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Life Cycle Assessment of Paper-Based Products: Prisma Review of Process-Based, Input–Output, and Hybrid Methods

Nurul S. Roslan[a], Shanti F. Salleh[a,*], Florianna Lendai Michael[a], Nashley U. M. Ujai[b], Abderrahim Zermane[c]

[a]Institute of Sustainable and Renewable Energy, University of Malaysia Sarawak, Jalan Datuk Mohd Musa, 94300 Kota Samarahan, Sarawak, Malaysia
[b]Faculty of Engineering, University of Malaysia Sarawak (UNIMAS), Jalan Datuk Mohd Musa, 94300 Kota Samarahan, Sarawak, Malaysia
[c]Safety Engineering Interest Group, Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
sshanti@unimas.my

Life Cycle Assessment (LCA) is a widely used method for evaluating the environmental impacts of a product throughout its life cycle. A critical component of LCA is life cycle inventory (LCI) - a phase that quantifies all inputs (materials, energy) and outputs (emissions, wastes) of a product or system - which requires selecting an appropriate data acquisition method aligned with the study's goals and context. This systematic review analyses 26 studies from SCOPUS using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method on the LCA of paper-based products (office paper, corrugated boxes, carton board packaging, and tissue papers), categorizing them into three methods: Process-Based, Input-Output (IO), and Hybrid. Each method's alignment with research objectives, data sources, and system boundaries is examined. The findings indicate that the hybrid method—combining detailed process data with broader secondary databases and/or economic models—offers greater adaptability and completeness. The hybrid method is particularly useful when balancing data availability with assessment scope. To support method selection, this review presents a flowchart that serves as a support for method selection for future researchers and practitioners in choosing appropriate methods for LCA.

1. Introduction

Sustainable consumption and production are central to the 12th Sustainable Development Goal (SDG 12), which emphasizes on decoupling economic growth from environmental degradation. Among the tools used to assess sustainability performance, Life Cycle Assessment (LCA) is particularly prominent due to its ability to quantify environmental impacts across the full life cycle of products and services (Finnveden and Potting, 2014). Recent literature found that 24,000 LCA studies were published from 1970 to 2024, demonstrating a rapid growth between 2010 to 2024 with 21,740 studies (Suah and Minjung, 2024). LCA is often used within the construction and energy sectors; it can also be applied to both agriculture and livestock. For instance, a systematic review was done for the analysis of LCA in buildings, and it was reported that LCA aids in providing insights into building material choices and their environmental impacts (Nwodo and Anumba, 2019). Not only that, but LCA is important for buildings to achieve green building certifications such as LEED v4 (Alshamrani et al., 2014). Laina et al. (2022) found that through LCA, the novel functional feed products (FP) that consist of innovative feed products enriched with bioactive compounds have a promising approach with documented sustainability elements regarding their total environmental impact as opposed to conventional feed. On the other hand, Haryati et al. (2021) demonstrate that Social LCA (S-LCA) is an effective tool to gauge the social impacts within the Malaysia oil palm industry, as it highlights the potential of linking 6 out of 17 Sustainable Development Goals (SDGs). This indicates a clear connection between micro level assessment of products/services and the macro level of SDGs' conceptualization at regional or country level.

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Despite a growing body of literature on LCA, there remains a lack of structured guidance on selecting suitable inventory approaches under varying conditions, particularly in sector-specific contexts such as paper-based product (Santos et al., 2022). Paper-based products are widely used in sectors such as packaging, printing, and hygiene (Coelho et al., 2020). Paper-based product industries are also environmentally sensitive as it consumes substantial raw materials, energy, and water, leading to considerable environmental burdens such as eutrophication, greenhouse gas emissions, material recovery and recycling efficiency (Aydemir et al., 2023). Conducting LCA requires four phases: goal and scope definition, inventory, impact assessment, and interpretation. As briefly mentioned, LCI is a phase that involves data collection on material and energy flows, and it is particularly critical because it serves as the foundation for subsequent environmental impact analysis (Pennington et al., 2004). Selecting an appropriate inventory data acquisition strategy is essential to ensure accuracy, feasibility, and relevance in LCA studies (Bicalho et al., 2017). The diversity of study objectives, available data, and system boundaries often require methodological flexibility. LCI methods for paper-based products are used inconsistently and without clear selection guidance, a systematic synthesis is needed to classify process, input–output, and hybrid studies by their fit to goals, data, and system complexity. This paper aims to fill this gap by systematically reviewing LCA literature related to paper-based products, with a focus on how different inventory methods are employed. Specifically, this review categorizes studies into three methodological groups—Process-Based, IO, and Hybrid methods—and evaluates how these methods align with the studies' objectives, data sources, and system complexity. By identifying patterns and proposing a decision-making framework, this paper aims to assist future researchers and practitioners in selecting methods that enhance methodological robustness and relevance when conducting LCA on paper-based product research.

