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REVIEW

# Consequential life cycle assessment of European livestock systems: current practices, limitations, and priorities

**Dengsheng Sun[1] · Marie Trydeman Knudsen[2] · Thomas Ponsioen[3] · Ricardo Teixeira[4] · Alina Chervinska[4] · Mariana Raposo[4] · Rahela Lucić[4] · Mali Gravell[5] · Nicholas Davison[5] · Lewis Cameron[5] · Sally Westaway[5] · Aurélie Wilfart[6] · Pietro Goglio[7] · Yue Wang[8] · Fatemeh Hashemi[2] · Vasco Diogo[9] · Bo P. Weidema[10] · Laurence G. Smith[1,5]**

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**Abstract**

A systems-level understanding of livestock production and its environmental consequences is essential for informing sustainability transitions and evidence-based policy in Europe. While life cycle assessment (LCA) is widely applied in this context, the use of consequential LCA (CLCA), which aims to capture market-mediated and structural system responses, remains comparatively limited. This study provides a critical synthesis of CLCA applications in European livestock systems through a PRISMA-guided systematic literature review complemented by an expert workshop. Twenty-three studies met the inclusion criteria, spanning multiple livestock groups, regions, and modelling approaches. Scenario development was dominated by technical or management-oriented adjustments, with limited use of optimisation-based, narrative, or policy-driven frameworks capable of exploring transformative system changes. Inventory construction typically relied on Ecoinvent, supplemented where necessary by experimental datasets, expert elicitation, survey data, or outputs from economic models. Most studies focused on midpoint indicators, and although uncertainty analysis was commonly included, its implementation was inconsistent across studies. Overall, most of the reviewed CLCA applications remain focused on incremental improvements within existing systems, limiting their ability to assess the consequences of more profound system transitions. Key limitations include both methodological challenges (particularly in scenario formulation and the representation of system-wide responses) and data gaps, notably the limited availability of regionally specific inventory data for marginal processes and endpoint characterisation factors. We recommend that future CLCAs adopt more structured and forward-looking scenario development approaches, strengthen inventory construction through updated and localised datasets, and consider the incorporation of both midpoint and endpoint indicators, while clearly acknowledging the limitations of both approaches. In addition, the systematic application of sensitivity and scenario-based uncertainty analysis is essential for assessing robustness. Addressing these practical and methodological dimensions will enhance the contribution of CLCA to analysing sustainability transitions of European livestock systems.

## Highlights

- Review analyses CLCA methods for environmental assessment of livestock systems.
- Studies focus on incremental changes, not transformative livestock pathways.
- Scenario development is narrow; broader scope is needed for future CLCA work.
- Regionalised inventory data are lacking, especially for marginal by-products.
- Findings support improved CLCA methods for sustainable livestock transitions.

Extended author information available on the last page of the article

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**Keywords** Consequential life cycle assessment · Livestock systems · Marginal suppliers · Scenario development · Inventory modelling · Sustainability transitions

## 1 Introduction

A systems-level understanding of livestock production and its environmental impacts is essential for supporting sustainability transitions in Europe's food system. Recent European policy strategies emphasise that achieving long-term resilience in the agricultural sector requires analytical tools capable of evaluating the consequences of technological, behavioural, and structural changes across food systems (European Commission, 2025). In this context, Life Cycle Assessment (LCA) provides a well-established framework for quantifying environmental burdens across entire production life cycles (ISO, 2006a, 2006b). In the livestock sector, complementary guidance documents such as the FAO Livestock Environmental Assessment and Performance (LEAP) guidelines further support consistent assessments of production systems and supply chains (FAO, 2014).

However, the extent to which LCA can inform sustainability transitions depends on the methodological approach adopted. Two main LCA approaches are commonly distinguished: attributional LCA (ALCA) and consequential LCA (CLCA). Attributional LCA estimates the environmental burdens associated with a product system as it is defined, without explicitly modelling market-mediated responses to changes in demand or supply. In contrast, CLCA aims to estimate the environmental consequences of decisions by identifying affected activities, marginal suppliers, substitution effects, and broader system responses, thereby accounting for indirect and market-mediated effects (Goglio et al., 2020; UNEP-SETAC, 2011).

Despite the growing policy relevance of forward-looking assessments such as CLCA, ALCA remains the dominant approach in LCA studies of livestock systems (Berton et al., 2025). While ALCA can be informative for tracing or tracking developments over time for existing production systems, it does not explicitly aim to represent market-mediated responses and indirect consequences in the way CLCA does. Consequential LCA addresses these limitations by modelling how changes (such as adjustments in herd size, feed composition, or production practices) affect upstream and downstream activities, including feed markets, land use, and by-product displacement (Salou et al., 2019). As with any decision-oriented modelling approach, CLCA relies on assumptions that influence the results. The relevance of these assumptions depends on the clarity of the research question and the consistency of scenario formulation (Anex & Lifset, 2014; Dale & Kim, 2014; Weidema, 2009).

Several reviews have examined LCA applications in specific livestock sectors, such as cattle (Baker & Axon, 2025; Baldini et al., 2017; Berton et al., 2025; Cruz-Rivero et al., 2025) or pigs (Gislason et al., 2023), as well as thematic applications such as the use of food waste as feed (Goldáraz-Salamero et al., 2025). However, a synthesis specifically examining how CLCA is applied to livestock systems is currently lacking. In particular, there is limited consolidation of how scenario development choices, identification of affected activities (including co-products and by-products), selection of impact categories, and uncertainty treatment are handled in practice. This gap is notable given that CLCA remains an evolving methodological framework, with ongoing debates regarding best practice and implementation.

In this review, we address this gap by evaluating the application of CLCA methods used in environmental assessments of European livestock systems. The objectives are to: (1) characterise the current status and thematic focus of livestock-focused CLCA studies in Europe; (2) examine approaches to scenario development; (3) analyse how studies identify and handle affected activities, including by-products and substitutes; (4) assess the selection of environmental impact categories and modelling methods and how results are communicated; and (5) evaluate approaches to uncertainty analysis. By synthesising current practices and areas of divergence, this review provides a structured overview of CLCA applications in European livestock systems and identifies opportunities for improving the robustness, transparency, and policy relevance of consequential modelling.

## 2 Methods

### 2.1 Search strategy for the literature review

The literature search and data extraction followed the PRISMA 2020 framework (Page et al., 2021). A PRISMA screening and selection process, including inclusion criteria and the number of records retained at each stage, is provided in the Supplementary Information SI1.

Searches were performed in Web of Science and Scopus using a predefined combination of terms (Level 1 AND Level 2 AND Level 3; Supplementary Information SI1 Sect. 1). Level 1 terms reflected the geographical scope (e.g., Europe, EU), Level 2 terms referred to livestock systems (e.g., livestock, cattle), Level 3 terms captured the methods (e.g., CLCA). Within each level, terms were combined using the OR operator. The number of retrieved records from each database was documented. Automated tools were used to filter records by publication year where possible, and all references were compiled in Excel for duplicate removal and counting.

A first screening of titles and abstracts excluded studies that did not meet the following criteria: (a) publication date between January 2012 and December 2024; (b) English language; (c) peer-reviewed journal article; (d) focused on the EU or European context; (e) addressed at least one of the major European livestock groups (cattle, pigs, sheep, goats, poultry); and (f) applied LCA. The review was limited to studies published from 2012 onwards. This cut-off was selected to capture more recent developments in CLCA practice, including increased availability of consequential modelling approaches and databases, as well as growing application of CLCA in policy-relevant assessments. Studies published after the December 2024 search cut-off were not considered for inclusion in the systematic review but were cited, where appropriate, to provide background information, contextualise the findings, or discuss recent methodological developments. Reasons for exclusion were recorded. Borderline cases were retained for a full-text review. Because it is often not possible to reliably distinguish between attributional and consequential approaches based solely on titles and abstracts, studies applying any form of LCA were retained at this stage to minimise premature exclusion.

In the second screening round, full-text articles were assessed against the same criteria. Studies were classified as CLCA when they explicitly described the assessment as consequential LCA or applied one or more recognised consequential modelling principles. These principles included system expansion, substitution modelling, identification of marginal suppliers or products, or modelling of market-mediated consequences associated with changes in demand or production systems. Studies relying exclusively on attributional allocation without applying these consequential modelling principles were excluded. In cases where studies combined attributional and consequential elements, inclusion required that consequential modelling formed an integral part of the assessment and contributed directly to addressing the study objectives. Any uncertainties were discussed with a second reviewer and, in complex cases, resolved through group discussion. Eligible studies were subsequently grouped by (a) type of LCA modelling, (b) livestock group or system, and (c) environmental impact categories assessed.

