTYPE, 'ar'))
 AND (PUBYEAR > 2013 AND PUBYEAR < 2026)
 AND (EXCLUDE(SUBJAREA, 'MEDI') AND EXCLUDE(SUBJAREA, 'PHAR') AND EXCLUDE(SUBJAREA,
 'CHEM'))

Table A1. Global overview of life cycle assessments on anaerobic digestion.

S/N	Country	Continent	Article Reference
1.	Indonesia	Asia	(Cahyani et al. 2019)
2.	Norway	Europe	(Lyng and Brekke 2019)
3.	Germany and Italy	Europe	(Florio et al. 2019)
4.	Italy	Europe	(Fusi et al. 2016)
5.	Vietnam	Asia	(Vu et al. 2015)
6.	China	Asia	(Wang et al. 2016)
7.	United Kingdom	Europe	(Evangelisti et al. 2014)
8.	United Arab Emirates	Asia	(Adghim et al. 2020)
9.	Egypt	Africa	(Ioannou-Ttofa et al. 2021)
10.	Italy	Europe	(Lijó et al. 2014)
11.	United Kingdom.	Europe	(Parkes, Lettieri, and Bogle 2015)
12.	Malaysia.	Asia	(Abu et al. 2023)
13.	China	Asia	(Duan et al. 2020)
14.	Zimbabwe	Africa	(Nhubu et al. 2020)
15.	Iran	Asia	(Behrooznia, Sharifi, and Hosseinzadeh-Bandbafha 2020)
16.	Egypt	Africa	(Hijazi et al. 2020)
17.	United Kingdom	Europe	(Whiting and Azapagic 2014)
18.	Germany	Europe	(Hahn et al. 2015)
19.	Malaysia	Asia	(Aziz and Hanafiah 2020)
20.	Sweden	Europe	(Feiz et al. 2020)
21.	China	Asia	(Xu et al. 2015)
22.	Germany	Europe	(Ertem, Neubauer, and Junne 2017)
23.	Mexico	North America	(Ramírez-Arpide et al. 2018)
24.	Italy	Europe	(Pacetti, Lombardi, and Federici 2015)
25.	France	Europe	(Hajjaji et al. 2016)
26.	Pakistan	Asia	(Yasar et al. 2017)
27.	United Arab Emirates	Asia	(Giwa 2017)
28.	China	Asia	(Wang et al. 2018)
29.	France	Europe	(Collet et al. 2017)
30.	China	Asia	(Jin et al. 2015)
31.	Hungary	Europe	(Fuchsz and Kohlheb 2015)
32.	Switzerland	Europe	(Zhang et al. 2020)
33.	India	Asia	(Kumawat, Gidwani, and Rana 2024)
34.	Italy	Europe	(Carnevale and Lombardi 2015)
35.	Belgium	Europe	(Van Stappen et al. 2016)
36.	India	Asia	(Singh et al. 2020)
37.	United Kingdom	Europe	(Styles, Dominguez, and Chadwick 2016)
38.	China	Asia	(Xiao et al. 2020)
39.	Spain	Europe	(Cano et al. 2018)
40.	Mexico	North America	(Ramírez-Islas et al. 2020)

(Continued)

Table A1. (Continued).

S/N	Country	Continent	Article Reference
41.	Belgium	Europe	(Van den Oever et al. 2021)
42.	Argentina	South America	(Morero, Groppelli, and Campanella 2015)
43.	Spain	Europe	(Ruiz et al. 2018)
44.	Italy	Europe	(Negro et al. 2017)
45.	Spain	Europe	(Arashiro et al. 2018)
46.	China	Asia	(Sun et al. 2019)
47.	India	Asia	(Soam et al. 2017)
48.	Germany,	Europe	(Thonemann and Pizzol 2019)
49.	Denmark	Europe	(Thomsen et al. 2017)

Appendix B

Table A2. Studies that might appear to meet the inclusion criteria, but which were excluded.

S/N	Study title	Reason
1.	Bottled Biogas – An Opportunity for Clean Cooking in Ghana and Uganda	No life-cycle assessment conducted
2	Citizens' willingness to pay for local anaerobic digestion energy: The influence of altruistic value and knowledge	No LCA Conducted
3	Biogas production and techno-economic feasibility studies of setting up household biogas technology in Africa: A critical review	narrative review without primary AD-LCA modelling
4	Prospects of China's biogas: Fundamentals, challenges and considerations	No LCA conducted
5	Systematic review of scale-up methods for prospective life cycle assessment of emerging technologies	No actual LCA conducted
6	Life Cycle Assessment (LCA) of Biochar Production from a Circular Economy Perspective	LCA conducted but not for AD
7	Experimental Study for Biogas Upgrading by Water Scrubbing under Low Pressure	No LCA conducted
8.	The LCA4CSA framework: Using life cycle assessment to strengthen environmental sustainability analysis of climate smart agriculture options at farm and crop system levels	Not primary AD-LCA.
9.	Improving the Process of Product Design in a Phase of Life Cycle Assessment (LCA)	Not AD-LCA
10	Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes	Technology review; no LCA modelling of AD
11	Effect of steam explosion pretreatment on chosen saccharides yield and cellulose structure from fast-growing poplar (<i>Populus deltoides</i> × <i>maximowiczii</i>) wood	Experimental process study; no life-cycle modelling
12	Innovative high-pressure water scrubber for biogas upgrading at farm-scale using vacuum for water regeneration	Process/engineering note; no LCA outcomes
13	Why using different Life Cycle Assessment software tools can generate different results for the same product system? A cause – effect analysis of the problem	Tool benchmarking; no AD case
14	A system boundary identification method for life cycle assessment	Generic LCA methodology; no AD application
15	Life cycle assessment of bioenergy product systems: A critical review	Secondary review; did not apply LCA to a specific AD system

Appendix C

Table A3. Risk of bias assessment.

Country	Functional Unit	System boundary	Type of biomass used	Software used	LCIA method and LCA Type	Impact categories used	Overall Risk of Bias	Reference/Study ID
yes	No	Yes	yes	Yes	Yes	Yes	Moderate	(Cahyani et al. 2019)
yes	yes	yes	yes	yes	yes	yes	Low	(Lyng and Brekke 2019)
yes	yes	yes	yes	yes	yes	yes	Low	(Florio et al. 2019)
yes	yes	yes	yes	yes	yes	yes	Low	(Fusi et al. 2016)
yes	yes	yes	yes	yes	yes	yes	Low	(Vu et al. 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Wang et al. 2016)
yes	yes	yes	yes	yes	yes	yes	Low	(Evangelisti et al. 2014)

(Continued)

Table A3. (Continued).

Country	Functional Unit	System boundary	Type of biomass used	Software used	LCIA method and LCA Type	Impact categories used	Overall Risk of Bias	Reference/Study ID
yes	yes	yes	yes	yes	yes	yes	Low	(Adghim et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Ioannou-Ttota et al. 2021)
yes	yes	yes	yes	yes	yes	yes	Low	(Lijó et al. 2014)
yes	yes	yes	yes	yes	yes	yes		(Parkes, Lettieri, and Bogle 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Abu et al. 2023)
yes	yes	yes	yes	yes	yes	yes	Low	(Duan et al. 2020)
yes	No	yes	yes	yes	yes	yes	Moderate	(Nhubu et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Behrooznia, Sharifi, and Hosseinzadeh-Bandbafha 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Hijazi et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Whiting and Azapagic 2014)
yes	yes	yes	yes	yes	yes	yes	Low	(Hahn et al. 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Aziz and Hanafiah 2020)
yes	No	yes	yes	No	Partially yes	yes	High	(Feiz et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Xu et al. 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Ertem, Neubauer, and Junne 2017)
yes	yes	yes	yes	yes	yes	yes	Low	(Ramírez-Arpide et al. 2018)
yes	yes	yes	yes	yes	yes	yes	Low	(Pacetti, Lombardi, and Federici 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Hajjaji et al. 2016)
yes	yes	yes	yes	yes	yes	yes	Low	(Yasar et al. 2017)
yes	yes	yes	yes	yes	yes	yes	Low	(Giwa 2017)
yes	yes	yes	yes	yes	yes	yes	Low	(Wang et al. 2018)
yes	yes	yes	yes	yes	yes	yes	Low	(Collet et al. 2017)
yes	yes	yes	yes	yes	yes	yes	Low	(Jin et al. 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Fuchsz and Kohlheb 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Zhang et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Kumawat, Gidwani, and Rana 2024)
yes	yes	yes	yes	yes	yes	yes	Low	(Carnevale and Lombardi 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Van Stappen et al. 2016)
yes	yes	yes	yes	yes	yes	yes	Low	(Singh et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Styles, Dominguez, and Chadwick 2016)
yes	yes	yes	yes	yes	yes	yes	Low	(Xiao et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Cano et al. 2018)
yes	yes	yes	yes	yes	yes	yes	Low	(Ramírez-Islas et al. 2020)
yes	yes	yes	yes	yes	yes	yes	Low	(Van den Oever et al. 2021)
yes	yes	yes	yes	yes	yes	yes	Low	(Morero, Groppelli, and Campanella 2015)
yes	yes	yes	yes	yes	yes	yes	Low	(Ruiz et al. 2018)
yes	yes	yes	yes	yes	yes	yes	Low	(Negro et al. 2017)
yes	yes	yes	yes	yes	yes	yes	yes	(Arashiro et al. 2018)
yes	yes	yes	yes	yes	yes	yes	Yes	(Sun et al. 2019)
yes	yes	yes	yes	No	No	yes	High	(Soam et al. 2017)
yes	yes	yes	yes	yes	yes	yes	Low	(Thonemann and Pizzol 2019)
yes	yes	yes	yes	yes	yes	yes	Low	(Thomsen et al. 2017)