2. Materials and methods

This study conducted a structured literature review to identify and categorise methodological approaches used in Life Cycle Assessment (LCA) of paper-based products (Figure 1).

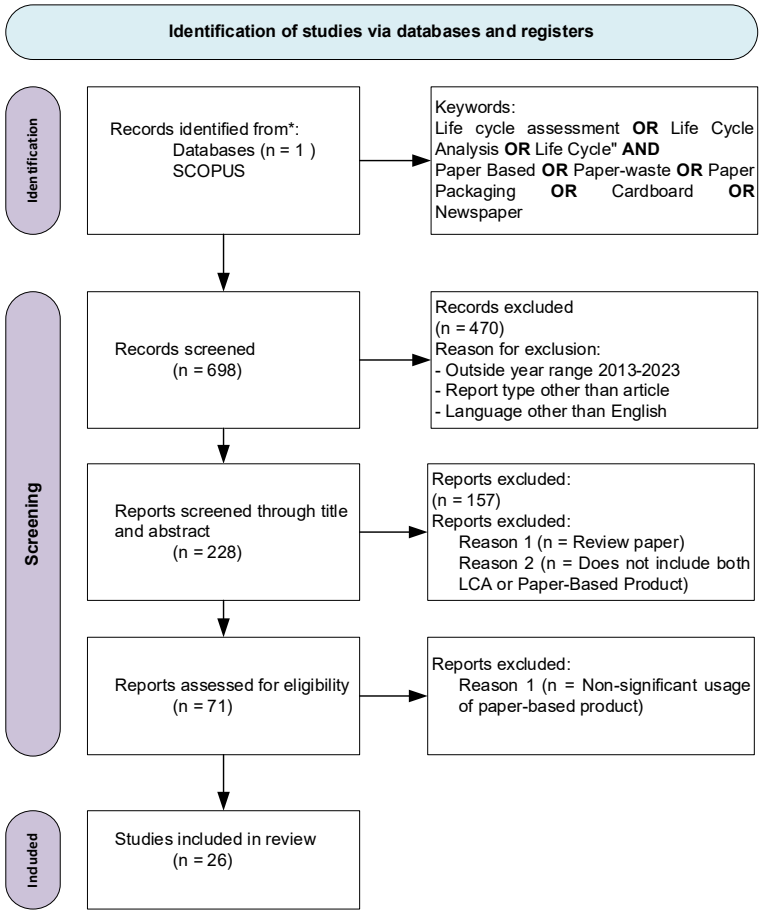

Figure 1: The PRISMA flow chart outline for the selection process

The objective was to examine how different LCA methods are applied and selection of method based on the study's objectives. A systematic search was carried out using a single electronic database, followed by screening and classification of the literature according to predefined methodological categories. In this paper, the SCOPUS database was chosen as it supplies Scientific, Technical and Medical (STM) journal articles which included references, and not only that, but it also provides a broader range of research metrics such as citation counts, h-index, journal rankings and author profiles, enabling more comprehensive bibliometric analysis compared to other databased (Burnham, 2006). To retrieve relevant articles, a set of keywords that best describes the focus area of this research was used, such as "Life Cycle Assessment" and "Paper-Based Product". The keywords were combined by using basic Boolean operators which are "AND" and "OR". Quotation marks ("") were used when searching for specific keywords that were searched with loose phrases. Other than "Life Cycle Assessment" and "Paper-Based Product", other keywords that represent the search term were also included such as "Life Cycle", "Life Cycle Analysis", "Paper-Based", "Paper Product", "Cardboard", and "Newspaper". Additional keywords were added to describe the commonly used terms to describe LCA and Paper-Based Product to capture a broader search. The search was conducted in May 2024 to include any additional studies published later in 2023. Upon retrieving the results based on the keywords stated, a total of 698 documents were found in SCOPUS. The articles that were found through the search strings are then further screened by their title and abstract to identify whether the showcased papers are pertinent to the objectives of the study. After the screening phase, the remaining articles were then categorized into Process-Based IO Process and Hybrid method. The definition for the methods is further explained in Results and Discussion. By categorizing LCA methods into these three methods, this study provides a structured framework for selecting appropriate LCA approaches based on the specific goals, data availability, and scale of the assessment.