To ensure comprehensive coverage of the relevant literature, the inclusion criteria were broadened to also consider studies assessing only part of the livestock production cycle, such as those focusing on the utilisation of livestock waste or by-products. This allowed inclusion of studies analysing consequential system elements that may not be captured in full life cycle assessments. In total, 23 studies met the inclusion criteria.

Data extraction followed PRISMA procedures (Supplementary Information SI1 Sect. 2). Two investigators independently extracted data using a predefined coding framework, and discrepancies were resolved through discussion. Extracted data were compiled in Excel and synthesised narratively in relation to the review questions.

## 2.2 Protocol for the expert group workshop

An expert workshop was held on 6 October 2025 with 15 participants (12 experts and 3 facilitators) to gather perspectives on methodological challenges and priorities in applying CLCA to livestock systems and to complement the insights from the literature review. Experts were identified and approached individually based on their recognised expertise in LCA and/or livestock production. Experts were purposively selected to include researchers and practitioners with experience in agricultural LCA, consequential modelling, livestock systems, and agri-food sustainability assessment, including participants from academia, research organisations, and consultancy practices. For this study, an expert was defined as an individual who (a) conducts LCA research in an academic or research organisation with demonstrated experience in agricultural, food, or livestock systems, or (b) works in an LCA consultancy with relevant experience in agri-food or livestock applications. Approximately 20 experts were contacted, of whom 12 participated in the workshop. The workshop was designed to capture methodological perspectives from participants with direct experience relevant to the study objectives, rather than to provide statistically representative stakeholder coverage. Prior to the workshop, participants received a protocol summarising key results from the literature search (Supplementary Information SI1 Sect. 3) and an informed consent form (Supplementary Information SI1 Sect. 4).

The three-hour workshop began with individual reflections on recent advances and challenges in CLCA. Participants were divided into three focus groups and guided through discussions on: (1) key research and methodological needs for CLCA of livestock systems, and (2) appropriate approaches for scenario development in CLCA. The session concluded with a plenary discussion to consolidate feedback and allow for broader exchange among participants.

During the breakout-group discussions, participants recorded their key ideas and recommendations as digital sticky notes using the Mural online collaboration platform, while facilitators also took detailed notes throughout both the breakout sessions and the plenary discussion. Following the workshop, the Mural outputs and facilitator notes were collated and reviewed by the authors to identify recurring themes relevant to the objectives of this study. Similar comments and recommendations were grouped into common methodological topics, including the application of CLCA to livestock systems, methodological development needs, future research priorities, and scenario development. The findings presented in Sect. 3.2 summarise the main themes identified across the workshop discussions and are intended to complement, rather than quantify or rank, the evidence identified through the systematic literature review.

# 3 Results

## 3.1 Literature review

Detailed study-level information extracted from the literature, including scenario development approaches, inventory data sources and methods, level of impact categories (midpoint or endpoint), and uncertainty analysis methods, is provided in Supplementary Information SI1 Sect. 5. The results presented in Sects. 3.1.1–3.1.4 synthesise patterns emerging from this table rather than reproducing study-specific details.

The included studies (n = 23) covered four major livestock groups: cattle (dairy and beef), pigs, poultry, and sheep, and spanned a range of European countries, particularly those with intensive livestock production such as Belgium, Denmark, France, Germany, Italy, the Netherlands, Spain, and the UK (Supplementary Information SI1 Sect. 5).

To summarise the thematic focus of the reviewed studies, we coded each article by topic based on the primary intervention or analytical focus (Table 1; Supplementary Information SI1 Sect. 5). Most studies addressed manure treatment and handling or alternative feeding strategies, reflecting interventions targeted at specific sub-systems within prevailing livestock production models. A smaller set of studies examined improving the existing system, defined here as farm- or supply-chain changes that modify the current system configuration without shifting to a fundamentally different production model (e.g., changing bedding materials, integrating on-farm biogas, or replacing fossil energy inputs). In contrast, studies coded as testing a new system analysed more structural reconfigurations, such as alternative land use or farm conversion pathways. A further subset focused on policy changes, where scenarios were explicitly defined by anticipated policy instruments. Finally, a small number of studies were coded as "Other"; these included analyses centred on human dietary change or methodological comparisons of LCA approaches.

### 3.1.1 Approaches to scenario development

To synthesise how scenarios are developed in existing CLCA studies, we inductively derived a set of scenario development approaches based on the rationales and assumptions reported in the reviewed literature. The resulting categories and their defining characteristics (Table 2) reflect a descriptive classification of current practice, rather than a prescriptive methodological framework. For example, we categorised the scenarios in Kimming et al. (2015) as "management-based", because the biogas and rapeseed oil systems were introduced to modify farm-level management strategies. Others might classify this study as "technical-based", depending on whether their emphasis lies on the introduction of biogas or Rape Methyl Ester (RME) technologies. Our intention is not to impose rigid categories, but rather to offer a simple framework that encourages LCA practitioners to explore more future-oriented approaches.

Based on the rationales observed in the reviewed studies, a total of six scenario development approaches were identified (Table 2). These categories reflect differences in how change is conceptualised, ranging from modification of specific technical processes, through farm-level decision changes, to broader system reconfiguration driven by policy or optimisation objectives.

**Table 1** Topics covered by studies applying consequential life cycle assessment for European livestock systems

| No | Topic | Number of studies | References |
|---|---|---|---|
| 1 | Manure treatment and handling | 9 | ten Hoeve et al., (2014); Styles et al., (2016); Willeghems et al., (2016); Lijó et al., (2018); Beyers et al., (2022); Styles et al., (2022); Beyers et al., (2023a); Mediboyina & Murphy, (2024); Santolin et al., (2024) |
| 2 | Alternative feeding strategy | 5 | Karlsson et al., (2015); Negro et al., (2017); Salemdeeb et al., (2017); van Zanten et al., (2018); Beyers et al., (2023b) |
| 3 | Improving the existing system | 3 | Kimming et al., (2015); van Stappen et al., (2016); Yesufu et al., (2020) |
| 4 | Policy change | 2 | Styles et al., 2018; Salou et al., (2019) |
| 5 | Testing a new system | 2 | Nguyen et al., (2013); Sharma et al., (2018) |
| 6 | Other | 2 | Dalgaard et al., (2014); Costa et al., (2023) |

*Topics refer to the primary intervention focus (Supplementary Information SI1* Sect. 5*) and are distinct from the scenario development approaches presented in* Tables 2 and 3

**Table 2** Definitions and characteristics of the scenario development approaches identified in the reviewed literature

| Approach | Definition | Key characteristics | References |
|---|---|---|---|
| Technical-based | Scenarios are developed based on the technical characteristics and performance parameters of specific technologies or production systems | (1) Parameter changes in technologies or processes<br>(2) Technology-specific assumptions (e.g., efficiencies, yields, emission factors)<br>(3) Context-specific applications (e.g., regional conditions, marginal suppliers)<br>(4) Focus on individual technologies or interventions | ten Hoeve et al., (2014); Styles et al., (2016); Salemdeeb et al., (2017); Negro et al., (2017); Lijó et al., (2018); Beyers et al., (2023a); Beyers et al., (2023b); Mediboyina & Murphy, (2024); Santolin et al., (2024) |
| Management-based | Scenarios are developed by modifying farm-level management practices or operational decisions within an existing production system | (1) Changes in farm-level management practices<br>(2) Focus on operational decision-making<br>(3) Production system structure unchanged<br>(4) Incremental or practice-oriented modifications | Karlsson et al., (2015); Kimming et al., (2015; van Stappen et al., (2016); van Zanten et al., (2018) |
| Factorial | Scenarios are developed using comprehensive storylines that combine multiple, interacting changes across the production system | (1) Internally consistent system-level storylines<br>(2) Simultaneous changes in land use, management, and inputs/outputs<br>(3) Beyond farm-level decision scope<br>(4) Captures interactions between system components | Nguyen et al., (2013); Dalgaard et al., (2014); Sharma et al., (2018); Styles et al., (2022); Costa et al., (2023) |
| Policy-based | Scenarios are developed based on anticipated or hypothetical policy instruments and associated targets | (1) Policy-driven assumptions (e.g., regulations, subsidies, targets)<br>(2) Explicit link to governance or policy objectives<br>(3) Assessment of environmental consequences of policy measures<br>(4) May induce structural or behavioural change | Styles et al., (2018); Salou et al., (2019) |
| Optimisation | Scenarios are generated through optimisation models that identify system configurations meeting predefined objectives or constraints | (1) Use of optimisation models<br>(2) Explicit objective functions (e.g., cost, emissions)<br>(3) Defined system constraints<br>(4) Identifies optimal configurations rather than predefined scenarios | Willeghems et al., (2016) |
| Combined | Scenarios are developed by integrating two or more scenario development approaches within a single study | (1) Integration of multiple scenario approaches<br>(2) Supports multi-dimensional scenario design<br>(3) Links technological detail with system-level dynamics<br>(4) Reflects methodological hybridity | Yesufu et al., (2020); Beyers et al., (2022) |

