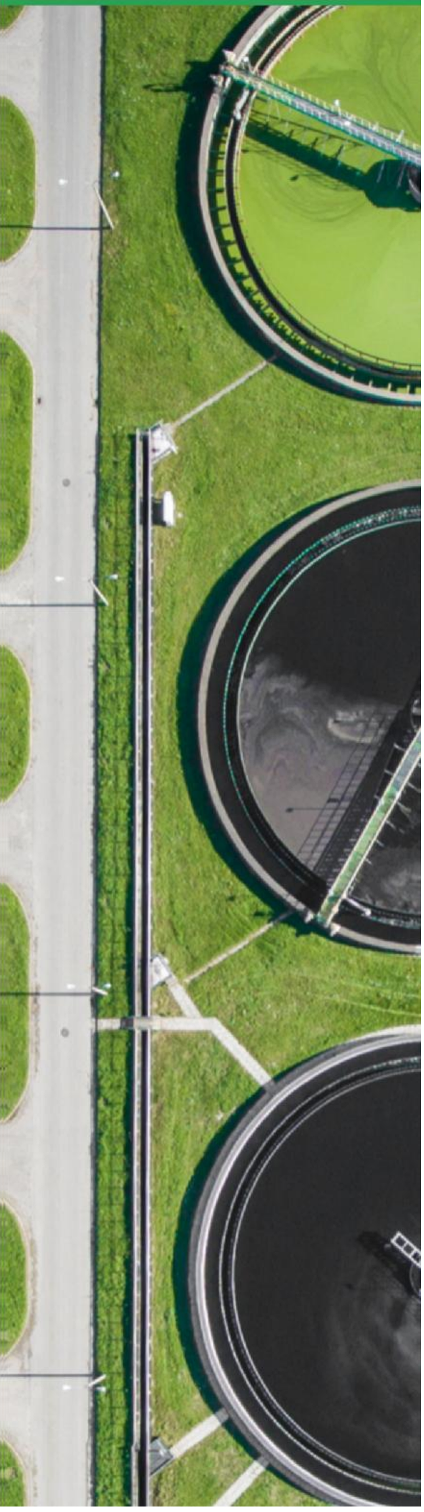
Transforming
Biosolids



Life Cycle Assessment of Biosolids Processing systems

Investigating variation and a best practice guide

J.Luo, S. Aryampa, R. Fisher, T. Wiedmann, R. Stuetz, December 2025

A report of a study funded by the ARC Training Centre for the Transformation of Australia’s Biosolids Resource

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About the report

The ARC Training Centre for the Transformation of Australia's Biosolids Resource has a primary goal of delivering world-class and innovative technological solutions and knowledge, to train the next generation of biosolids practitioners in cutting-edge, transformational approaches, and to guide best practice in the biosolids sector. A key project delivered by the Centre was ensuring sustainability in biosolids management by exploring the role of Biosolids Management in preserving Earth's resilience (Project 3B). The project used tailored sustainability assessment frameworks to quantify the environmental, economic and social impacts of key biosolids treatment alternatives. The assessments included carbon, water, energy and nutrient management, life cycle assessments. Carbon, energy, flows of nutrients, variability in sludge and biosolids composition, and emissions were studied and modelled using Life Cycle Analysis (LCA) and Material Flow Analysis (MFA). This report presents the results of that research. For further information visit: www.transformingbiosolids.com.au

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Executive summary

As Australia's biosolids sector faces increasing regulatory pressures and growing volumes of wastewater, adapting and innovating processing systems has become essential. Sustainability assessment tools are now key to helping utilities evaluate current practices and compare alternative approaches effectively. To ensure informed and unbiased decisions, developing a consistent and reliable assessment framework is increasingly important and should be prioritised.

This report presents findings from research conducted as a part of the project ***The role of Biosolids Management in preserving Earth's resilience*** undertaken with the ARC Training Centre for the Transformation of Australia’s Biosolids Resource. The primary aim of the project is to develop a generic and flexible environmental sustainability framework for assessing existing and emerging biosolids treatment technologies.

The current study examines past applications of life cycle assessment (LCA) to biosolids processing systems. The aim is to identify factors contributing to variability and inconsistent results in previous LCAs, and to determine key modelling practices and parameters causing these variations. Additionally, a best-practice guide has been developed to provide practical recommendations for conducting consistent, transparent, and reliable LCAs of biosolids processing systems.

Key findings:

- **Inconsistent results and contradictory findings of past LCAs**: Past LCAs have shown significant inconsistencies in carbon footprint outcomes and disagreements in the comparative environmental performance between biosolids systems. This underscores the risk of misinterpretation and potential misinformed decision-making.
- **Key areas of methodological variation**: Significant differences exist in how past LCAs defined system boundaries and accounted for secondary benefits of biosolids. Additionally, large variation was observed in inventory data, particularly pollutant emissions, with data source selection playing a crucial role in influencing results.
- **Critical factors driving result variability**: Critical factors causing variability in carbon footprint results were identified, such as the system boundary definitions on biogas leakage from anaerobic digestion and assumptions regarding carbon sequestration potential from biochar. Special attention is needed in these areas when conducting or reviewing carbon footprint assessments on biosolids processing systems.
- **A best practice guide is provided**: A best practice guide has been developed offering clear recommendations for defining system boundaries, prioritising data sources, accounting for co-benefits, and interpreting results. The adoption of these recommendations will support more consistent, transparent, and reliable LCA outcomes.

Based on the study conducted, we have identified gaps and potential shortfalls in applying LCA for assessing biosolids processing systems and present a set of recommendations for future environmental sustainability assessment practices.

- **Use LCA as a strategic decision support tool**: LCA should be employed comprehensively to evaluate the environmental impacts of biosolids processing systems, particularly focusing on off-site impacts and environmental trade-offs.
- **Ensure methodological consistency and transparency**: Standardised and transparent methodological practices are essential, especially regarding system boundary definitions and

offsetting assumptions. Methodological recommendations outlined in this report can serve as a foundation for developing clear and consistent practices.

- **Prioritise site-specific data collection**: Key inventory data with the potential to significantly influence LCA outcomes have been prioritised, and recommendations on preferred data sources are provided in this report. Utilities are encouraged to assess the availability of these key data within their organisations. Active engagement across different teams and collaboration with academia are recommended to address critical data gaps.
- **Interpret results with caution**: Interpretation of LCA results must acknowledge the methodological practices applied. Sensitivity analyses should be conducted to examine the influence of key methodological approaches and parameter choices.

1. Introduction

Australia is currently witnessing a nationwide shift in biosolids processing systems. Increasing sludge volumes and aging infrastructure have necessitated system upgrades to meet growing demand. At the same time, growing awareness around resource recycling, rising concerns over emerging contaminants and new regulatory requirements have driven the need to explore innovative technological solutions. For the water industry, this transition presents significant potential opportunities to enhance environmental benefits, explore new market opportunities, and positively reshape public perceptions of biosolids. However, it also brings uncertainties and risks, including potential financial burdens and environmental trade-offs.

In this context of substantial infrastructure investment, informed decision-making supported by robust environmental sustainability assessments is essential to reduce risks, align development with sustainability goals, and ensure the long-term effectiveness of biosolids processing systems. Life cycle assessment (LCA) has emerged as a key tool in the water sector, used for both carbon accounting and evaluating broader environmental impacts (see Box 1 for an introduction to LCA). Its ability to provide a comprehensive, system-level perspective and minimise the risk of burden shifting across impact categories makes LCA particularly valuable for supporting sustainable biosolids management strategies.

Despite its advantages, the application of LCA to biosolids processing systems continues to face challenges due to inconsistent methodological practices. Past studies have revealed significant variations in how LCA has been applied, often resulting in divergent, and sometimes contradictory assessment outcomes. These inconsistencies hinder the comparability of results across studies, reduce the practical value of existing LCA data in supporting decision-making, and may ultimately undermine the credibility of LCA as a reliable tool for guiding biosolids management decisions.