3. Results and Discussion

This section defines the main methodological approaches used in LCA (Process-Based, IO, and Hybrid methods) and presents a comparative analysis of their application in existing studies related to paper-based products. The section also examines how each method addresses inventory data acquisition, system boundary treatment, and methodological suitability relative to specific research objectives. By analyzing published case studies, the section evaluates the strengths and limitations of each approach and establishes a basis for selecting an appropriate LCA method based on study scope, data availability, and system complexity.

3.1 Definition of Categories

In LCA, the approach of acquiring data for inventory includes process-based, IO, and hybrid methods. Process-Based method quantifies environmental impacts by modeling specific physical processes in the product life cycle. It provides detailed results but may suffer from system boundary truncation (Nakamura and Nansai, 2016). IO method uses economic input-output (EIO) tables to estimate environmental impacts of sectoral monetary exchanges, offering economy-wide coverage but lower detail (Mattila, 2018). Hybrid method integrates both to mitigate truncation errors and improve completeness.

3.2 Comparative Analysis

In this paper, a comparative analysis of various studies that utilize Process Based, IO Process and Hybrid method in LCA was done by examining the execution of inventory phase, assumptions, data sources, and to the relevance of the methodology to specific applications. Process Based is a data intensive method, as it involves constructing a detailed inventory of inputs and outputs for each unit process within the system boundary, allowing for a comprehensive impact assessment and interpretation (Castiello et al., 2020). This method maps the full life cycle of a product or service—from raw material extraction to end-of-life treatment and is suited to complex systems that require detailed process data to accurately assess environmental impacts. Several key studies have applied this approach into conducting LCA for paper-based waste, offering insights into the implementation of the inventory phase, including data sourcing, as well as the integration of scenario analysis and assumptions.

Based on Table 1, studies using unit-process primary data align with product- or plant-level objectives, enabling validation against records and fine-grained hotspot detection. Household waste sampling (Edjabou 2021) similarly improves representativeness for downstream modelling. Strengths are granularity and credibility; limits are effort, access, and narrower system coverage. IO/EIO applications leverage secondary databases/tools (SimaPro, ecoinvent, WRATE) and national statistics to model broad scenarios where primary data are infeasible or confidential. They support completeness and policy-scale comparisons but trade off site specificity and temporal/geographic precision. While hybrid method integrate primary unit-process data with databases and literature (often ~1:2 primary:secondary), balancing detail and coverage and enabling benchmarking. They are powerful for complex systems but require transparent IO–process linking to avoid double counting and

should include uncertainty analysis. Overall, method choice should follow study goals, data availability/quality, and system complexity: process for detailed product questions, IO for economy-wide scenarios, and hybrid when both local precision and system completeness are needed.

Table 1: Comparative overview of process-based, IO and hybrid method for paper-based product

Method	Main Data Sources	Objective	Key Strengths	Limitations	Journal Articles
Process-based	Primary unit-process data; plant records; questionnaires; waste sampling	Product/plant optimization; hotspot identification	High granularity; validated data; context relevance	Data-intensive; limited boundary breadth	(Mourad et al., 2014); (Lozano-Medina et al., 2018); (Casallas et al., 2018); (Edjabou et al., 2021)
Input-Output	Ecoinvent/WRATE; SimaPro; national trade/industry statistic	Policy/economy-wide, multi-scenario comparisons	System completeness; scalable; rapid scenario	Low site specificity; temporal/geographic mismatch risk	(Asdrubali et al., 2016); (Burnley, 2019); (Sevigné-Itoiz et al., 2015)
Hybrid	Primary unit processes, with databases and literature (often ~1:2)	Complex systems needing both detail and coverage	Balanced precision/completeness; benchmarking	Linking opacity; double-counting risk; needs uncertainty checks	(Bui et al., 2022); (Ferrara and Feo, 2021); (Provost-Savard et al., 2023); (Zhang et al., 2015)