*References correspond to representative studies in which each approach was applied*

Technical-based approaches were the most commonly used. These approaches focus on changes to specific technologies or processes, with assumptions tailored to the geographical context and the technical characteristics of the system under evaluation. Typical applications include manure and waste management technologies, such as slurry treatment (Beyers et al., 2023a; ten Hoeve et al., 2014), and biogas production for combined heat and power generation (Lijó et al., 2018; Mediboyina & Murphy, 2024; Styles et al., 2016). Technical-based approaches were also applied to feeding strategies when modelled primarily as changes in feed ingredients or processing technologies (Beyers et al., 2023b; Negro et al., 2017). Additional examples are detailed in Supplementary Information SI1 Sect. 5.

Management-based approaches were also frequently applied. These approaches represent changes in farm-level decision-making and management practices, such as adjustments in feeding regimes, manure handling strategies, or on-farm energy use, while keeping the overall production system structure largely unchanged. Examples include alternative feeding strategies (Karlsson et al., 2015; van Zanten et al., 2018) and system improvements such as the integration of on-farm biogas plants (Kimming et al., 2015; van Stappen et al., 2016). Further examples are provided in Supplementary Information SI1 Sect. 5.

Factorial approaches typically involve coordinated changes across multiple system components and often extend beyond the farm level. These approaches are characterised by internally consistent storylines in which land use, production orientation, inputs, and outputs change simultaneously. Sharma et al. (2018) explored alternative uses of poorly drained farmland across livestock production, while Nguyen et al. (2013) examined farm conversion scenarios driven by increased consumer demand for grass-based milk, resulting in substantial shifts in land use, management practices, and input–output balances.

Less commonly applied approaches included policy-based approaches, where scenarios are driven by anticipated policy interventions (Salou et al., 2019; Styles et al., 2018), and optimisation approaches, where scenarios were generated using formal optimisation models (Willeghems et al., 2016).

Finally, some studies combined multiple approaches, such as Beyers et al. (2022), who integrated technical and factorial elements to evaluate slurry acidification in high-density pig-producing regions (Denmark, Limburg, Catalonia). These regions were selected based on their importance to European pork production and trade, the presence of commercially available slurry acidification technologies, and the urgency of emission reductions. See Supplementary Information SI1 Sect. 5 for complete details of all studies.

The relationship between study topics and scenario development approaches is summarised in Table 3, providing an overview of how different research topics have been investigated using different scenario development approaches. Studies focusing on manure treatment and handling were predominantly associated with technical-based approaches, whereas alternative feeding strategies were mainly investigated using technical- or management-based approaches. In contrast, studies addressing broader system changes, such as policy interventions or new production systems, were more commonly associated with factorial, policy-based, or optimisation approaches. Nevertheless, the same study topic could be examined using different scenario development approaches depending on the decision context, system boundaries, and modelling objectives.

However, the choice of approach was not determined by topic alone. Similar topics could be analysed using different approaches depending on the scale of intervention, system boundaries, and intended decision context. Overall, technical-based and management-based approaches were primarily associated with incremental changes within existing systems, whereas factorial, policy, and optimisation

**Table 3** Relationship between study topics and scenario development approaches in the reviewed CLCA studies

| Topic | Approach | | | | | | |
|---|---|---|---|---|---|---|---|
| | Technical-based | Management-based | Factorial | Policy-based | Optimisation | Combined | Total |
| Manure treatment and handling | 6 | | 1 | | 1 | 1 | 9 |
| Alternative feeding strategy | 3 | 2 | | | | | 5 |
| Improving the existing system | | 2 | | | | 1 | 3 |
| Policy change | | | | 2 | | | 2 |
| Testing a new system | | | 2 | | | | 2 |
| Other | | | 2 | | | | 2 |
| Total | 9 | 4 | 5 | 2 | 1 | 2 | 23 |

*Values indicate the number of reviewed studies classified within each combination of study topic and scenario development approach. Each study was assigned to one primary topic and one predominant scenario development approach* approaches were more commonly applied to broader system-level transformations.

#### 3.1.2 Approaches for inventory construction

In CLCA, inventory construction is closely linked to the modelling of system responses to change, which represents a key distinction from ALCA. Rather than describing average production systems, CLCA requires the identification of marginal suppliers and the representation of substitution mechanisms that occur in response to changes in demand. This often involves modelling market-mediated effects and system-wide adjustments, which may be addressed using simplified assumptions, partial equilibrium models, or hybrid approaches combining process-based data with economic modelling. Modelling broader system responses often requires substantial data and analytical effort, which may partly explain why many reviewed studies focused on relatively localised technical or management interventions rather than large-scale system transformations.

The reviewed studies used diverse strategies to construct consequential inventories, particularly for identifying affected activities and handling co-products within expanded system boundaries (see Supplementary Information SI1 Sect. 6 for key concepts in CLCA). Most studies relied on a combination of data sources, including LCI databases, expert-based estimates, experimental results, survey data, and outputs from modelling exercises.

Ecoinvent was the most frequently used database and served as the primary source for identifying marginal products or suppliers (Supplementary Information SI1 Sect. 5). Depending on the geographical scope of the study, other data sources were also used, including global and EU-level databases (Dalgaard et al., 2014), as well as national or regional sources (Dalgaard et al., 2014; Styles et al., 2018; Willeghems et al., 2016).

When database information was unavailable or insufficiently representative of local conditions, additional data sources were used, such as expert judgement, experimental datasets, or first-hand surveys. Modelling approaches also played an important role in generating inventory data for CLCA. For example, Costa et al. (2023) used an economic farm-emission model to optimise farm management decisions, while Salou et al. (2019) used the MATSIM-LUCA economic model to simulate agricultural market conditions in 2030 under different policy scenarios, with model outputs informing the construction of consequential inventories. See Supplementary Information SI1 Sect. 5 for complete details.

#### 3.1.3 Selection of impact categories

In the reviewed studies, the selection of environmental impact categories was closely linked to the study goal and scope and thus formed part of the Life Cycle Impact Assessment (LCIA) scoping stage, rather than a purely technical step following inventory construction (Fig. 1). Most studies applied midpoint-level LCIA methods (Supplementary Information SI1 Sect. 5), drawing on established frameworks such as IPCC (2006, 2007), ReCiPe (Huijbregts et al., 2017), CML 2001, and ILCD (European Commission, 2010).

At the midpoint level (Fig. 1), global warming potential was by far the most frequently assessed impact category, followed by acidification and land use. Twelve studies included at least one eutrophication indicator (terrestrial, freshwater, or marine), while resource use, energy use and resource depletion were also commonly considered. A recurring core set of indicators emerged across topics: climate change, acidification, at least one form of eutrophication, land use, and resource or energy use.

The choice of impact categories reflects both methodological conventions in agricultural LCA and dominant environmental pressures associated with livestock production systems. For example, eutrophication-related indicators were more frequently included in studies focusing on monogastric systems and manure-intensive regions, whereas land use and climate-related indicators dominated assessments of ruminant systems. This variation highlights the importance of aligning impact category selection with the production system, geographical context, and decision question addressed.

A smaller subset of studies extended the analysis beyond midpoint indicators by including endpoint-level impact categories (Table 4). Six studies combined midpoint and endpoint indicators, while one study relied exclusively on endpoint assessments. Endpoint indicators were most often related to human health, with fewer studies addressing ecosystem damage or resource scarcity at the endpoint level. The relatively limited use of endpoint indicators reflects both methodological caution and the comparatively lower methodological maturity, greater uncertainty, and more limited regional specificity of endpoint characterisation factors compared with midpoint characterisation factors. At the same time, this pattern suggests an opportunity to broaden the interpretation of CLCA results where decision contexts require more aggregated or damage-oriented environmental information.