The substantial variability observed in past LCA studies highlights the need for a systematic understanding of the sources of variation and the development of a harmonised LCA framework to support reliable decision-making. While previous studies have identified differences across various aspects of LCA, such as system boundary definitions, technical assumptions, and assessment outcomes, there remains a lack of systematic analysis of the different sources of variation and structured insight into the underlying causes of these inconsistencies. Moreover, current knowledge is limited regarding the extent to which these sources of variation influence LCA results, which constrains the ability to interpret findings and apply them effectively in decision-making.

Developing clear insights into sources of variation and establishing a harmonised assessment framework can offer a valuable opportunity to improve the reliability and transparency of LCA for biosolids. This will enable water utilities to access more consistent, comparable environmental data and make better-informed, strategic decisions. Ultimately, improved consistency in LCA will support more sustainable biosolids management and better alignment with broader environmental objectives.

1.1. Aim of this report

This report aims to review past applications of LCA to biosolids processing systems, identify key sources of variation, and develop a harmonised assessment framework. By examining inconsistencies in previous studies, the report highlights current challenges in applying LCA to biosolids and areas where results may be misinterpreted. Based on these insights, the report proposes a set of best-practice recommendations and key considerations for conducting and interpreting LCAs in the context of biosolids management.

The key components of this study include:

- A review of previous LCA studies on biosolids processing systems to examine variations in methodological practices, assumptions, and reported results.
- Application of a partial harmonisation framework to identify key factors influencing LCA outcomes
- Propose standardised practices for conducting consistent and transparent LCAs for biosolids systems.

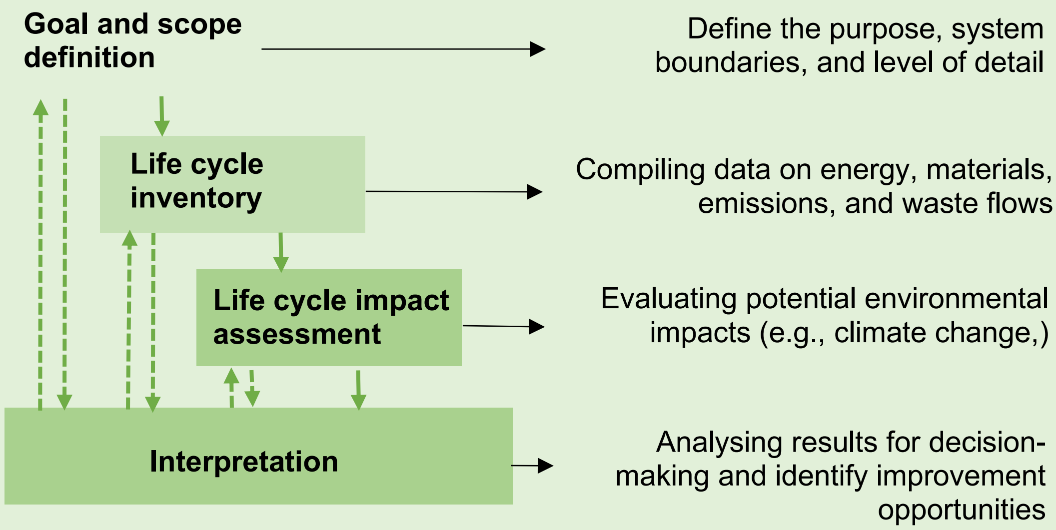
Box 1.

What is LCA

Life Cycle Assessment (LCA) is a quantitative assessment tool used to evaluate the environmental impacts of a product, process, or service across its entire life cycle. It offers a holistic perspective by accounting for impacts associated with upstream and downstream systems, extending beyond the direct system boundaries.

LCA methodology

LCA is typically conducted following international standards (ISO 14040/14044), and consists of four main steps:



2. Variations in past biosolids LCAs

2.1. Application of LCA for biosolids systems

LCA has been applied to biosolids processing since the late 1990s, when it first emerged as a reliable tool for quantifying environmental impacts in wastewater treatment, including biosolids processing systems[1]. Early industry studies used LCA to inform strategic choices such as centralised versus decentralised treatment configurations[2], and identifying energy-saving potentials[3]. Australia was an early adopter of LCA for biosolids systems, with a study conducted in 2001 where LCA was used to assess the potential global warming potential (GWP), and human toxicity impacts of Sydney Water's future biosolids processing systems[4].

The holistic nature of LCA makes it uniquely invaluable for biosolids processing systems[4]. It offers a comprehensive evaluation of environmental impacts across all stages of the life cycle, not limited to wastewater treatment plants. By considering upstream and downstream activities, such as transportation, land application, and the potential benefits of reuse, LCA provides a more accurate representation of the overall environmental burden associated with biosolids management and captures environmental credits from beneficial reuse. It also assesses a broad range of environmental impacts, including carbon emissions, energy consumption, nutrient flow, and potential toxicity, thus offering a more complete and integrated assessment of the sustainability of biosolids processing systems.

2.2. What is variation and why it's important

Variation, in simple terms, refers to the differences observed between different LCA studies. More specifically, it is differences driven by intentional methodological choices, assumptions, and data sources that vary across studies, resulting in disparities in the outcomes. These variations can occur at different stages of the LCA process and can be induced by different factors (Fig. 1).

Understanding and identifying these variations is essential to ensure that LCA results remain both robust and relevant. The flexible nature of LCA and the lack of system-specific guidelines create opportunities for methodological differences. When methodological choices, such as data sources or boundary definitions vary, reported environmental performance can differ substantially (Fig.2) and lead to misinterpretation. For example, one study may report a low GWP for a system because it adopts a narrow system boundary, while another shows higher impacts simply by using a different emissions factor. In such cases, decision-makers could draw contradictory conclusions about which option is most sustainable. Recognising these sources of variation and adopting measures to minimise them provides a foundation for reliable, transparent use of LCA outcomes and supports the development of new, consistent LCA models.

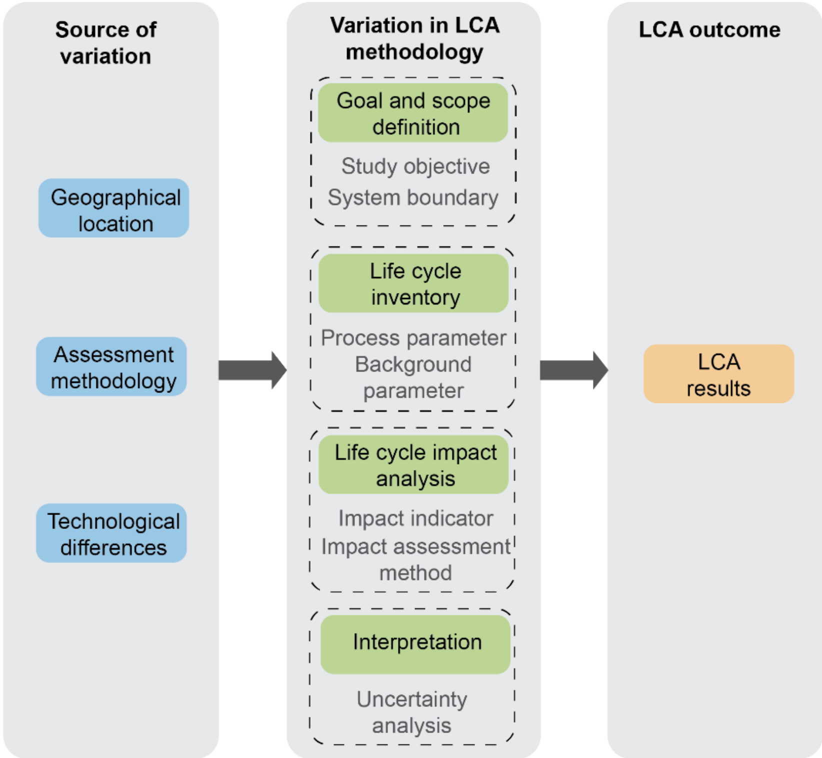


Fig. 1 Variations in life cycle assessment methodology, sources and impacts on results

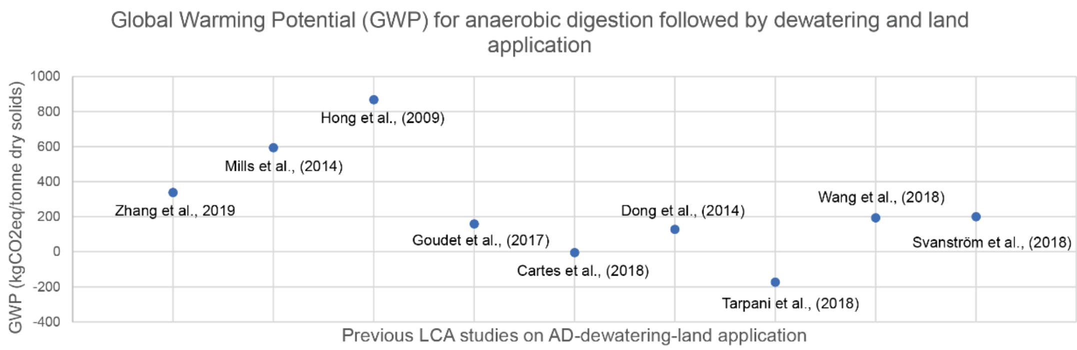


Fig. 2 Variations on Global Warming Potential (GWP) results reported on anaerobic digestion followed by land application from previous studies.