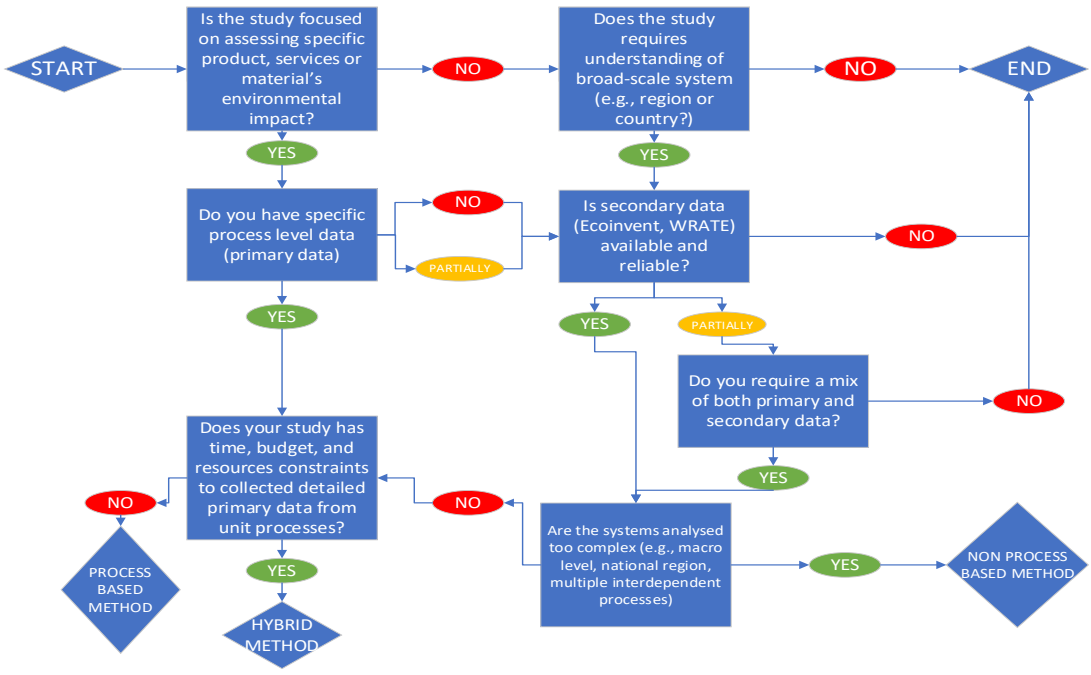

Figure 2: The flowchart to indicate the appropriate method to be applied based on the objective of the study

Based on the discussion, Figure 2 presents a structured decision-making flowchart to support the selection of an appropriate Life Cycle Assessment (LCA) methodology based on the study's objectives, data availability, and system complexity. The flowchart begins by assessing whether the study is focused on evaluating the environmental impact of a specific product, service, or material. If so, the framework proceeds to evaluate the availability of primary data. If not, the chart then considers whether the study aims to assess broader systems—such as national or regional scales—which would suggest the suitability of IO method. If neither condition is met, the selection process terminates, indicating that the study's objective or scope may require revision. For

product-focused studies, the framework next examines whether specific process-level (primary) data are available. If such data are accessible, and if there are no significant constraints in terms of time, budget, or resources, Process-Based is recommended due to its capacity to capture detailed system-specific environmental performance. If constraints are present, Hybrid method may be more feasible, balancing detail with practicality. If only partial or no primary data are available, the framework shifts focus to secondary data sources, such as databases (e.g., Ecoinvent, WRATE) or literature. Where these sources are available and reliable, the framework further considers whether a combination of primary and secondary data is required. If the system is under study is highly complex—such as multi-regional, macro-scale, or composed of interdependent subsystems, then IO method is suggested. If the system is less complex, the decision between a Hybrid or Process-Based method will depend on the presence of data constraints. This decision-support framework ensures that methodological choices are aligned with study goals, available resources, and the required level of detail. It offers a structured basis for method selection that reduces the risk of misalignment between the study design and the capabilities of the chosen LCA approach.

4. Conclusions

In conclusion, the selection of inventory methods in Life Cycle Assessment (LCA) must be strategically aligned with the study's objectives to ensure relevance, accuracy, and validity. Process-based LCA is most effective for product-specific or technology-focused assessments where detailed, site-specific data is available. In contrast, IO LCA is suitable for economy-wide or policy-level analyses where comprehensive system boundaries are prioritized over granular detail. Hybrid LCA, which was the most applied method across the reviewed studies, offers the flexibility to capture both detailed and systemic environmental impacts by combining primary and secondary data sources. The frequently used 1:2 ratio of primary to secondary data—particularly involving unit processes, LCA databases, and literature—supports a balanced approach, enabling both precision and broader applicability. The integration of multiple data types in hybrid methods requires careful management to avoid issues such as double counting and data inconsistency. The use of standardized databases like Ecoinvent and WRATE enhances comparability and transparency, while primary data collection increases the contextual relevance of findings. Ultimately, the credibility of an LCA study depends not just on technical modelling but on the method selection and transparent data integration.

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