#### 3.1.4 Uncertainty analysis

Uncertainty analysis quantifies how uncertainties in model inputs influence the results. In LCA, the explicit characterisation of uncertainty enables statistical comparison of scenarios and supports more robust interpretation of results. Conceptually, uncertainty in LCA is often described using a tiered framework, distinguishing between Tier 1 (screening-level), Tier 2 (probabilistic), and Tier 3 (advanced or detailed) approaches (Bamber et al., 2020).

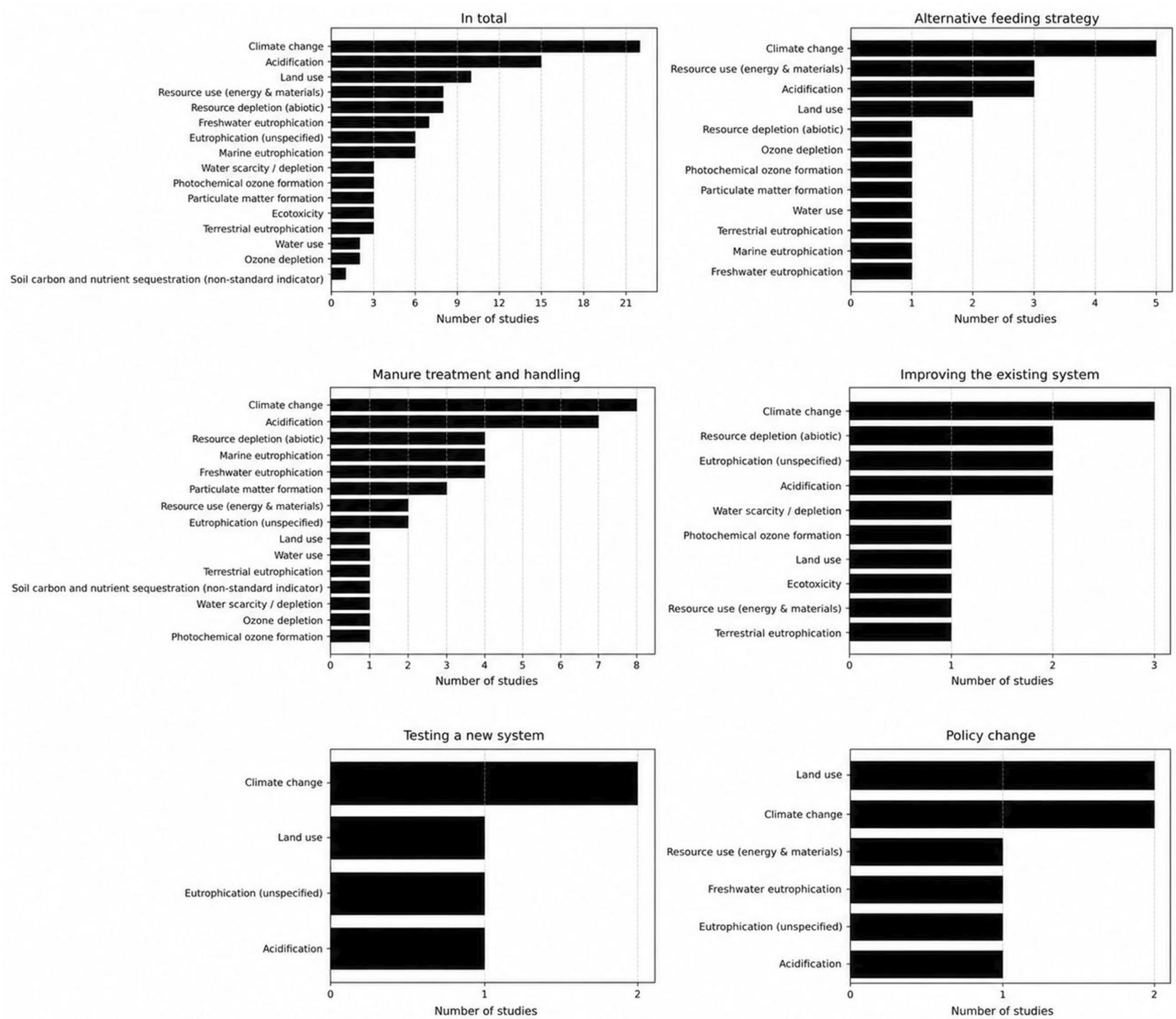


**Fig. 1** Inclusion of impact categories at the midpoint level across the range of identified topics. The data for Fig. 1 can be found in Supplementary Information SI1 Sect. 7

**Table 4** Studies that conducted LCIA at the endpoint level

| No | Reference | Impact categories covered | | |
|---|---|---|---|---|
| | | Human health | Ecosystems | Resource depletion |
| 1 | Santolin et al. (2024) | x | x | x |
| 2 | Beyers et al. (2023a) | x | | |
| 3 | Beyers et al. (2022) | x | | |
| 4 | Salou et al. (2019) | | x | |
| 5 | Salemdeeb et al. (2017) | x | | |
| 6 | Negro et al. (2017) | x | x | |
| 7 | van Stappen et al. (2016) | x | | |

Across the reviewed studies, uncertainty analysis was reported in 18 cases and was implemented almost exclusively using Tier 2 and Tier 3 approaches; no studies relying solely on Tier 1 screening-level uncertainty analysis were identified.

Monte Carlo simulation, a widely applied Tier 2 method, was used to assess parameter uncertainty through random sampling of input distributions (e.g., Santolin et al., 2024). In some cases, Monte Carlo methods were combined with more advanced analysis and thus formed part of Tier 3 approaches (Negro et al., 2017). Other approaches to uncertainty propagation were also observed, including aggregate uncertainty ranges with and without highly uncertain indirect land use change burdens (Styles et al., 2016). See Supplementary Information SI1 Sect. 5 for complete details.

Sensitivity analysis was the most frequently applied Tier 3 approach and focused on identifying influential input parameters. Examples include testing alternative marginal technologies, feed or energy substitution options, or alternative background processes (Beyers et al., 2023a, 2023b; Karlsson et al., 2015; Negro et al., 2017). The magnitude of parameter variation depended on context; Sharma et al. (2018) applied ± 10% changes, while ten Hoeve et al. (2014) used minimum and maximum values reported in the literature.

In addition, several studies applied scenario analysis (i.e., multi-parameter uncertainty analysis), in which combinations of uncertain assumptions were explored simultaneously (Lijó et al., 2018; Styles et al., 2016; van Zanten et al., 2018). For example, Yesufu et al. (2020) generated 34 combinations of feed substitution pathways, electricity sources, fertilisation rates, crop yields, and displaced pasture. Although referred to as sensitivity analysis by the authors, this approach corresponds to a multi-parameter uncertainty analysis rather than single-parameter sensitivity testing.

## 3.2 Focus group workshop

The expert workshop was conducted to complement the literature review by capturing practitioner perspectives on the application of CLCA to livestock systems. Discussions focused on two main topics: (1) key development needs for applying CLCA to livestock systems, and (2) approaches to scenario development in this context. The key perspectives identified through these discussions are outlined below.

### 3.2.1 CLCA in livestock systems: scope and applications

Workshop participants emphasised that CLCA is particularly suited to analysing the environmental consequences of decisions, including changes in production volume, technology adoption, or policy interventions. For livestock systems, this includes consequences that extend beyond the farm gate, such as changes in feed sources, land use, or upstream and downstream activities affected by demand shifts.

Several examples of market-mediated responses were discussed, including substitution between feed ingredients, displacement of crop production across regions, and cascading effects when displaced co-products affect secondary markets. Participants stressed that such effects are central to CLCA and require explicit modelling of affected activities, rather than simple attribution of existing production systems. Experts also noted that CLCA should be applied only when aligned with a clearly articulated research question and decision context. This requirement was not framed as a limitation of CLCA per se, but as a general prerequisite for any LCA study intended to inform decisions. Overall, participants identified the explicit representation of indirect and market-mediated effects as a principal feature distinguishing CLCA from ALCA in livestock system assessments.

### 3.2.2 Development needs for applying CLCA to livestock systems

Participants distinguished between development needs that are generic to CLCA and those that are particularly relevant for livestock systems. At a general level, CLCA involves uncertainty related to future constraints, market responses, and technological trajectories. Participants emphasised that uncertainty arises not from subjective choices, but from the inherent difficulty of predicting which activities are unconstrained and therefore affected under future conditions. This highlights the need for transparent documentation of assumptions and systematic exploration of uncertainty.