2.3. Study design for investigating variations

This study adopted a two-phase framework to investigate the variations in LCAs of biosolids processing systems. The first phase involved a comprehensive literature review of peer-reviewed studies to identify the sources and extent of variability contributing to inconsistencies across existing studies. The selection criteria for reviewed publications are described in detail in our earlier publication[5]. Methodological differences across all LCA stages were investigated. Inventory data from reviewed studies was extracted to build a structured literature inventory database which enables the identification of discrepancies in input data and provides a foundation for future LCAs. LCA outcomes from the reviewed studies were analysed both quantitatively and qualitatively, focusing on direct numerical comparisons of global warming potential (GWP) results, as well as differences in conclusions drawn on the environmental performance of different biosolids treatment options.

Building on the identified sources and extent of variation in existing LCA studies, the second phase introduced a novel approach, partial harmonisation, to quantify the relative significance of individual inputs and assess their influence on the variability of LCA results (see Box 2 for descriptions of partial harmonisation and harmonisation). This method builds on the existing harmonisation method used in LCA meta-analysis, which recalculates results using standardised system boundaries and assumptions across foreground and background systems[6]. Compared to full harmonisation, which modifies all methodological elements simultaneously, partial harmonisation uses an incremental approach, modifying one input at a time while keeping others unchanged. This one-at-a-time adjustment isolates the influence of each input, allowing for a clearer understanding of its specific contribution to variability in results.

Partial harmonisation was applied to selected high-quality LCA studies with comprehensive methodological documentation and complete inventory data (see Appendix A for the full list). Variability from three major sources, system boundary definitions, background data (e.g., electricity mix, supply chain impact for fertilisers), and foreground data (e.g., energy recovery assumptions), was assessed across three biosolids processing technologies: anaerobic digestion (AD), composting (COMP), and pyrolysis (PY).

To quantify the magnitude of change in LCA results caused by input adjustments, the Average Harmonised Value (AHV) was calculated as follows:

$$\sum_{i=1}^{n} \left| LCA_{i,after} - LCA_{i,before} \right| / n \quad \text{Eq.1}$$

Where:

n is the total number of studies included in the analysis.

$LCA_{i,before}$ is the LCA result of the i^{th} study before adjustment.

$LCA_{i,after}$ is the LCA result of the i^{th} study after adjustment.

AHV measures the average change in LCA outcomes across studies after partial harmonising a specific input. This provides an indicator of both the level of inconsistency in the original literature and the sensitivity of results to specific LCA inputs, offering insights that cannot be obtained from conventional harmonisation or contribution analysis alone.

Box 2

What is LCA harmonisation?

LCA Harmonisation is a methodological approach used to improve the comparability and consistency of LCA results **based on previous studies**. It involves aligning key assumptions, system boundaries, and background data sources to reduce variability caused by methodological differences.

What is LCA partial harmonisation?

Partial Harmonisation is a targeted form of LCA harmonisation that focuses on aligning specific parameters or system boundary components rather than fully standardising all aspects. It aims to identify and adjust the most influential factors that contribute to variability in LCA results, such as system boundaries, key emissions, or foreground data inputs.

2.4. Variation in LCA methodologies

1.1.1 System boundary: what's included (and what's not) matters:

The system boundary definition in LCA is essentially a set of rules that determines which parts of the process are included in the analysis and which are not. However, there are no universal standards for where the boundary should be drawn, and boundary conditions often differ depending on the system configuration. How these boundaries are defined can make a significant difference in the reported environmental outcomes of biosolids systems, with major implications for decision-making based on LCA results. For example, one assessment might only focus on what happens within the treatment plant, while another might include the entire life cycle, from sludge generation to long-term impacts after end use in agriculture. Some studies account for the energy consumption of a digester, while others might also consider fugitive emissions from potential leakage. These choices can lead to very different conclusions, even for the same technology.

Our review has found a wide range of approaches for boundary definition in biosolids LCAs across all three levels of system boundary (see Box 3 for more information).

- For the **process level boundary**, energy consumption showed good consistency across most systems, while there was considerable variation in how pollutant emissions were treated, with some key emissions not commonly accounted for despite their clear environmental relevance (more detailed information on the process level boundary of previous studies is illustrated in Fig. 3).

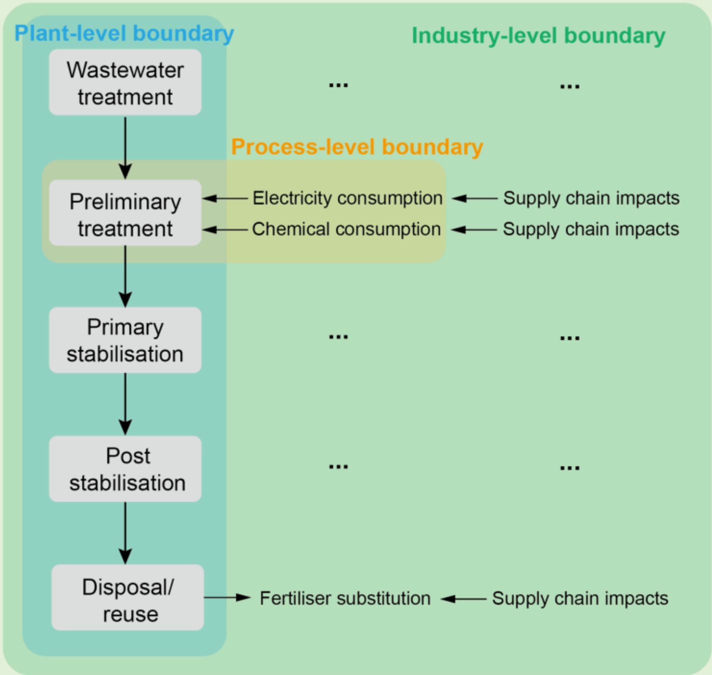
- For the **plant level boundary**, some studies omitted early or supporting steps or focused only on activities occurring within the treatment plant. This narrow focus can lead to an underestimation of environmental impacts.
- For the **industry level boundary**, most studies lacked detailed documentation of the background processes adopted, making it difficult to fully understand the boundary conditions. We also observed significant variation in how waste streams, such as reject water, were handled and defined.

Partial harmonisation identified several key factors for which the system boundary definition can have a particularly strong influence on LCA results (key results listed in Appendix-A). For example, whether studies include or exclude direct greenhouse gas emissions, especially methane and nitrous oxide, from digestion, composting, and land application can significantly affect reported outcomes. In some cases, emissions are omitted or not clearly defined, leading to inconsistencies between studies. Additionally, some other aspects, such as the inclusion of energy recovery and carbon sequestration can also lead to large variations in the results.

Variations in boundary definitions arise both from genuine operational differences, such as whether biogas is flared or used for electricity generation, and also from inconsistent methodological choices. In many cases, omissions or inclusions lack clear justification, making it difficult to determine the reasons behind differences in study outcomes.

Box 3

Different layers of system boundary



- **The process-level boundary** specifies the inputs and outputs for each process
- **The plant-level boundary** details the technical processes considered in the assessment
- **The industry-level boundary** encompasses both upstream and downstream processes for biosolids processing

1.1.2 Accounting for co-benefits: how to estimate the environmental credits

How secondary benefits are accounted for in LCA studies is another major source of variation[7]. In the context of biosolids management, secondary benefits refer to the additional environmental credits that can be achieved beyond the primary goal of waste treatment. Common examples include generating renewable energy from biogas, which can offset grid electricity, and substituting biosolids for synthetic fertilisers, reducing the demand for fossil-based fertiliser production. Properly accounting for these co-benefits is important for accurately reflecting the environmental profile of biosolids processing systems and providing a competitive edge for technologies with additional benefits in comparative analyses. However, our review found that previous studies have used a range of different methods to quantify these benefits, which can have a significant impact on the environmental outcomes reported.

For energy recovery, many studies assume that electricity or heat generated from biogas can offset conventional energy use. However, there is often a lack of clarity about the type of energy being displaced (such as whether it is average grid electricity or a specific fuel source) which makes it difficult to compare results and fully understand the environmental benefits claimed. In addition, the partial harmonisation outcomes demonstrated that the choice of electricity mix is a key background factor influencing results (see Appendix A), highlighting the potential impact of variation in substituted energy sources and underscoring the importance of transparent reporting.

Fertiliser substitution is also handled in a variety of ways by previous LCAs. The actual environmental benefit of using biosolids as a fertiliser depends on how much of the nutrients in the biosolids are available to crops, what type of synthetic fertiliser is replaced, and which stages of the fertiliser life cycle are considered. Many studies lack detailed documentation and do not fully account for these factors. For instance, boundary conditions for the substituted mineral fertiliser varied greatly: some studies accounted only for the production phase, while others also included the transportation and application of the mineral fertiliser. These inconsistencies can lead to either overestimation or underestimation of the environmental benefits.

1.1.3 Data inputs: how they're chosen changes the story

In LCA, inventory data refers to the information and data collected on all inputs (such as chemical and energy consumption) and outputs (such as emissions and secondary benefits) throughout each stage of a process or system. The quality and consistency of this data are fundamental to producing reliable LCA results. However, our review found substantial variation in the data used across different studies, especially for pollutant emissions (detailed in Append-B). This variation is partly due to inherent differences in local conditions and operational practices at treatment facilities, but it is also heavily influenced by the choice of data sources and underlying assumptions, which can introduce further uncertainty into the results. For instance, assumed rates of biogas leakage varied greatly across studies, leading to significant differences in the reported global warming potential for anaerobic digestion systems.

Our analysis also identified several key process parameters that contribute most to variability in results, such as the amount of electricity recovered from anaerobic digestion, the extent of fertiliser substitution from digested sludge, fugitive emissions from composting, and energy use during composting. In many cases, studies relied heavily on generic values from the literature for these parameters, without accounting for site-specific conditions that could significantly influence outcomes. This reliance on generic data can reduce the accuracy and relevance of LCA findings.

1.1.4 The challenge of variation in results: too many answers, not enough clarity

Quantitative analysis across published studies shows substantial variability in reported GWP results for biosolids processing systems. No single processing method consistently demonstrates environmental superiority (see Fig. 4). While AD often reports lower average GWP values than other technologies, these differences are not always statistically significant. It was identified that unit processes such as digestion and cogeneration, drying, and thermal treatments (incineration and pyrolysis) significantly contributed to variation in overall results, influenced greatly by variations in assumptions related to energy recovery, fugitive emissions, and drying energy demands.

Further review of comparative LCA studies reveals some broad patterns, but also many areas of uncertainty (Fig. 5). For example, AD typically outperforms composting across a range of environmental impact categories. However, for many other technology comparisons, there is no clear consensus. For instance, studies comparing incineration and composting report mixed results, some concluded on the environmental superiority of incineration, while some presented the opposite conclusion, and some other studies found no clear winner between the two systems (Fig. 5).

Environmental trade-offs are also evident. AD generally achieves better performance for GWP reduction, while incineration may be favoured for reducing ecotoxicity and acidification, potentially due to emissions associated with land application of digested biosolids.

Overall, these findings highlight that there is no single solution that fits into every context. The environmental performance of biosolids processing systems depends on the specific impact category considered and the assumptions made in each study. In general, for water utilities, this variability underscores the need for careful interpretation of LCA results and reinforces the importance of transparent, standardised assessment methods to support sound decision-making.

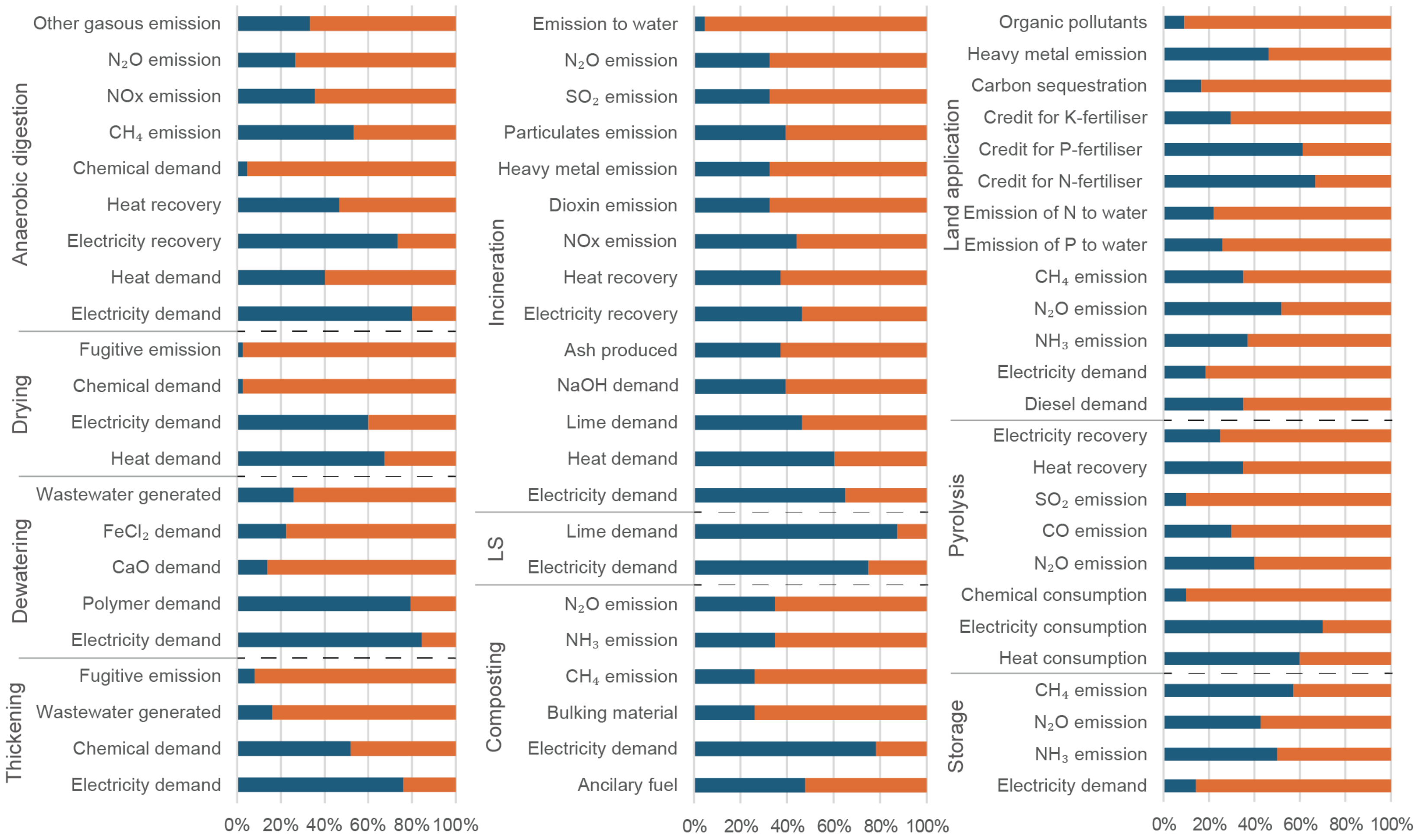


Fig. 3 Process-level boundaries of life cycle assessment studies on biosolids processing. The chart displays the percentage of studies that included various processes (blue bar) for different technologies; LS: lime stabilisation

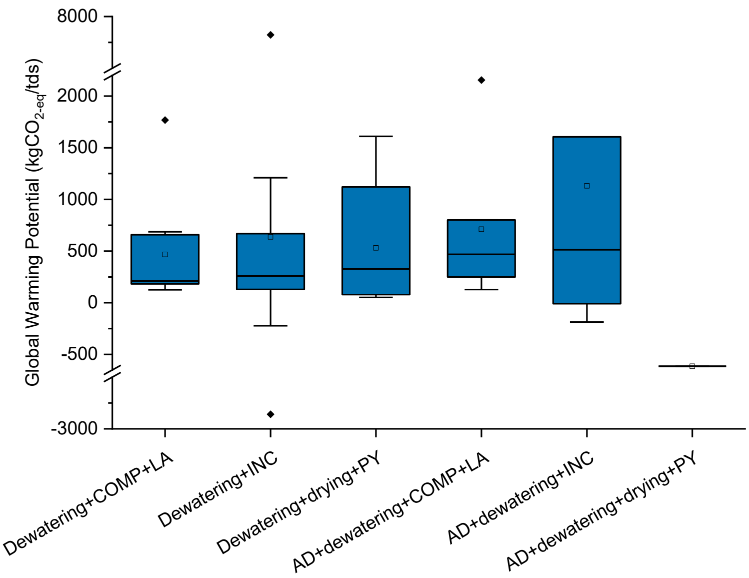


Fig. 4 Comparison of results from past life cycle assessment studies on the global warming potential (kgCO2-eq/tone dry solids (tds)) of different biosolids processing systems. AD: anaerobic digestion

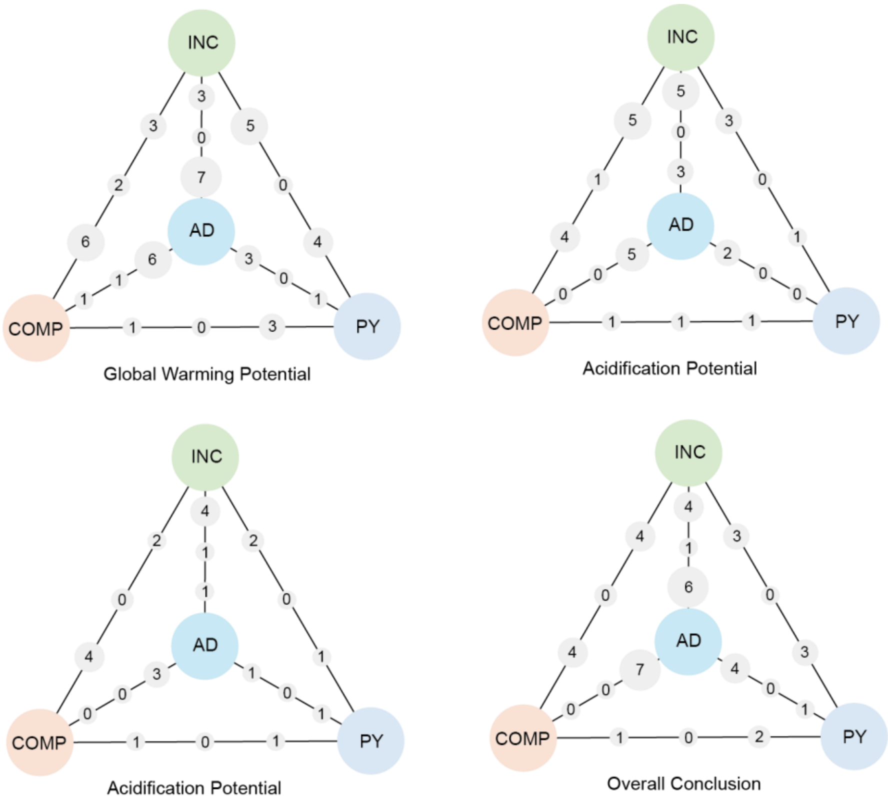


Fig. 5 Qualitative comparisons of results on the relative environmental performance of different biosolids processing systems from past life cycle assessment (LCA) studies. Each circle represents a comparison between two systems. The number in each circle indicates how many studies concluded that the system had a better performance for a specific impact category compared to the system in the opposite direction. The circle in the middle represents the number of studies that concluded equal performance between the systems. (AD): anaerobic digestion followed by dewatering and land application; (COMP): Dewatering followed by composting and land use of produced compost, (INC): incineration with landfill of incineration residual, (PY): drying followed by pyrolysis and land use of pyrolysis biochar

3. Best practice guide on biosolids LCA

LCA is a valuable tool for water utilities to assess the environmental performance of biosolids processing systems, support technology selection, optimise operations, and drive sustainability improvements. However, the complexity and diversity of biosolids processes mean that differences in methodology and data can lead to significant variation in LCA results. To address this, the report presents a best practice guide designed to help water utilities strengthen the robustness, transparency, and comparability of their LCA studies. In addition, a practical checklist is provided to assist industry partners in reviewing LCA reports for biosolids processing. This checklist is grounded in best-practice recommendations and harmonised LCA frameworks to ensure greater consistency and clarity in environmental assessment. The review checklist is presented below with the best practice guide attached in the Appendix-D.

Table 1: Checklist for Reviewing LCA Studies of Biosolids Processing Systems

Alignment	Item	
Objective and functional unit definition		
	Is the objective of the LCA clearly stated?	
		Technology-level objective
		Design-level objective
		Planning-level objective
	Are the intended users of the results identified?	
	Is the functional unit clearly defined (preferably per tonne dry solids)?	
	Is the information on functional unit, e.g., input sludge characteristics (e.g., moisture, nutrient content), documented?	
Impact coverage		
	Are core impact categories included?	
		Global Warming Potential
		Human and Ecotoxicity
		Eutrophication Potential
		Acidification Potential
	Are any expanded categories considered?	
System boundary definition		
	Is the process-level boundary clearly defined and documented?	
	Is the plant-level boundary clearly defined and documented?	
	Is the industry-level boundary clearly defined and documented?	
	Is there any significant omission compared to the recommended boundary definition	
	Are exclusions justified and documented?	
Co-benefits and system expansion		
	Is the substituted electricity mix provided, and based on local context?	
	Is the fraction of generated electricity used internally considered, and transmission loss included in substitution	
	If future scenarios are modelled, is the changing electricity mix considered?	
	Are substituted fertiliser types clearly documented?	
	Are fertiliser substitution benefits calculated using nutrient availability?	
	Are the full life cycle impacts of substituted fertiliser (other products) included?	
Life cycle inventory analysis		
	Are primary (site-specific) data used for electricity consumption and electricity recovery	
	Are the metadata (e.g., time, location, assumptions) for all data sources documented?	
	Is data quality assessed or discussed (e.g., using a pedigree matrix)?	
	Are the mass balances of key substances (nutrients, carbon, and TS) provided	

	Are background data sources (e.g., ecoinvent) clearly cited?
	Are inventory data reported per FU and per unit process?
	Is the biosolids LCI tool adopted where applicable?
Life cycle impact assessment	
	Is the LCIA method aligned with the ALCAS guide for Australia?
	Is biogenic carbon treated consistently (e.g., CO_2 from biosolids as climate-neutral)?
	If thermal technologies are included, are the limitations of LCIA methods (e.g., PFAS, microplastics) acknowledged?
Results interpretation	
	Are the results broken down by unit process?
	Is a contribution/hotspot analysis conducted?
	Are uncertainty analyses performed?
	Are sensitivity analyses performed?
	Are limitations and assumptions clearly discussed?

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Appendix A: Partial harmonisation outcomes

Table A-1 Partial harmonisation results for anaerobic digestion systems, with key factors highlighted

LCA input	AHV ($kgCO_2$-eq/tds)
Background processes	
Electricity mix	162
Polymer consumption from dewatering	3
Transportation to the land application site	7
Fertiliser substituted	51
System boundary	
System Boundary for facility construction	0
Anaerobic digestion fugitive emission	94
Anaerobic digestion electricity recovery	22
Anaerobic digestion heat balance	8
Thickening electricity consumption	7
Thickening chemical consumption	3
Dewatering reject water treatment	45
Dewatering FeCl3 and PAC consumption	31
Transportation to the land application site	4
Fuel and electricity consumption from land application	9
Fugitive emissions from land application	71
Fertiliser substitution from land application	10
Use phase of mineral fertiliser and carbon sequestration	80
Process parameter	
Anaerobic digestion electricity consumption	17
Anaerobic digestion fugitive emission	39
Anaerobic digestion electricity recovery	67
Thickening electricity consumption	9
Thickening chemical consumption	2
Dewatering electricity consumption	8
Dewatering chemical consumption	2
Land application fuel consumption	3
land application fugitive emission	41
land application fertiliser substitution	62
Parameter transportation	20

Table A-2 Partial harmonisation results for composting systems, with key factors highlighted

LCA input	AHV (kgCO2-eq/tds)
Background processes	
Polymer consumption from dewatering	3
Energy balance of the system	175
Material consumption for incineration	11
Impact from ash transportation	5
System boundary	
Thickening	17
Dewatering	59
Reject water treatment	5
Electricity consumption during drying	29
Material consumption during incineration	19
Energy balance during incineration	211
Gas emissions during incineration	124
Ash disposal	18

Process parameter	
Dewatering consumptions	30
Incineration material consumption	11
Incineration electricity demand	83
Drying electricity demand	89
Incineration and drying heat balance	167
Incineration electricity recovery	209
Emissions from incineration	130
Transportation	5
Landfill	8

Table A-3 Partial harmonisation results for pyrolysis systems, with key factors highlighted

LCA input	**AHV (kgCO2-eq/tds)**
Background processes	
Electricity mix	136
Polymer consumption during dewatering	9
Drying heat demand	66
Transportation	38
Fertiliser substitution	13
System boundary	
Thickening consumptions	41
Dewatering consumptions	199
Reject water treatment	14
Drying and pyrolysis heat consumption	39
Pyrolysis material consumption	6
Pyrolysis fugitive emission	10
Direct pyrolysis product substitution	28
Transportation	38
Fertiliser substitution	26
Land application GHG emission	11
Land application carbon sequestration	163
Process parameters	
Thickening and dewatering consumption	42
Reject water treatment	14
Drying energy consumption	128
Pyrolysis electricity consumption	29
Pyrolysis GHG emission	23
Transportation	41
Land application fertiliser substitution	36
Land application GHG emission	8
Land application carbon sequestration	11

Appendix-B Variations in life cycle inventory

LCI refers to the quantified inputs (e.g. electricity, chemicals) and outputs (e.g. emissions, resource recovery) associated with a system throughout its life cycle. For biosolids processing systems, significant variation in LCI data was observed across reviewed studies.

While some parameters, such as nutrient content in sludge and methane content in biogas, were relatively consistent, most environmental flows showed high variability. Most flows had a relative standard deviation (RSD) exceeding 50%, with pollutant emissions showing the greatest variation (average RSD: 134%), much higher than energy inputs (77%) or material use (70%) (Fig. A-2). End-use processes, especially land application and incineration, tended to show higher variability, likely due to a higher number of environmental flows associated with pollutant emission.

This review also explored the factors behind such variability. Local conditions and process-specific parameters were identified to influence certain flows. For example, electricity recovery from anaerobic digestion was strongly correlated with volatile solids content (R^2 = 0.88), and incineration energy use increased with higher input sludge moisture content. However, differences in data sources and assumptions also played an important, perhaps more critical, role in influencing inventory data.

Most studies relied heavily on literature values or empirical calculations. This was especially true for emissions, where primary monitoring is limited [8]. However, local factors (e.g. climate, soil type, fertiliser type) were often ignored. For instance, nitrogen emissions from land application are location-sensitive, but this was rarely reflected in emission factors[9]. Furthermore, a comparison of inventory data from various sources highlighted that literature data source selection and assumptions in empirical calculations were major drivers of the variation for some environmental flows. For instance, high electricity use estimates for AD in Zhou et al. [10] were based on the assumption that only electricity (and not heat) was used as an energy source to power the digester and provide necessary heat. Emissions data for incineration also varied widely, as some studies relied on design standards or regulatory limits rather than actual plant performance or monitoring data.

Additionally, inadequate reporting of technology details (e.g. specific composting methods or incineration setups) limited the ability to understand how configurations affect results. A common issue was “multi-layer citation”, where studies cited older LCAs without checking original data quality. This practice reduces transparency and can lead to the propagation of outdated or unverified information.

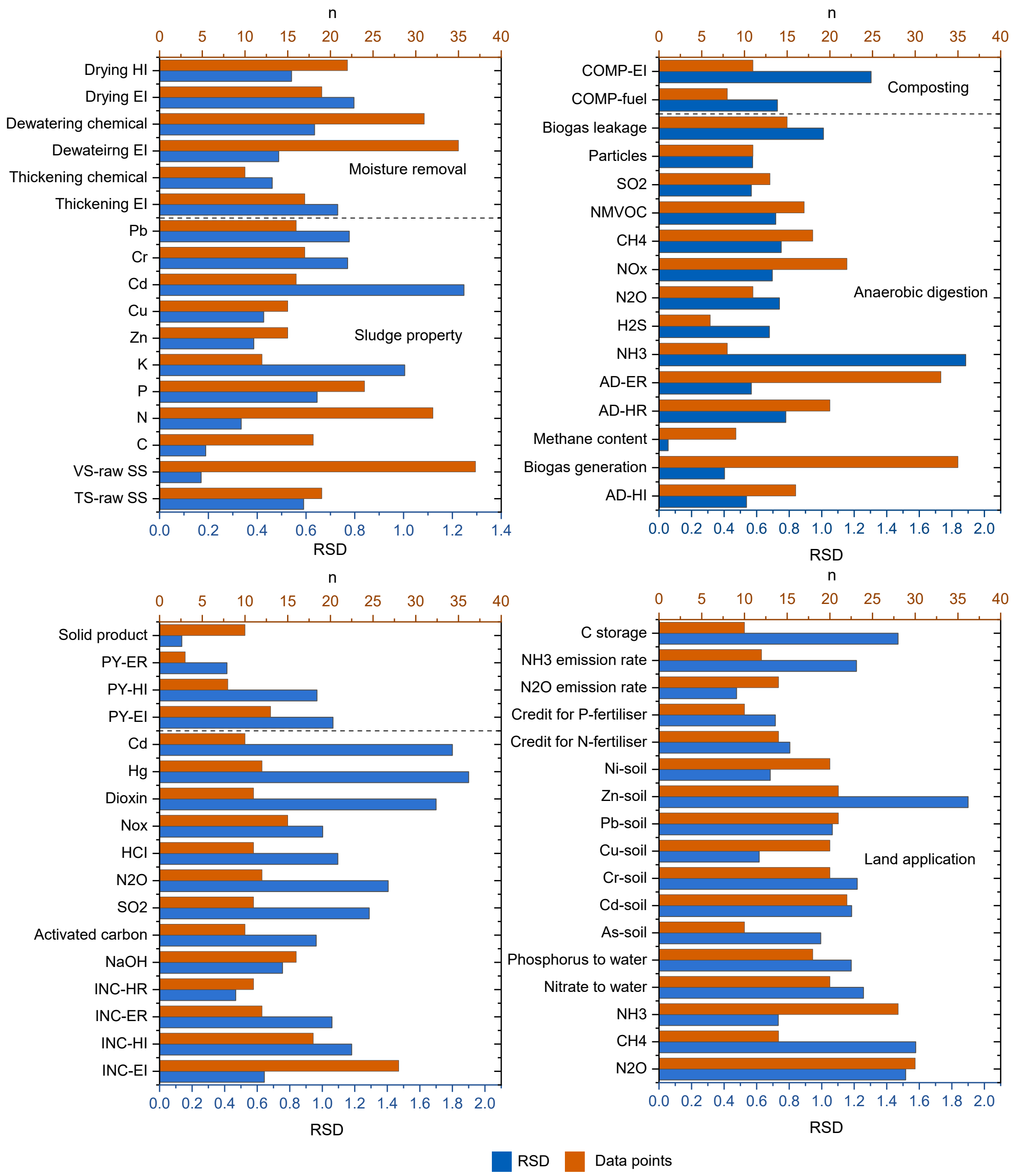

Fig. A-1 Meta-analysis results of inventory data from review studies, including Relative Standard Deviation (RSD) and numbers of data points gathered. TS: solid content, VS: volatile solid content; SS: sewage sludge, EI: electricity input; HI: heat input, AD: Anaerobic digestion, ER: electricity recovery, HR: heat recovery, COMP: composting, INC: incineration, PY: pyrolysis.

Appendix-C Best practices guide on biosolids LCA

General LCA Guidelines and Manuals

LCA is a well-established international methodology governed by standardised guidelines and manuals that ensure consistency and transparency. However, the flexible nature of LCA allows for methodological variations for different applications. Therefore, to achieve best practice, it is important to consult guidance at different levels before applying biosolids-specific recommendations (Fig. 7). The following outlines key LCA guidelines across these different levels of application.

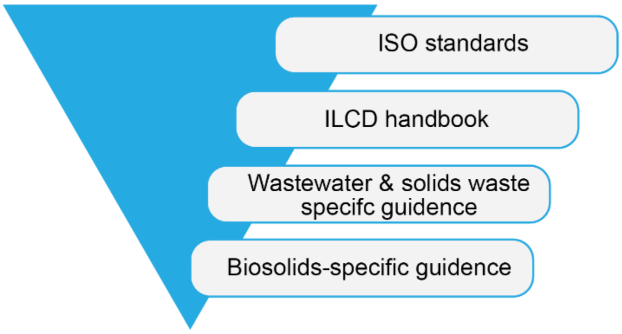

Fig. A-2 The different levels of standards and guidelines

- **ISO Standards**:

The core international standards for conducting LCAs are the ISO 14040 series, which established a baseline for LCA studies, defining terminology and methodological approaches

- **ILCD Handbook**:

The International Reference Life Cycle Data System (ILCD) Handbook, developed by the European Commission's Joint Research Centre, supplements ISO standards with detailed methodological guidance

- **Sector-specific guidance**:
    - Solid Waste Management LCA Guidance. Laurent et al. (2014)'s review and methodological recommendation identifies common methodological flaws and offers detailed recommendations to align solid waste LCA practice with ISO and ILCD standards for improved rigour and data quality.
    - Wastewater Treatment LCA Guidance. Corominas et al. (2020) provide targeted best practices for wastewater treatment LCAs, emphasising clear goal definition, suitable functional units, comprehensive inventory data, and relevant impact assessments.

Objectives and Functional Unit (FU)

- **Clarify the LCA objective**:

The objective of the assessment should be clearly documented, such as technology comparison, operational optimisation, or strategic planning, as a clear objective is needed to guide methodological choices and defines the scope. Common objectives include:

- Design-level comparison of treatment options (e.g., different potential processing options for a targeted plant)
- Technology-level identification of hotspots and improvement opportunities (e.g., for optimising an existing facility or a specific potential design)
- Planning-level evaluation of broader system strategies (e.g. comparing centralised or decentralised biosolids processing systems at a regional level)

Identifying and engaging the intended users of the results early in the objective definition stage is also recommended to ensure that the study addresses their needs and supports relevant, actionable decisions.

- **Functional unit definition**:

Most LCA studies adopted the mass of sewage sludge treated as the functional unit

- Clearly state whether FU is based on dry mass, wet mass, volume, or other metrics. **A dry mass–based FU (e.g., per tonne dry solids of thickened sludge treated**) is preferred, as it is most commonly used and enables straightforward comparisons across studies.
- A biosolids-based functional unit (e.g., per dry tonne of biosolids produced) should be applied with caution. Especially for design-level comparative assessments, the varying degree of mass reduction during biosolids processing between different systems should be considered.
- Provide detailed information about the reference flow (e.g., input sludge characteristics, moisture content, volatile solids, nutrient and heavy metal content) and system description to enable meaningful comparison and interpretation.

Impact coverage

Selecting appropriate impact categories is essential to comprehensively capture the environmental consequences of the assessed system and to avoid burden shifting between different categories. The choice of impact coverage should align with the study's objectives and stakeholder concerns. Based on previous LCA studies, the following impact categories are generally relevant and environmentally significant for biosolids processing systems; however, these recommendations should be adapted to the specific context and goals of each LCA.

- **Core impact categories for biosolids LCA**
    - GWP: Biosolids processing systems contribute to direct and indirect greenhouse gas emissions (as well as offsets), and GWP is the most commonly adopted impact category, closely aligning with public concern and regulatory focus.
    - Human Toxicity and Ecotoxicity: Heavy metals and persistent pollutants in biosolids pose risks to human health and ecosystems.
    - Eutrophication Potential: Nutrient emissions (particularly nitrogen and phosphorus) from biosolids processing and end-use can potentially contribute to nutrient enrichment and ecosystem disruption
    - Acidification Potential: Emissions of substances like ammonia and nitrogen oxides can lead to soil and water acidification

- **Expanded impact categories for comprehensive assessment**
    - Resource depletion: the use of non-renewable energy and materials, including fossil fuels and minerals, should be assessed to understand the resource footprint of biosolids treatment pathways.
    - Land use and land use change: consider the occupation and transformation of land, especially relevant for treatment facilities in urban areas.
    - Photochemical Ozone Formation (Smog Potential): Volatile organic compounds (VOCs) and nitrogen oxides emitted during treatment processes can contribute to ground-level ozone formation, impacting air quality and human health.

System boundary definition

The primary aim of system boundary definition is to include all relevant environmental flows in the analysis to accurately capture the full range of potential impacts and benefits associated with the system, thereby avoiding burden shifting between life cycle stages. The review and meta-analysis of past LCAs have shown that variations in system boundary definition are a major source of differences between studies and significantly influence the results. The following section presents standardised recommendations for boundary definition and documentation.

- **LCI framework modelling**:

Attributional modelling is recommended over consequential modelling for biosolids LCAs. Attributional LCA offers a clear representation of the current environmental impacts and resource flows associated with biosolids processing systems, which is essential for evaluating operational performance and benchmarking within water utilities. Biosolids systems involve complex, site-specific processes, such as sludge characteristics, treatment configurations, and land application practices, that are difficult to capture accurately in consequential models due to their focus on market-driven changes and indirect effects. Additionally, data availability for biosolids processes is often limited, making the broader assumptions required for consequential modelling less reliable.

- **Process-level boundaries**:

Process-level boundaries should be clearly defined and documented for each unit process within the treatment train.

- A mass balance should be established for each unit process covering key elements and materials (mass balances for nitrogen, phosphorus, carbon, total solids and water should be included), with potential losses accounted for through relevant environmental flows.
- All relevant environmental flows should be included, such as energy consumption (electricity, heat), chemical use, emissions to air, water, and soil, materials requiring subsequent management (e.g., reject water), and avoided products. **A recommended system boundary definition is provided and should be adopted as appropriate based on data availability (Appendix-D)**.
- The process-level boundary should align with the selected impact categories, ensuring that all necessary process flows are included to adequately support the impact assessment of the relevant categories.

- **Plant-level boundaries**:
    - All processing stages involved in biosolids treatment should be included within the plant-level boundary. This typically encompasses thickening, main stabilisation, dewatering, transportation, short- or long-term storage, and beneficial reuse.
    - Construction and demolition stages may be excluded depending on the study's objective, as they typically contribute a small portion of the overall impact compared to the operational phase. However, when impact categories such as resource depletion are considered, where capital goods can represent a significant share of the impact, these stages should be included.
    - Transportation impacts should be included with transportation distances, modes, and materials transported clearly documented.
- **Industry-level boundaries**:
    - Background data source should be clearly documented, including background database used, specific process within the database or from literature adopted, and boundary condition of the adopted background process.
    - Waste generation, including reject water and odorants, should be documented, and their subsequent treatment should be included up to the final discharge stage (e.g., treated effluent release and filtered odorant emissions).
    - For co-benefits accounting, refer to the next section
- **Exclusion of processes and environmental flows**:

Depending on the study objective and facility-specific context, certain processing stages or environmental flows may be excluded. For example, in a design-level study comparing two systems, processing stages common to both can be omitted from the analysis. However, any exclusions from the recommended system boundary must be clearly documented and justified.

- **System boundary documentation**:

All three levels of system boundaries should be documented to ensure a transparent understanding of the boundary conditions. The use of semi-schematic diagrams illustrating the processing stages and environmental flows is recommended to support clear communication.

System expansion for co-benefits accounting

System expansion should be used to account for the secondary benefits of biosolids processing systems. Recommendations on the selection of substituted products, boundary definition for substitution are provided in the following section:

- **Energy recovery:**
    - Specify the alternative energy source being displaced (e.g., local grid electricity mix, coal, natural gas).
    - Clarify whether recovered electricity is used internally or exported to the grid; when used internally, substitution with 'market for' processes that account for transmission losses should be adopted.
    - When crediting heat recovery, provide details on the form of heat recovered, the transmission infrastructure, and the end-user; select background processes accordingly.
    - For scenario modelling involving future projections, anticipated changes in the electricity mix should be incorporated.

- **Fertiliser Substitution Benefits:**

Benefits from substituting mineral fertilisers should be calculated based on the following equation, with a few recommendations listed below:

$$BFS = (NC \times (k_{biosolids}/k_{mineral})) \times (impact_{production} + impact_{trans\&use}) \quad \text{Eq.1}$$

BFS: the environmental benefits from fertiliser substitution, *NC*: the nutrient content in biosolids [kg N, P, K/FU], $k_{biosolids}$: the nutrient availability factor for biosolids or biosolids-based products, $k_{mineral}$: the nutrient availability factor for the substituted mineral fertiliser, [kg N, P, K/kg fertiliser], $impact_{product}$: the environmental impacts from the production of mineral fertilisers; $impact_{trans\&use}$: the environmental impacts from the transportation and use phase of mineral fertilisers.

  - The **plant-available fraction** of nutrients in biosolids should be considered when accounting for fertiliser benefits. Estimation methods for available nitrogen from biosolids end-use guidelines across various states and territories can be applied. For phosphorus availability, the PLCI model developed by ten Hoeve et al. (2018) provides a useful reference. Alternatively, average values from the literature inventory database may be used. Performing sensitivity analyses based on the range reported in the literature is also recommended.
  - The **type of fertiliser substituted** should correspond to the agricultural practices of the application area. If unknown, urea, ammonium phosphates, and single superphosphate can be used as default choices, following Alvarez-Gaitan et al. (2016).
  - The substitution should consider the **full life cycle of mineral fertiliser** application. Fertiliser production and transportation impacts can be included using background processes from databases. Data on field emissions following mineral fertiliser application can be sourced from Yoshida et al. (2018) or other relevant studies.

- **Other co-benefits**

For accounting for other co-benefits (e.g., substitution of building materials), the following information should be clearly documented and justified:

  - **Alternative product**: Specify the type, properties, and geographical context of the alternative product assumed to be replaced.
  - **Replacement rate**: Define the equivalent quantity of the alternative product that can be substituted by the biosolids-based product.
  - **Additional processing stages:** Report any extra processing steps required to enable substitution, such as transportation or treatment of biosolids.
  - **Boundary conditions for substitution:** Clearly describe the system boundaries applied to the substituted product, ideally including its full life cycle.

Life cycle inventory analysis

The life cycle inventory analysis phase involves collecting data for all processes within the defined system boundaries, based on the established goal and scope of the study. The literature review has shown that many previous LCAs suffer from a lack of context-specific inventory data, insufficient inventory descriptions, inadequate documentation of assumptions, and limited data quality evaluation. The following recommendations outline best practices for comprehensive, context-relevant and transparent inventory compilation.

- **Data source selection:** Plant-specific operational data should always be used where possible to reflect site-specific conditions. Data collection efforts can be prioritised according to the provided inventory data list. (Appendix-D)
- **Metadata documentation**: Metadata for both primary and secondary data should be transparently reported. For primary data, this includes details such as the temporal scope (time period covered), geographical location, sample size, measurement techniques, and representativeness. For secondary data, the source origin, underlying assumptions, calculation methods, and any modifications applied should be clearly provided. A good practice can be found in Yoshida et al., (2018). Avoid "multi-layer citation," where data from studies relying on secondary sources are used without critical assessment.
- **Data quality assessment:** The pedigree matrix approach (consult the Ecoinvent database's data quality guidelines) should be adopted to evaluate collected data and identify critical aspects related to data sources.
- **Use consistent and reliable background data**: Recognised life cycle inventory databases (e.g., ecoinvent) should be prioritised as sources for background data. When these databases are used, detailed documentation should be provided on the specific processes selected. If background data is sourced from literature, documentation should describe the system boundaries and the geographical relevance of the data.
- **Biosolids LCI database**: A biosolids LCI database containing Australian-specific primary data is currently being developed and will soon be available to industry partners. Its use as a reference database and benchmarking tool is highly recommended.
- **LCI presentation**: All collected inventory data should be reported per functional unit at the unit process level to enable reproducibility of the results. When a mass-based functional unit is used, mass reductions at each processing stage should also be documented.

Life cycle impact assessment

The life cycle impact assessment (LCIA) stage involves the translation of the collected inventory data into selected impact categories. A few recommendations on methodological choices for the LCIA phase are listed below:

- Various LCIA methodologies are available within existing commercial LCA software. The selection of an appropriate LCIA method should consider its relevance to the assessed system and local context. The Australian Life Cycle Assessment Society (ALCAS) has published a **Best Practice Guide for Life Cycle Impact Assessment in Australia**, which identifies preferred LCIA methods for different impact categories, considering the Australian context. Consultation of this guide is recommended when selecting the most suitable LCIA method.
- **Midpoint indicators** should generally be prioritised over endpoint indicators, as they provide more detailed and transparent information at the impact category level. When endpoint indicators are used, they should be presented alongside midpoint indicators and aligned with the assessment's objectives (useful information for risk assessment, stakeholder communication).
- Despite ongoing scientific debate, organic carbon in biosolids should be considered **biogenic carbon**. If there is a significant industrial input in the influent, a sensitivity analysis is recommended. Related biogenic CO2 emissions are regarded as climate-neutral.

Conversely, carbon sequestration in soil following land application of biosolids or biosolids-derived products (typically assessed over a 100-year timeframe) should be credited for consistency when accounting for biogenic carbon.

- **Methodological challenges** remain in fully capturing the potential impacts of biosolids systems through LCIA. Certain contaminants associated with biosolids, such as pathogens, odours, microplastics, and PFAS, are not adequately addressed by current LCIA methods. For studies comparing thermal technologies, which can destroy PFAS, with conventional treatments, a discussion should be included on the limitations of LCA and the additional benefits of thermal technologies in PFAS removal.

Results interpretation

The results interpretation phase is critical for translating LCA results into actionable insights, especially given the complexity of biosolids systems. Overall, the interpretation of the results should be conducted in accordance with the objective defined and take into account the intended audiences.

- **Results presentation**: Results should be presented in a way that enables reproducibility, such as providing breakdowns at a unit process or environmental flow level. Good practices can be found in Zhou et al. (2022).
- **Contribution analysis and hotspot identification**: Especially important and should be conducted for technology-level objectives, this analysis should identify key sources of environmental impacts and discuss potential improvement strategies.
- **Uncertainty analysis**: Monte Carlo simulations should be used to assess parameter uncertainty, particularly for comparative studies with design-level objectives that inform decision-making. Transparent reporting of uncertainty is essential to avoid overinterpretation of precise values. Specific guidance on uncertainty methods is available from Alyaseri et al. (2019), and uncertainty data can also be sourced from the biosolids life cycle inventory tool.
- **Sensitivity analysis**: A sensitivity analysis should be performed on critical assumptions such as nutrient availability, key emission factors, and contaminant content. For technology-level studies, global sensitivity analysis is recommended to enhance system understanding. Good examples include Gourdet et al. (2017) and Chang et al. (2023). Literature ranges for biosolids inventory data are available from the biosolids inventory tool.
- **Discussion on limitations**: Discussion should be provided on the limitations from areas such as system boundaries choices, data gaps and data quality issues, particularly where primary data are scarce or literature values have wide variability.