In the context of livestock systems, specific development needs include representation of feed markets, land use dynamics, and manure-related flows, as well as better integration of feedback mechanisms across production stages. Limited availability of primary data was discussed as a broader challenge for LCA rather than a CLCA-specific issue, but one that becomes particularly salient when modelling future-oriented livestock scenarios. Participants emphasised that many methodological challenges in livestock CLCA arise from representing system-wide responses and future market dynamics under substantial uncertainty.

### 3.2.3 Topics for future CLCA applications

Workshop participants identified several areas where further CLCA applications could support understanding of livestock system transitions. These include diverse livestock systems (e.g., organic and mixed crop–livestock systems), nutrient cycling and carbon dynamics, water footprints, social well-being, rebound effects, temporal dynamics, climate sensitivity, and stakeholder perspectives.

Participants also highlighted the importance of transparency, reproducibility and engagement with a broader range of stakeholders when defining scenarios and interpreting results. Integrating social dimensions and behavioural responses was seen as particularly relevant for understanding indirect effects, while economic modelling was considered valuable for representing market effects, provided that model structure and data granularity are consistent with CLCA requirements.

Collectively, these perspectives highlighted the importance of integrating environmental, economic, and social dimensions, together with stakeholder engagement, when defining and evaluating future CLCA applications.

#### 3.2.4 Scenario development practices

Participants observed that scenario development in CLCA currently lacks structure. A key recommendation was to clarify whether scenarios are intended to explore incremental adjustments within existing systems or more transformative decision contexts. A collaborative (co-design) approach to scenario development was recommended, starting from jointly defined narrative storylines and progressing towards quantitative representation of market responses, especially in demand-driven contexts relevant to CLCA.

Participants emphasised that, in line with CLCA principles and ISO 14044 (ISO, 2006b), all affected activities should be included, unless shown to be insignificant. Identification of affected activities, whether upstream or downstream, increased or displaced, was considered central to CLCA and should be treated consistently regardless of whether main products or co-products are involved. Economic allocation is often considered inconsistent with CLCA principles and acceptable only as a pragmatic approximation in rare cases where system expansion is infeasible due to missing data and the absence of alternative production pathways. This issue was not considered related to product circularity.

Rather than converting attributional databases to CLCA-specific formats, participants emphasised the importance of unit-process, unallocated datasets with sufficient transparency. Such datasets allow both ALCA and CLCA to be applied consistently through appropriate system-linking rules. Participants therefore viewed transparency in system modelling and data structure as essential for methodological consistency and reproducibility in both ALCA and CLCA applications.

## 4 Discussion

The objective of this study was to provide an overview of CLCA applications in European livestock systems and to assess how consequential modelling is currently implemented in this domain. We structured the analysis around typical CLCA phases (scenario development, inventory construction, impact assessment, and uncertainty analysis), drawing on insights from both the literature review and the expert workshop to identify implementation challenges and development priorities.

Taken together, the expert workshop and literature review highlight both the value and the practical demands of CLCA for assessing environmental changes in livestock systems. CLCA offers important insights into indirect and market-mediated environmental effects associated with decisions affecting livestock production; yet its application remains demanding in practice, largely due to data limitations and challenges in consistently operationalising established CLCA principles in complex, biologically and materially interconnected systems. Workshop participants emphasised the need for clear research questions, transparent system boundaries, careful identification of affected activities, and access to appropriate system-level data, as these factors can substantially influence uncertainty in CLCA results.

Expert perspectives align with literature patterns: most studies focus on manure treatment and handling and feeding strategies, with few examining transformative changes. Scenario approaches vary widely; inventories rely heavily on Ecoinvent; midpoint LCIA dominates; and substantial uncertainty remains regarding market-mediated effects.

The following discussion identifies key CLCA aspects warranting attention, explores structured scenario development, examines technical modelling aspects, and reflects on methodological limitations and interdisciplinary collaboration needs.

### 4.1 Scope, ambition, and scenario development in CLCA studies

Our results show that most current studies focus either on the environmental impacts of livestock systems as they operate today or on the consequences of incremental changes within these systems. Manure treatment and handling and alternative feeding strategies remain the most frequently studied topics. Feed production accounts for 65–95% of environmental impacts in monogastric systems, with manure treatment and handling as an additional contribution (Garcia-Launay et al., 2018; Méda et al., 2021; Wilfart et al., 2016), justifying this focus.

Technical-based and management-based approaches dominate, focusing on product- or farm-level changes rather than large-scale transformations. This pattern reflects both the practical orientation of many livestock studies and the relative simplicity of modelling incremental interventions within existing production systems. While such framing is not unique to CLCA, broader consequential scenarios generally require more extensive assumptions and modelling effort than localised interventions.

The reviewed studies suggest an important distinction between product-level scenarios, which typically involve localised changes within existing production systems, and broader system-level scenarios, such as dietary shifts or changes in livestock numbers, which require representation of market responses and feedback mechanisms. The need to capture such indirect and system-wide effects is a defining characteristic of consequential, as opposed to attributional, approaches. Linking product-level interventions to system-level outcomes therefore remains analytically demanding.

Such system-level changes are central to contemporary policy debates, including recent EU sustainability policy initiatives, which call for assessments of the environmental implications of profound transformations in agricultural systems rather than marginal adjustment alone. Examples of relevant transformation pathways are found in normative foresight scenarios, such as the EAT–Lancet Commission (Willett et al., 2019), the Afterres 2050 scenarios (Solagro, 2026), and the TYFA scenario for agroecological Europe (Poux & Aubert, 2018). These scenarios often involve substantial reductions in livestock numbers, shifts in dietary patterns, and large-scale land use reallocation. To date, however, their environmental assessments have typically relied on attributional or hybrid approaches, while system-wide consequences and market-mediated responses have rarely been evaluated using fully consequential frameworks.

Several studies used simplifying assumptions due to system complexity (Costa et al., 2023; Nguyen et al., 2013; Salou et al., 2019; Styles et al., 2018) or data limitations (Willeghems et al., 2016). Some of these challenges are generic to prospective LCA and scenario-based environmental assessment more broadly, particularly where future system configurations and technological developments must be represented. In CLCA, however, these uncertainties are amplified because the affected activities, substitution mechanisms, and market responses directly shape the resulting environmental consequences. Across both the reviewed studies and the expert workshop discussions, transparent documentation of assumptions, system boundaries, and causal pathways emerged as important for interpreting results and assessing their robustness in policy-oriented applications (EEA, 2018; Ekvall & Weidema, 2004; Weidema, 2003).

Both the literature and the expert workshop highlighted the value of integrating system knowledge and stakeholder perspectives into scenario development. Iterative engagement with domain experts, for example through structured elicitation, can help clarify causal pathways, reveal overlooked interactions, and improve the realism of assumptions (Hemming et al., 2018; Reed et al., 2009). Such participatory approaches are increasingly recognised in prospective and system-oriented LCA more generally, but may be particularly valuable in CLCA due to the need to explicitly represent indirect and cross-sectoral effects.

Comparable transdisciplinary approaches have also been formalised in prospective LCA techniques. For instance, Langkau et al. (2023) developed a stepwise framework that applies a transdisciplinary process, combining foresight methods with iterative expert and stakeholder participation, for integrating future scenario development into prospective inventory modelling. Such frameworks could offer a transferable template for CLCA of livestock systems. Adaptations to specific requirements of consequential modelling would nonetheless be required, for example, regarding the identification of marginal technologies, market-mediated effects, co-product handling, feed system interactions, and technology development pathways.

Similarly, integrating CLCA with complementary models, such as economic or biophysical models, can improve the representation of indirect effects and feedback mechanisms that single models may miss (Nilsson et al., 2016). For decision-oriented applications, scenario development should follow established principles from foresight and decision-support research, emphasise internal consistency, transparency of assumptions, and explicit links between narrative and quantitative modelling (Córdoba-Pozo & Rouwette, 2023; Galang et al., 2025; Mora et al., 2020; Wiebe et al., 2018). Applying such principles could help clarify how ecosystem, social, and economic objectives interact and support iterative exploration of trade-offs and sustainability priorities.

Overall, the existing studies highlight that while CLCA has strong potential to assess the environmental consequences of livestock system transitions, its application to transformative and policy-driven scenarios remains limited in practice. This limitation does not arise solely from CLCA methodology itself, but also from the way research questions and scenarios are currently framed within livestock sustainability research. The current scope of CLCA applications in livestock systems is therefore shaped by both methodological complexity and the tendency to prioritise incremental, technically tractable interventions over broader systemic transitions.

The findings suggest that advancing the application of CLCA in livestock systems depends not only on methodological development, but also on stronger scenario-design workflows capable of supporting broader system-level questions. This includes (1) making scale and decision context explicit, (2) transparently mapping system boundaries and causal pathways to justify included and excluded mechanisms, and (3) using expert input and complementary models where needed to represent key feedback and market-mediated responses. Advancing CLCA in this direction will require closer integration with scenario-based foresight approaches and complementary modelling tools, allowing consequential environmental analysis to better support the assessment of broader livestock-system transition pathways.

### 4.2 Inventory building – challenges and solutions

In CLCA, system expansion broadens system boundaries to capture direct and indirect consequences and avoids allocation by incorporating co-products within expanded boundaries (Weidema & Schmidt, 2022; Yang, 2016).

Unlike ALCA, CLCA inventory construction requires explicit representation of how production systems and markets respond to changes in demand or supply. The forward-looking nature of CLCA requires identifying which activities respond to decisions under specific constraints. While CLCA aims to include all significant consequences (ISO, 2006b), uncertainty increases when identifying which activities are constrained or unconstrained in future markets. The challenge lies in empirically identifying affected activities and documenting uncertainties that depend on market structure, technology, policy, and scale.

Workshop discussions and the reviewed studies highlighted how differences in the affected supplies of energy or materials, such as fossil fuel- versus biomass-based energy provision, can lead to substantially different results. Comparable challenges arise in manure treatment and handling and other by-product-related flows, where system responses depend strongly on nutrient balances, regulatory constraints, and competing uses.

Practical inventory construction is strongly shaped by the characteristics and limitations of available databases. When using CLCA databases such as Ecoinvent, practitioners must be aware that market classifications may not reflect regional realities, particularly for constrained markets such as animal manure (Santolin et al., 2024). Aggregated background databases may obscure variability between farm types and technologies, reinforcing the importance of transparent unit-process data. Databases also tend to lack explicit representation of within-system variability, such as differences among farm types or management intensities, affecting the representativeness of foreground system characterisation and underscoring the continued importance of targeted primary data collection (Marton et al., 2016).

While data representativeness and transparency are general LCA concerns, they become particularly important in livestock CLCA because environmental outcomes may depend strongly on regional feed sourcing, manure handling pathways, and co-product interactions.

Geographical suitability is another key consideration. Using global databases for country-specific assessments can increase uncertainty (Costa et al., 2023) or distort results in impact categories such as land use change (Dalgaard et al., 2014). However, depending on the study objectives, this choice may also be acceptable or even advantageous. For instance, Styles et al. (2022) used Ecoinvent marginal processes in a UK-based study to generate results intended to be generalisable to other industrialised countries, demonstrating that inventory choices directly shape the spatial and political interpretation of results.

Beyond geographical considerations, the choice between general and agriculture-focused databases also affects CLCA quality. Agriculture-focused databases (Product Environmental Footprint agricultural datasets, Biganzioli et al., 2018; Agri-footprint, Blonk Consultants, 2022; AGRIBALYSE, Koch et al., 2024) offer detailed livestock coverage but are developed for ALCA and lack marginal suppliers and substitution effects (van Zanten et al., 2014; Weidema et al., 1999), requiring careful adaptation when used in CLCA applications.

European livestock databases currently have important gaps in coverage and transparency, especially for by-product flows. To address these limitations, the expert group recommended prioritising datasets that provide detailed, unallocated unit-process data with clear documentation of system boundaries and production practices. Rather than mechanically converting aggregated ALCA datasets into CLCA formats, a more robust approach combines transparent process-level foreground data with explicitly modelled consequential background processes, provided that substitution mechanisms are clearly documented (Santolin et al., 2024). Other proposals included constructing inventories using integrated assessment models (Maes et al., 2023) and incorporating regional survey data (Güldemund et al., 2025).

These considerations highlight that inventory construction is not merely a technical step but a key determinant of CLCA outcome interpretability. In practice, robust CLCA inventory development requires transparent documentation of substitutions, careful evaluation of the geographical and technological representativeness of background datasets, and explicit justification of the procedures used to identify affected activities and marginal suppliers. Combining database information with primary data, regional statistics, expert knowledge, or complementary modelling approaches may help address limitations in existing datasets, particularly for livestock systems characterised by strong regional variability and complex by-product interactions. Improving transparency, regional specificity, and documentation of affected activities and their associated uncertainties is therefore essential for producing results that robustly inform policy and practice.

### 4.3 Selecting impact categories for decision support

Most studies applied midpoint LCIA. This reflects common practice in agricultural LCA more broadly, as midpoint indicators provide a transparent link to causal pathways through which interventions trigger changes in production, land use, and nutrient flows. In CLCA, this transparency is particularly important because environmental consequences are traced through indirect and market-mediated system responses.

Endpoint indicators, which aggregate impacts into damage categories related to human health, ecosystem quality, and resource availability, offer a complementary role. For example, Salou et al. (2019) combined midpoint and endpoint categories following recommendations from the International Reference Life Cycle Data System (JRC and IES, 2010), while Santolin et al. (2024) assessed impacts solely at the endpoint level, arguing that aggregated indicators can facilitate interpretation for non-technical audiences (RIVM, 2011). However, endpoint indicators are also associated with higher uncertainty and reduced transparency, as they rely on additional modelling assumptions, weighting steps, and value choices that may obscure underlying drivers of change. Their use therefore requires careful justification in relation to the study goal and audience.

In livestock-focused CLCA, impact category selection is particularly important because livestock systems are closely linked to land occupation and land use change, nutrient cycling, and interactions between climate change, biodiversity, and soil quality. Categories such as land occupation, eutrophication, and climate change are especially relevant due to land competition between feed production, food crops, and ecosystem conservation. Moreover, some livestock practices may generate environmental benefits in specific contexts, such as soil carbon sequestration, improved nutrient recycling, or landscape-level biodiversity support, which are not consistently captured by standard midpoint indicators and require explicit consideration when relevant. In addition to biodiversity impacts, ecotoxicity impacts are also relevant when comparing extensive agroecological livestock systems to more intensive livestock systems (Knudsen et al., 2019; van der Werf et al., 2020).

Rather than assuming that more indicators necessarily improve decision-making, the literature suggests that a carefully selected, well-justified set of midpoint indicators, potentially supplemented by endpoint modelling for synthesis or prioritisation, is more effective than indiscriminate expansion of impact categories. This approach is consistent with methodological guidance recommending midpoint–endpoint complementarity rather than substitution when interpretation benefits outweigh added uncertainty (van Zelm et al., 2025). Several frameworks exist to guide category selection, including Product Environmental Footprint guidelines (European Environmental Bureau, 2018), though these should be applied cautiously in a CLCA context as they do not explicitly represent planetary boundary exceedances.

At the same time, both the reviewed literature and broader methodological discussions suggest that some environmentally relevant dimensions may remain underrepresented, particularly biodiversity-related impacts, ecotoxicity, and broader ecosystem interactions associated with livestock-system transitions. These observations highlight the importance of aligning impact category selection not only with methodological conventions, but also with the environmental mechanisms and decision contexts under investigation.

Monetary or damage-based endpoint modelling can synthesise complex information and highlight the relative importance of pathways, provided assumptions are explicit (Pizzol et al., 2015). Such approaches support prioritisation but are less suited for diagnosing mechanisms. Aggregated indicators inform decisions only when used alongside disaggregated information and qualitative judgment (OECD, 2018).

In CLCAs of livestock systems, an interpretation-oriented strategy (centred on a well-justified set of midpoint indicators and selectively complemented by endpoint or monetary metrics) offers a pragmatic balance between transparency, analytical depth, and decision relevance.

Recent developments in LCIA methods and computational LCA tools may also support future advances in livestock CLCA applications. Several newer LCIA frameworks have expanded the number and specificity of impact categories, including biodiversity, water scarcity, particulate matter, and ecosystem-related indicators. Examples include the GLAM approach (Jolliet et al., 2018), IMPACT World + (Bulle et al., 2019), and the Environmental Footprint framework (European Commission, 2021a), which offer improved regional specificity and broader indicator coverage compared with earlier frameworks such as ReCiPe or CML. While such developments may improve environmental coverage, they also increase challenges related to interpretation, uncertainty, and consistency across studies. In a CLCA context, harmonisation therefore depends not only on adopting broader indicator sets, but also on identifying impact categories that are most relevant to the specific decision context and consequential pathways being assessed.

In parallel, emerging computational tools and open-source LCA frameworks, such as Brightway (Mutel, 2017), may improve flexibility, transparency, and traceability in consequential modelling by facilitating scenario analysis, sensitivity analysis, regionalisation, and integration with complementary models. The open and modular architecture of such frameworks also facilitates the construction of custom consequential system models. Such developments could help support more complex and transparent CLCA applications in livestock systems, particularly for studies involving dynamic market responses or large-scale system transitions.

### 4.4 Uncertainty analysis – gaps and priorities

Most studies incorporated uncertainty analysis into their CLCA modelling, indicating broad recognition of its importance for impact assessment. Uncertainty is widely acknowledged as a major factor affecting the reliability of LCA results (McKone et al., 2011), though the relative importance of different uncertainty sources varies substantially across studies (Bamber et al., 2020). Some uncertainty sources are shared between ALCA and CLCA, such as model, scenario, and parameter uncertainty (Lloyd & Ries, 2007) stemming from data variability, limited representativeness, assumptions of linearity, and incomplete system knowledge. In CLCA, however, additional uncertainty arises from the need to characterise how markets and production systems respond to changes, including the identification of affected (marginal) technologies and the scale and direction of market-mediated substitutions (Bamber et al., 2020).

Addressing these uncertainties involves both quantification and interpretation. Well-designed sensitivity and scenario analyses explore alternative system hypotheses and response pathways, contributing to an understanding of system behaviour and structural dependencies.

Among the studies reviewed, Monte Carlo analysis, sensitivity analysis, and scenario analysis were commonly applied, primarily addressing parameter uncertainty and alternative scenario assumptions. However, uncertainty related to model structure, such as the representation of markets, substitution mechanisms, or behavioural responses, was less frequently explored. While established standards provide general guidance on uncertainty and sensitivity analysis (e.g., Heijungs, 2024), the reviewed studies show substantial variation in how comprehensively different uncertainty sources are treated in practice, particularly beyond parameter uncertainty.

For future CLCA applications, at least a basic level of parameter uncertainty analysis is advisable, for example through Monte Carlo simulation. More in-depth approaches can provide additional insights, such as identifying influential variables that dominate result variability (sensitivity analysis) or exploring combinations of assumptions that lead to qualitatively different outcomes (scenario analysis).

In a consequential context, such analyses are particularly informative when used to test alternative representations of system responses, rather than only small perturbations around a single assumed pathway. Targeted sensitivity analysis is therefore essential for assessing the implications of simplifying assumptions and for evaluating the robustness of scenario-based conclusions, especially when CLCA results are intended to support policy-relevant decision-making (Saltelli et al., 2008).

Additional guidance for addressing CLCA-specific uncertainty has been proposed, including drawing on methodologies from economics to better characterise uncertainties related to market-mediated substitution effects, affected markets, and substitution magnitudes (Bamber et al., 2020). These recommendations were also endorsed by the expert group, underscoring the need for more systematic and transparent treatment of uncertainty that reflects the forward-looking and decision-oriented nature of CLCA in future studies.

### 4.5 Integration with policy, economics and social dimensions

To strengthen the relevance of CLCA for decision-making, closer collaboration between LCA practitioners and other disciplines is essential. This includes integrating social dimensions (Rivera-Huerta et al., 2019) and economic considerations (Salou et al., 2019; Wang et al., 2016) into CLCA-based assessments to better anticipate behavioural responses, market effects, and trade-offs between sustainability and economic viability (Bayram et al., 2024). While interdisciplinary integration is increasingly encouraged across sustainability assessment more broadly, it is particularly important in CLCA because consequential modelling explicitly seeks to capture indirect and broader system responses to change.

Such integration is particularly relevant in the European context, where policy initiatives such as the European Green Deal (European Commission, 2021), the Common Agricultural Policy (CAP, European Commission, 2021b), and climate and biodiversity strategies increasingly require ex ante assessment of system-wide and cross-sectoral impacts. CLCA can explore the consequences of CAP eco-schemes, methane mitigation, nutrient regulation, and land use targets. True Cost Accounting shows promise for revealing production externalities (Baltussen et al., 2025).

The expert group also highlighted the need for closer collaboration with social scientists, for example to analyse rebound effects or unintended consequences at different system scales, and to account for behavioural changes within scenario development. Such perspectives are important for capturing non-economic drivers of system change, including social norms, institutional constraints, and political dynamics that may influence market responses beyond purely price-driven mechanisms (e.g., policy disruptions from trade wars and embargoes).

For policy-oriented applications, scenario development should explicitly consider interactions among environmental, social, and economic objectives. Exploring the environmental implications of system transitions, including dietary and livestock-production changes proposed in broader sustainability frameworks (e.g., Rockström et al., 2025), requires iterative assessments of trade-offs across multiple sustainability priorities.

In this context, both the literature review and expert discussions suggest that current CLCA applications predominantly examine intensive farming systems. To address challenges inherent in these systems, such as dependence on concentrate feeds, antimicrobial use, and high greenhouse-gas emissions, future CLCA applications could more extensively examine alternative and innovative livestock systems. Examples of such systems include organic livestock systems (Zira et al., 2021), integrated crop–livestock systems (Parajuli et al., 2018; Pereyra-Goday et al., 2024), organic crop–livestock systems (Guarnaccia et al., 2024), integrated crop–livestock–bioenergy systems (Xing et al., 2022), agroecology-based livestock systems (Genest-Richard et al., 2025), and precision livestock farming systems (Bragaglio et al., 2023; Lovarelli et al., 2024).

These systems are particularly relevant for livestock CLCA because they involve interactions among land use, nutrient cycling, biodiversity, and resource use that extend beyond individual production processes. Assessing such systems in a consequential framework requires analytical approaches capable of capturing multidimensional interactions across ecosystem, economic, and social domains.

When designing such forward-looking policy-relevant scenarios, system boundaries and the geographical scope must be clearly defined from the outset to ensure internal coherence across ecosystem, economic, and social dimensions. Clear alignment between scenario narratives, modelling assumptions, and policy questions is therefore a prerequisite for CLCA to support integrated sustainability assessment and policymaking.

### 4.6 Limitations of the review

This review focused on European studies to ensure relevance to regional production systems and policies while maintaining a coherent scope. In addition, the review focused on terrestrial livestock systems. The included studies addressed cattle, sheep, pigs, and poultry; no eligible studies focusing on goats were identified. Fisheries and aquaculture were excluded, although both face similar methodological challenges.

The review also included only peer-reviewed publications and did not consider grey literature such as EU project reports, standards and guidance documents, or commercial studies, which may contain relevant CLCA applications and method developments. This choice reflects a trade-off between methodological transparency and completeness, as grey literature often lacks consistent peer review but may nonetheless play an important role in applied policy contexts.

Moreover, the expert workshop was constrained by time, limiting the depth with which some prepared questions could be explored, and the relatively small number of participating experts introduces the potential for self-selection bias. Nevertheless, the combination of a systematic literature review and structured expert elicitation enabled the identification of recurring challenges, limitations, and research priorities in current livestock-focused CLCA studies.

Regarding our classification of scenario development approaches, we acknowledge that these reflect our own interpretations and may not align with alternative views. This classification was developed inductively to support comparison across studies rather than to prescribe methodological categories.

Finally, the literature search was completed in December 2024. Consequently, studies published after this date were not eligible for inclusion in the systematic review, although selected publications were cited where relevant to provide background information or discuss recent methodological developments. While this temporal cut-off may exclude some recent contributions from the review itself, it was necessary to ensure transparency and reproducibility of the review process.

### 4.7 Final synthesis: the unbearable lightness of changing

One intention of this review is to draw greater attention within the LCA community to the potential of CLCA for assessing the environmental consequences of decisions affecting livestock systems. While this review focuses on European applications, valuable insights can also be drawn from CLCA studies conducted in other regions, which address similar challenges related to market dynamics, system boundaries, and sustainability transitions (e.g., Arulnathan et al., 2025; Galloway et al., 2024; Wang et al., 2025). Several reviewed studies also examined feeding strategies and feed substitutions, illustrating how feed sourcing and land use interactions can substantially influence consequential outcomes in livestock systems. Together, these findings highlight the importance of explicitly representing feed-related market dynamics and indirect effects in future CLCA applications, while situating European evidence within the broader discussion on sustainable food-system transitions (e.g., Dougherty et al., 2023).

The discussion highlighted key methodological challenges related to data, transparency, system representation, and uncertainty, while also identifying scenario development as particularly influential in shaping the relevance and interpretability of CLCA studies.

Throughout our discussion and expert workshop, scenario development emerged as central to CLCA modelling. Participants particularly emphasised collaborative and narrative-based approaches to scenario design, in which qualitative storylines guide subsequent quantitative modelling. Such approaches may reduce the risk of overlooking important processes or drivers in the early phases of scenario formulation and are increasingly used in Social LCA and participatory sustainability assessments (Møller et al., 2025). Co-developing scenarios with economists was also strongly encouraged, as explicit representation of economic mechanisms can improve the interpretability of results, especially when assessing the environmental implications of policy instruments at local, national, or EU scales. In addition, CLCA scenarios exploring alternative production systems or governance configurations may help analyse how environmental consequences emerge from broader structural changes rather than isolated technical interventions.

Applying systems thinking in CLCA scenario design also requires situating livestock within broader food-system contexts, including dietary change, land use competition, and nutrient needs. Recent studies increasingly emphasise scenarios involving reduced animal-protein consumption and greater reliance on plant-based foods in line with nutritional and environmental objectives (e.g., Darmon et al., 2024). CLCA can help explore the environmental consequences of such dietary and production transitions without presupposing specific solutions.

Among the livestock groups examined in this review, ruminant and monogastric systems are often discussed differently in the literature, reflecting prevailing analytical perspectives rather than universally applicable conclusions. Ruminant systems are often analysed in relation to ecosystem services, carbon storage, and landscape management (e.g., Dumont et al., 2018; Tittonell et al., 2016), whereas pig and poultry systems are more commonly assessed through product-oriented perspectives. Examples such as alternative breeding strategies in poultry (Rauw et al., 1998) illustrate the types of structural changes that could be examined within CLCA as exploratory scenarios, without implying judgements about feasibility or desirability.

In this context, CLCA offers a valuable framework for examining the environmental implications of future-oriented livestock system scenarios. By making indirect effects and system-wide consequences more explicit, CLCA can support more informed evaluation of sustainability transitions and policy-relevant system changes.

## 5 Conclusion

Through a systematic literature review and an expert workshop, this study provides an integrated overview of CLCA applications in European livestock systems and identifies key methodological challenges and priorities for improving current practice. The workshop offered a platform for practitioners to discuss shared barriers and priorities, complementing and strengthening insights from the literature review.

The main conclusions are as follows:

(1) The research focus of current CLCA studies remains relatively narrow

Most existing CLCA studies target incremental improvements within current livestock systems, particularly manure treatment and handling and alternative feeding strategies, reflecting both the dominant sources of environmental impacts and the prevailing scope of published studies. Only a limited number of studies examine more transformative system changes, despite growing policy interest in agroecological and regenerative approaches and other structural transitions of livestock systems across the EU.

(2) Scenario development is constrained by both research focus and modelling complexity

Scenario formulation in CLCA has primarily relied on technical-based and management-based approaches, with relatively few studies examining broader system transformations. This pattern reflects both prevailing research questions and practical challenges associated with modelling consequential system responses and market-mediated effects. Future studies could benefit from broader research ambition and stronger integration of approaches capable of representing feedback mechanisms, market responses, and structural transitions.

(3) Inventory construction requires improved data quality and localisation

Robust CLCA inventories depend on high-quality, up-to-date, geographically relevant data. This requires careful selection of data sources aligned with the spatial and technological scope of the study, as well as continued development of regionalised datasets, particularly for marginal products and by-products, to better capture local market conditions and system behaviours. Strengthening localisation, data transparency, and documentation of inventory assumptions is essential for improving the credibility and policy relevance of CLCA results.

(4) Impact category selection should be interpretation-oriented

Most studies relied exclusively on midpoint LCIA, with limited use of endpoint indicators. To support meaningful interpretation of environmental trade-offs, assessments could include a well-justified set of relevant midpoint indicators (e.g., climate change, acidification, eutrophication, ecotoxicity, biodiversity, land use, resource use), potentially supplemented by endpoint or damage-based indicators when their purpose and limitations are clearly articulated.

(5) Uncertainty analysis is essential for robust CLCA interpretation

Monte Carlo simulation, sensitivity analysis, and scenario analysis were the most common methods in the reviewed studies. Future CLCA applications should routinely include uncertainty analysis, with particular emphasis on sensitivity and scenario analysis as tools for exploring alternative system responses and testing the robustness of results, especially when assessing complex or transformative scenarios. In uncertainty and sensitivity analyses for CLCA, particular attention should be given to the identification of affected (marginal) technologies and the scale and direction of market-mediated substitutions.

Taken together, these findings underscore the need for a shift in emphasis from refining existing systems toward systematically exploring alternative and potentially more sustainable livestock system configurations. Systems thinking will be essential for addressing the environmental challenges facing the sector. Consequential LCA is well positioned to support this transition, provided that its application is guided by clearly articulated research questions, transparent assumptions, and explicit attention to uncertainty, enabling balanced and evidence-based contributions to policy and sustainability debates.

## 6 Supplementary Information

This supplementary information contains: Section 1, the literature-review search string; Section 2, search results and the PRISMA screening flow diagram; Section 3, the expert-workshop protocol; Section 4, the workshop informed-consent form; Section 5, characteristics of the 23 reviewed studies; Section 6, key concepts in consequential life cycle assessment; and Section 7, the data used to create Figure 1.

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## Declarations

**Conflicts of interest** The authors declare no competing financial or personal interests.



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## Authors and Affiliations

**Dengsheng Sun[1] · Marie Trydeman Knudsen[2] · Thomas Ponsioen[3] · Ricardo Teixeira[4] · Alina Chervinska[4] · Mariana Raposo[4] · Rahela Lucić[4] · Mali Gravell[5] · Nicholas Davison[5] · Lewis Cameron[5] · Sally Westaway[5] · Aurélie Wilfart[6] · Pietro Goglio[7] · Yue Wang[8] · Fatemeh Hashemi[2] · Vasco Diogo[9] · Bo P. Weidema[10] · Laurence G. Smith[1,5]**

✉ Dengsheng Sun
dengsheng.sun@slu.se

Marie Trydeman Knudsen
mariet.knudsen@agro.au.dk

Thomas Ponsioen
tcponsioen@hotmail.com

Ricardo Teixeira
ricardo.teixeira@tecnico.ulisboa.pt

Alina Chervinska
alina.chervinska@tecnico.ulisboa.pt

Mariana Raposo
mariana.raposo@tecnico.ulisboa.pt

Rahela Lucić
rahela.lucic@tecnico.ulisboa.pt

Mali Gravell
m.c.gravell@reading.ac.uk

Nicholas Davison
n.davison@reading.ac.uk

Lewis Cameron
l.cameron@reading.ac.uk

Sally Westaway
s.westaway@reading.ac.uk

Aurélie Wilfart
aurelie.wilfart@inrae.fr

Pietro Goglio
pietro.goglio@unipg.it

Yue Wang
yue3.wang@wur.nl

Fatemeh Hashemi
fh@agro.au.dk

Vasco Diogo
vasco.diogo@agroscope.admin.ch

Bo P. Weidema
bweidema@plan.aau.dk

Laurence G. Smith
laurence.smith@slu.se; l.g.smith@reading.ac.uk

[1] Animal-Centered Environments Group, Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Box 190, 234 22 Lomma, Sweden

[2] Department of Agroecology, Aarhus University, Blichers Allè 20, 8830 Tjele, Denmark

[3] FootPrinting, Nieuwe Kanaal 7, Wageningen 6709 PA, The Netherlands

[4] MARETEC—Marine, Environment and Technology Centre, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal

[5] School of Agriculture, Policy and Development, University of Reading, Reading RG6 6EU, UK

[6] INRAE, Institut Agro, SAS, 65 Rue de Saint Brieuc, 35000 Rennes, France

[7] Department of Agricultural, Food, and Environmental Sciences, University of Perugia, Borgo XX Giugno 74, 06121 Perugia, Italy

[8] Animal Production Systems Group, Wageningen University & Research, P.O. Box 338, 6700 AH Wageningen, The Netherlands

[9] Life Cycle Assessment Research Group, Reckenholzstrasse 191, 8046 AgroscopeZürich, Switzerland

[10] Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark