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AUSTRALIAN LIFE CYCLE ASSESSMENT SOCIETY

The 12th Australian Conference on Life Cycle Assessment: Next-generation LCA to support sustainability transitions

18 - 20 November 2025

Novotel Melbourne on Collins, Melbourne, Australia

Book of Abstracts and Proceedings

ISBN 978-0-646-72976-3

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Australian Life Cycle Assessment Society (ALCAS)
PROCEEDINGS OF THE 12TH AUSTRALIAN LIFE CYCLE ASSESSMENT CONFERENCE
Next-generation LCA to Support Sustainability Transitions

Edited by: Tokede, Olubukola and Renouf, Marguerite

First published 2026
978-0-646-72976-3

Published by:
Australian Life Cycle Assessment Society Inc
PO Box 12062 A'Beckett Street, Melbourne, VIC, 3001

Format:
Digital (PDF)

Date:
November 18 – 20, 2025

ALCAS Declaration
These proceedings comprise peer-reviewed papers presented at the 12th Australian Life Cycle Assessment Conference (ALCAS 2025), held in Melbourne, Australia. The collection explores emerging research, methods, and applications of life cycle assessment across industry and academia, highlighting next-generation LCA approaches to support sustainability transitions in Australia and beyond.

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Various authors of accepted conference papers.

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Abstracts

LCAutomate: Development of an automation code for LCA unit process creation, LCIA calculation, and graphical representation

Dr. Nicole Bamber [1]***, Dr. Ian Turner*** [1]***, Dr. James Bamber*** [2]***, Dr. Nathan Pelletier*** [1]

1.University of British Columbia

2.Logisymetrix

There is a growing body of research on the simplification of LCA – methods to increase the efficiency of de-tailed, process-based LCA, removing barriers to performing LCA whilst maintaining an acceptable degree of rigor. If done appropriately, this could lead to greater uptake and implementation of LCA methodology and better, evidence-based decision support. Kiemel et al. (2022) found that automated calculation of LCIA results and automated LCI data generation were two areas of particular potential for simplification. Many LCA tools are being developed that aim to automate LCI generation, but few have focused on automated LCIA calculation. Automated calculation (also requiring serial unit process creation) is particularly important in the case of large datasets, especially if they contain replicates of the same process – such as survey results from multiple farmers in the same industry, or time-series results from the same facility. For this reason, The UBC PRISM Lab (www.prismlab.weebly.com) has developed a Python-based LCA automation tool called LCAutomate, that interfaces with the openLCA software, using the Application Programming Interface (API) provided by Green Delta. This tool automates the LCA process from unit process creation to the calculation of LCIA results, including uncertainty assessment, contribution analysis, and graphical visualization. Development of this tool in the Python environment will allow for further integration with methods such as statistical analysis, and future integration of LCA with machine learning and other operations research methods. We demonstrate the utility of this automation software using a case study of a week-over-week dynamic LCA of Canadian egg production. This illustrates the potential for substantial time savings when analysing large datasets, which would otherwise be prohibitively time- and labour-intensive. Automating the LCI data entry and LCIA processes, rather than the generation of LCI data, allows for time savings without sacrificing the collection of large high-quality primary datasets.

Recent developments in the Australian Lifecycle Inventory Database (AusLCI)

Ms. Jamie Brown [1], ***Ms. Barbara Nebel*** [2], ***Mr. Tim Grant*** [1]

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2.thinkstep-anz

Recent updates to the Australian Life Cycle Inventory (AusLCI) database have standardised inventory modelling to align more closely with international reporting standards and datasets. The updates include integration with ecoinvent version 3 which supports AusLCI with the latest global datasets. Additionally, the inclusion of an EN15804-compliant dataset aligns AusLCI with international standards for Environmental Product Declarations in construction, facilitating the generation of EPDs under established international frameworks. The updates also introduce residual supply mix emission factors, enabling market-based electricity reporting, which accounts for renewable energy certificate transactions and is now required at the state level for EPD standards and nationally under schemes such as Climate Active. These updates improve consistency in the application of inventory data across Australian life cycle assessments.

What people just don’t understand about LCA

Ms. Nicole Sullivan
thinkstep-anz

To the converted, LCA is a tool that opens possibilities and illuminates hidden spaces of environmental impact. But there are many myths and misconceptions that relate to both LCA devotees and newcomers alike.
No matter where you are on the LCA spectrum, misunderstandings abound. They are grounded in lack of knowledge, lack of technical skill, lack of context, assumptions, wishful thinking and more.

This presentation will unpack common errors in thinking about LCA, including its benefits, errors and limitations, methods (who doesn’t want a debate about hybrid versus process LCA?), how it can be used at different stages of a project cycle, what it includes, etc.

After misconceptions are clarified, a clear way of thinking about LCA and what it can deliver will be outlined. It will have a focus on a strategic goal and scope to ensure that an LCA delivers what it needs to, and its limitations are understood before time and money are invested.

The presentation will close with an explanation of how the results of LCAs can be used to make a positive impact without stretching it too far so that it becomes a vehicle for greenwash. LCA is a powerful and impactful tool, but only when used wisely.

Communicating LCA results via EPDs: What are EPD Owners telling us?

Mr. Steve Mitchell ***, Ms. Kelly Taylor***

EPD Australia

In the last 10 years, EPD Australasia has published over 2,000 EPDs with verified LCA data for a large range of products. The data is developed and provided by over 140 Australia and New Zealand companies. But why do they do it? This presentation will cover the drivers for companies to undertake an LCA and voluntarily report on the potential environmental impact of their products. The representation will cover the international context driving EPD uptake and the pressures to drive development costs down without compromising data quality.

Confessions of an EPD Verifier: Part II - AI, Tools, and Evolving Product Category Rules

Mr. Andrew Moore

Life Cycle Logic

The Environmental Product Declaration (EPD) verification landscape is evolving rapidly with the integration of Life Cycle Assessment (LCA) and EPD tools, Artificial Intelligence (AI), and updated Product Category Rules (PCRs).

This presentation offers practical recommendations for organisations (EPD owners) and LCA consultants to streamline the verification process, ensuring robust and reliable EPDs. It highlights strategies for leveraging AI effectively, avoiding common pitfalls in LCA/EPD tool usage, and navigating the complexities of new PCRs. Real-world examples illustrate how these approaches can enhance efficiency without compromising accuracy. By adopting these recommendations, organisations can achieve faster, cost-effective verifications, facilitating broader EPD adoption and supporting sustainable decision-making.

10 years of BlueScope EPDs – learnings and next steps

Ms. Philippa Stone
BlueScope

In July 2015 BlueScope published an Environmental Product Declaration (EPD) for hot rolled coil, the first EPD published in Australia under the EPD Australasia Program. Today BlueScope has published EPDs across most of its product range, including key branded products such as COLORBOND® steel. Over this ten-year period, the EPDs for a number of these products, including hot rolled coil, have been updated twice.

This presentation will unpack the lessons learned by BlueScope over the past ten years and the changing market drivers for EPDs in this time. It will also look to the future, highlighting how BlueScope is currently using LCA to support the sustainability value proposition of its products and to create value for its customers.

Multicriteria analysis for evaluating trade-offs - Supporting decision-making in scaling up circular economy innovations

Dr. Mayuri Wijayasundara [1], Mrs. Anjulee Boralessa [2], Ms. Viveka Edussooriya [2], Mr. Yashodha Gunasekara [2], Dr. Rangam Rajkhowa [3]

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Transitioning to a circular economy requires evidence-based evaluation of emerging alternatives and innovations. Life cycle assessment (LCA) provides a robust framework for quantifying environmental impacts and supporting decision-making in this context.

A study was carried out to evaluate five processes developed by the Institute for Frontier Materials (IFM) at Deakin University for producing pigments from textile waste. Lifecycle carbon footprint analysis and financial cost modelling exercise conducted here informs decision-making on scaling the most environmentally and economically viable process to industrial production, supporting strategic technology selection and market positioning.

This study applies LCA methodology to assess the cradle-to-gate carbon footprint of the five pigment production processes scaled from pilot to industrial level: (1) pigment paste via vacuum filtration, (2) pigment paste via vacuum filtration with radiation treatment, (3) pigment powder via spray drying, (4) pigment powder via spray drying with radiation treatment, and (5) pigment powder via jet milling with radiation treatment.
The results indicate that, among paste-based processes, vacuum filtration combined with radiation treatment yields the lowest environmental impacts. In contrast, for powder-based processes, jet milling with radiation treatment shows the highest environmental sustainability, reducing the carbon footprint by over 50% compared to the spray drying pathway.

The case study illustrates how LCA can effectively guide complex decisions in scaling up innovative technologies with minimal environmental burdens. It underscores the critical role of LCA in providing practical, evidence-based insights to advance circular economy transitions and offers a framework for industries seeking environ-mentally sustainable production pathways. A multi-criteria evaluation integrating lifecycle carbon footprint assessment and cost modelling was undertaken to compare the environmental and economic performance of the five pigment production processes. However, due to commercial confidentiality, cost data and associated results are not presented in this paper, and only the LCA and cost modelling outcomes are presented as results.

Midpoint characterization model for water consumption impacts on aquatic ecosystem: RESCUE model

Dr. Masaharu Motoshita [1], ***Dr. Kamrul Islam*** [1], ***Dr. Markus Berger*** [2], ***Dr. Anne-Marie Boulay*** [3], ***Mr. Georg Seitfudem*** [3], ***Dr. Amandine Pastor*** [4], ***Dr. Stephan Pfister*** [5], ***Dr. Francesca Verones*** [6], ***Dr. Matthias Finkbeiner*** [7]

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The impacts of water consumption through life cycle of products/services/organizations have been the subject of considerable. AWARE model has been widely used for the assessment of the impacts of water consumption as a generic midpoint indicator, while demand for ecosystem-specific characterization models for water consumption has been increasing with the growth of request and interest on sustainable management of ecosystems along with the international initiatives, e.g. IPBES, Taskforce on Nature-related Financial Disclosures, and Nature Positive Initiative. In response to this demand, we have developed a new midpoint characterization model for assessing the impacts of water consumption on aquatic ecosystems: RESCUE model. The developed ecosystem specific model has some similarity with AWARE model in the modelling concept, while it specifically captures the potential impacts on aquatic ecosystems. First, environmental water requirement for aquatic ecosystem is defined based on the flow regimes in a watershed, and then, overconsumption of water by human activities is determined to assess the extent of deprivation of water for aquatic ecosystem as a potential impact on ecosystems. We have developed characterization factors for around 11,000 watersheds covering the whole globe which can be also aggregated into country scale. As a result, 80% of the global watersheds where we consume water already face the deprivation of water for aquatic ecosystem. The extent of deprivation reaches at 60% of water for aquatic ecosystem requirement. In this presentation, we present the details of the model and results, and highlight the similarity and differences between RESCUE and AWARE model.

Sustainability of global abiotic resource production: Integrating regional water constraints into life cycle-based assessment

Dr. Kamrul Islam [1], ***Dr. Keitaro MAENO*** [1], ***Dr. Ryosuke Yokoi*** [1], ***Prof. Damien Giurco*** [2], ***Prof. Shigemi Kagawa*** [3], ***Prof. Shinsuke Murakami*** [4], ***Dr. Masaharu Motoshita*** [1]

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3. Kyushu University

4. The University of Tokyo

Abiotic resource production is essential for economic development and the low-carbon transition but also causes significant environmental pressures. As a key component of the life cycle inventory in life cycle assessment (LCA), data on resource production—particularly water consumption—is critical for evaluating environmental impacts. Although mining accounts for only 2–4.5% of global freshwater consumption, it severely stresses arid and overexploited regions, often exceeding regional carrying capacities (RCCs) and threatening aquatic ecosystems. These pressures highlight the need for a regionalized, inventory-level understanding of water consumption in LCA. This study proposes a novel global abiotic resource production boundary constrained by regional water availability. Using water consumption intensity data for 32 major abiotic resources, we estimated global water consumption and identified overproduction by comparing consumption volumes to RCCs at the watershed level. We also analysed future water consumption under shared socioeconomic pathways (SSPs) that may lead to RCC exceedance. We used the 2010 global mining dataset from the SNL database (3,319 sites, 32 resources, representing 70–75% of global production). Water consumption was mapped at 0.5-degree resolution and combined with RCC estimates from the WaterGAP 2.2d model (~11,000 watersheds). Overproduction was quantified as water consumption beyond proportionally allocated RCCs. Under five SSP scenarios, future water consumption (2010–2100) was projected for coal, copper, iron, and nickel. In 2010, abiotic resource production resulted in ~6,739 (±1,564) million m^3 of water consumption—about 7% of global industrial freshwater consumption. Copper showed the highest overconsumption (37%), while coal had the largest volume (382 million m^3). By 2050, water consumption for copper, iron, and nickel may rise by 241%, 119%, and 239% under SSP1. Our framework provides a basis for evaluating the water sustainability of global abiotic resource production and informing strategies to manage future demand within environmental limits.

Comparison of LCIA approaches in a farming case study

***Dr. Maartje Sevenster* [1], *Dr. John Kirkegaard* [2], *Dr. Julianne Lilley* [2]**

1.CSIRO

2.Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Activity data from a 30-year on-farm experiment with six soil-management treatments were used to develop inventory data for environmental partial life-cycle assessment (LCA). The purpose was to compare treatments based on environmental outcomes and evaluate conservation agriculture (CA) in Australia.

Multiple trade-offs highlight the need for a nuanced approach to sustainable intensification and show that rules-based CA is not sufficient to guarantee low greenhouse gas (GHG) emissions, nor low overall environmental impact. In general, trade-offs were found to exist between impacts from on-farm activities versus upstream manufacture of inputs; between GHG emissions and land use (yield) versus other environmental categories; and between different on-farm GHG emission sources. Despite these trade-offs, the treatments all had similar overall scores in the Human health and Ecosystems damage categories. There was no single treatment with low, or high, impact scores across all environmental indicators, indicating that trade-offs need to be carefully considered when making farm-management decisions in the context of net-zero or carbon-neutral farming.

Multiple LCIA methods were applied, with associated adjustments of inventory and classification. The lack of consistency between LCIA methods, not just in characterisation models but also in classification, increases the risk of ill-informed decision making. Details of the match between inventory and impact assessment method are not often discussed in LCA studies. While foreground inventory is within the sphere of control – and the responsibility – of the LCA practitioner, background data are increasingly detailed and complex, and it is typically not feasible to check and adjust background inventory to match the LCIA method of choice. Documentation and metadata are often not sufficiently transparent. As LCA is increasingly mainstreamed and commercialised, and LCI as well as LCIA increasingly complex, the verification of data and methods can no longer be considered the responsibility of practitioners as was once the case.

Using LCAs to Support Fortescue's Sustainability Journey and LCA Capacity Building

Ms. Ilka Mitchell
Fortescue

Over the past 20 years, Fortescue has established itself as a global leader in iron ore exports from Australia. In recent years, the organization has embarked on an ambitious diversification strategy, expanding its metals portfolio and aggressively pursuing green energy and technology solutions. This shift is driven by a recognition that, as a major emitter, Fortescue must do more to decarbonize its operations and position itself as a leader in the energy transition. In pursuit of this, the company has committed to achieving real-zero emissions across its Pilbara operations, going beyond net-zero by eliminating fossil fuels rather than relying on offsets.

Recognizing that existing technologies were not advancing quickly enough to meet these ambitious targets, Fortescue established dedicated business arms to develop the green technologies, renewable energy solutions, and hydrogen production capabilities needed to meet its goals. As One Fortescue, the company shifted to-wards becoming a vertically integrated, diversified global business.

With this shift has come the recognition of a new set of trades off that need to be considered, and the need for new skills sets within the business to support this. One of the skill sets that has been bought into the business is Life Cycle Analysis. This presentation will focus on how Fortescue has stood up a team, how it supports a global business, how it has used technical mentors within the LCA space to fast track our capacity building, and how this skill set is supporting the sustainability goals that Fortescue has. This presentation explores how LCA has been used within the business, along with the challenges that have come as part of this journey.

From Transparency to Impact: Advancing Embodied Carbon Reduction in the Australian Construction Industry

Mr. Baron Law , Mr. Evan Smith

Holcim

As the construction sector accelerates its sustainability transition, Environmental Product Declarations (EPDs) are emerging as a critical tool for driving transparency and reducing embodied carbon. This presentation will showcase the development of Australia's first process EPD certification, the advancements Holcim has made through our EPDs on Demand 2.0 project, and the integration of EPD data into Holcim's database system for customer reporting, which will drive a comprehensive framework to ensure continuous improvement.

Key updates from EPDs on Demand 2.0 include automated EPD and verification report generation, compliance with new EPD standards, and updated life cycle assessment (LCA) database factors. With expanded materials coverage, allowing Holcim to continue to expand its range of EPDs including for its decorative concrete range (Geostone), ECOPact Max/Active, and mobile plants. Digitalisation has enabled more comprehensive embodied carbon monitoring, allowing real time reporting to ensure compliance to EPD validity.

Looking ahead, we envision a future of fully automated EPD generation, integration with Materials Intelligence Software like ORIS, and expanded collaborations with online databases that mine EPD data with AI APIs such as EC3 and the Low Carbon Materials Hub. By leveraging data APIs and geospatial intelligence, we aim to accelerate the adoption of low-carbon materials and support the next-generation LCA framework for a more sustainable built environment.

The Power of Early-Stage LCA: Driving Sustainable Design Decisions Before It's Too Late

***Mr. Sam Sandhay,* Fei Ngeow**

Cerclos

The path to sustainability in the built environment begins long before the first brick is laid—it starts in the earliest design phases, where decisions have the greatest potential to reduce carbon impact. However, many professionals hesitate to conduct lifecycle assessments (LCA) at this stage, due to concerns over data uncertainty and hence the results' reliability, the perceived complexity of the LCA, and the belief that the effort required does not justify the benefits at this stage. However, delaying LCA until later project phases often results in design decisions that are difficult or costly to alter, ultimately locking in high-carbon outcomes.

At Cerclos, we challenge this mindset. This presentation provides insights on the effectiveness of early stage LCA in sustainable design decision making and challenges the assumption that precise data and significant time in-vestment are necessary for meaningful results. In fact, being "vaguely right" early on is far more effective than being "precisely wrong" when it's too late to make meaningful changes. Our software enables designers, engineers, and sustainability consultants to quickly assess embodied and operational carbon impacts, set meaningful carbon reduction targets, and compare design alternatives—all within a matter of hours or days, not weeks.

Our findings emphasise that by integrating LCA from the outset, project teams gain the confidence to embed sustainability into their decision-making process without compromising cost or performance objectives. This presentation will explore real-world case studies demonstrating how early-stage LCA has successfully influenced project outcomes, proving that informed, proactive decision-making is the key to delivering low-carbon, high-performance buildings and infrastructure.

Bridging the Gaps: Aligning Industry Needs with Robust Sustainability Methods

***Mr. William Westaway* , Mr. Patrick Jeannerat**
Perspektiv Australia Pty Ltd

Sustainability decision-makers are under increasing pressure: they must demonstrate environmental integrity while navigating complex often conflicting methodologies. Faced with uncertainty or overly burdensome pro-cesses, many disengage—slowing progress when momentum is most needed. As sustainability experts, we have a responsibility to offer clear, actionable pathways that enable manufacturers and infrastructure projects to confidently communicate their environmental performance—without drowning in documentation, but with the assurance their claims are credible, defensible, and future-proof. Across our work in infrastructure, mining, construction, and heavy industry, we see a growing demand for practical solutions that move beyond traditional Environmental Product Declarations (EPDs). While EPDs provide a standardised snapshot, they are often the final output of sustainability efforts, not a reflection of the entire journey. The next generation of sustainability validation could go further—embracing dynamic, scenario-based tools like future-facing EPDs that capture an organisation's trajectory toward net zero. These approaches must recognise continuous improvement and identify, empowering businesses to demonstrate not just where they stand today but how they're progressing. This presentation is both an insight and a call to action. We'll outline key opportunities where sustainability science can better align with real-world industry needs: streamlining validation processes, ensuring claims hold up under scrutiny, and equipping businesses to tell their sustainability story confidently. We also invite the academic and professional community to collaborate—how can we refine sustainability methodologies to be both rigorous and accessible? How do we turn clear, credible guidance into meaningful, measurable outcomes? By bridging the gap between robust science and practical application, we can give decision-makers the clarity and confidence they need to accelerate impactful change.

Developing a national standard for on-farm GHG accounting

Dr. Annette Cowie
NSW Department of Primary Industries and Regional Development

There is a multitude of protocols, standards, calculators and platforms for GHG reporting, emissions trading and climate action claims. Standards and calculators vary with respect to system boundaries (sources and sinks included), allocation of life cycle emissions between co-products and between actors in the supply chain, and treatment of biogenic carbon fluxes. While it can be valid to apply different methods for different purposes, the plethora of different tools and standards creates confusion for users.

Mandatory climate-related financial disclosure, which commenced in January 2025, requires large corporates to report against the Australian Sustainability Reporting Standards. While most agricultural businesses are below the threshold for scope 1 reporting, most will be required to supply data for the scope 3 reporting of companies along their supply chain.

For other sectors, the National Greenhouse and Energy Reporting Scheme (NGERS) provides detailed methodology for quantification of emissions. However, the agriculture sector is not covered by NGERS, so there is no Australia-specific GHG reporting guidance available to the agriculture sector.

Recognising this gap, the Australian government is funding the development of voluntary emissions estimation and reporting 'standards' (VEERS) for the agriculture, fisheries and forestry industries. The CRC Zero Net Emissions Agriculture is working with the Department of Climate Change, Energy, the Environment and Water to develop a framework standard. Detailed methodology guidance will also be developed, both for organisation level and product level reporting. The standards will be consistent with the quantification methods and emissions factors used in Australia's national greenhouse gas inventory.
The voluntary national standards are intended to:

- improve the quality and consistency of GHG accounting methods and tools
- improve GHG accounting at the farm level to support mitigation action and market access
- reduce the reporting burden on farmers and land managers
- ensure farmers and landholders have trusted tools to understand their emissions.

Life cycle optimization of Canadian egg production for least environmental impacts and best animal welfare outcomes

***Dr. Ian Turner* , Dr. Nathan Pelletier**
University of British Columbia

In many regions around the world, egg industries are navigating a transition away from conventional cage pro-duction systems to alternative systems, driven primarily by animal welfare concerns. Alternative systems may, however, be characterized by differences in environmental impacts, and trade-offs across different kinds of animal welfare outcomes. Simultaneous improvement of both animal welfare and environmental performance, therefore, represents a set of potentially conflicting objectives that must be reconciled to support long-term sustainable development of egg production. In this study, reconciliation of these objectives was explored using a life cycle optimization-based approach and a case study of the Canadian egg industry. The environmental impacts of Canadian egg production in non-organic housing systems were quantified using environmental life cycle assessment, while animal welfare impacts were estimated using a recently developed animal welfare life cycle impact assessment method. These impacts were subsequently incorporated into a multi-objective optimization model solved using the weighted sum approach to determine the optimal distribution of egg production across alternative housing systems, given estimated differences in environmental and animal welfare impacts. Fifteen optimization scenarios were investigated, representing different sets of stakeholder preferences for improved environmental and animal welfare outcomes. Across all scenarios, the optimal solution was to produce all eggs in enriched colony systems, indicating these systems adequately minimize negative environmental impacts, while also maximizing positive welfare impacts. The results may provide valuable decision support for the Canadian egg industry, while also presenting a novel framework combining environmental LCA, animal welfare assessment, and mathematical optimization. This framework may be leveraged to provide decision support in the presence of potentially competing objectives with respect to environmental and animal welfare impacts, and may be extended in the future to also incorporate economic objectives to help better support evidence-based decision making for sustainable development of egg industries worldwide.

Partially dynamic life cycle assessment of Canadian egg production, differentiated by housing system and hen feather colour

***Dr. Ian Turner* , Dr. Nathan Pelletier**
University of British Columbia

Temporal changes in life cycle inventory data and impact assessment results are often overlooked in environmental life cycle assessment (LCA). Dynamic LCA (dLCA) has been proposed as a solution to this issue, though applications in agricultural systems remain relatively limited, particularly with respect to livestock production systems. Given anticipated increases in demand for livestock products and their substantial re-source/environmental impacts, identification and dissemination of sustainability best management practices in this sector is desirable. DLCA may be a useful tool for this, highlighting specific hotspots to target within live-stock systems that may otherwise be obscured when viewing production cycles using data that is averaged over time and space. This analysis presents the first partially dynamic LCA of a livestock system using a case study of the Canadian egg industry. Three partially dynamic LCA models were built: one representing production in enriched colony cages, and two representing production in aviary systems with white and brown feathered birds. Each incorporates dynamic inventories based on weekly productivity, mortality, and feed consumption data collected from Canadian egg farmers. The analysis yielded two key results. First, it illustrated how the environmental impacts of Canadian egg production change as the lay cycle progresses. Second, for those results beyond the standard 52-week lay cycle currently utilized in Canada, it facilitated comparisons of estimated im-pacts over extended lay cycles to previous analyses, in which the impacts of lay cycle extension were explored using LCI data derived from predictive models, as opposed to primary data. These results may subsequently be used in future analyses to determine optimal lay cycle lengths from an environmental perspective, which may differ from the currently utilized, relatively short cycle lengths and/or optimal cycle lengths from an economic perspective. This may also provide additional nuance to discussions regarding the sustainable development of the Canadian egg industry.

Updates to Australian agricultural LCI data in AusLCI

Dr. Isobel Hume [1], ***Dr. Sandra Eady*** [1], ***Dr. Marguerite Renouf*** [1], ***Dr. Maartje Sevenster*** [2], ***Mr. Tim Grant*** [1]
1.Lifecycles
2.CSIRO

Life cycle inventory (LCI) data for Australian agricultural commodities has been available in the Australian LCI (AusLCI) database since 2014. In 2024/25, the dataset was updated and expanded through work conducted by Lifecycles in partnerships with AgriFutures Australia (via the LCAgMetrics project funded by a Federal Government Sustainability Reporting Uplift Grant) and CSIRO (funded by the Grains and Cotton Research and Development Corporations). The LCAgMetrics project aimed to i) represent a wider range of agricultural commodities at farm gate, ii) represent current agricultural practices, iii) add post-farm processing, and iv) comply with best practice protocols for LCI development. This paper describes these broad project outcomes and reflects on the evolving data sources for agricultural LCI development. The coverage of the existing AusLCI data to farm gate (broadacre cropping, cotton, sugarcane, beef, some horticulture) was extended to include sheep (meat and wool), diary, meat chicken, pork, fodder, pulses and rice. Region-specific and state-average processes are represented to capture around 95% of national production. Current practices are represented using the latest publicly available gross margin data, reviewed and validated by commodity-specific experts. A notable development was new inventory for key post-farm processes (milling, ginning, scouring, animal feed processing, meat processing, haulage etc.) to enable supply chains metrics beyond the farm gate. Updates to ensure consistency with international consensus LCIA methods and international databases (ecoinvent) were mostly related to direct land use change and water use. The project identified new and evolving sources of digital and spatial data to support inventory development, related to land use change, nitrogen loss potentials, farm dams, and for performing whole of industry nutrient / fertiliser mass balances. The updated inventory development methods have been documented in a methodology document to support ongoing LCI development in Australian agriculture.

Digital Life Cycle Assessment for Sustainable Construction: A Review

Mrs. Evelyn Liew ***, Prof. Dominic Ek Leong Ong , Dr. Mohammud Irfaan Peerun***
School of Engineering and Built Environment, Griffith University

The construction sector remains a significant contributor to global greenhouse gas emissions and material re-source depletion. In response to escalating environmental concerns, Life Cycle Assessment (LCA) has gained prominence as a reliable methodology for quantifying and mitigating environmental impacts across the life-cycle of built assets. This study critically reviews the integration of digital technologies with sustainability practices. A mixed-methods approach, combining bibliometric analysis and a structured questionnaire was employed to evaluate current adoption levels and practices. Although digital tools such as Building Information Modelling (BIM), Digital Twins, and Internet-Of-Things (IoT) exhibit strong potential to enhance sustainability in the construction sector, their implementation re-mains limited and fragmented. Notable challenges include the lack of interoperable systems and fragmented data standards throughout the project lifecycle stages. In response to these barriers, the paper introduces a holistic framework designed to enhance data interoperability among digital tools and across lifecycle phases. The framework combines static and dynamic data sources, supports scenario analysis, and feeds results into interactive dashboards to inform decision-making. It aligns with international standards and is adaptable to certification benchmarks. While the framework shows strong potential for practical adoption, further pilot testing and regional customisation are needed. This study calls for coordinated industry collaboration to build digital capacity, establish standardised protocols, and mainstream LCA into routine workflows to support the transition towards net-zero and circular built environments.

Overcoming Data-Intensive Challenges in Building Life Cycle Assessment

Mr. Francisco Carbajal
Capana Group

Life cycle assessment (LCA) plays a significant role in evaluating the environmental impacts of building activities and is increasingly integrated into green building certification schemes. Despite its potential for comprehensive environmental impact assessment, the application of LCA to buildings remains challenging. This is particularly true for architects and engineers, who often attempt to carry out LCA themselves, only to find the process complex and time consuming, especially when applied to entire building systems.

Enabling architects and engineers to perform LCA early and easily during design can provide valuable insights, support better decision making, and help reduce environmental impacts. By integrating LCA directly into their workflow, the opportunity arises to inform design choices when they have the greatest impact.
This presentation addresses the data collection challenges in building LCA by showcasing the integration of Building Information Modelling (BIM) and LCA. A BIM-LCA prototype has been developed as a plug-in for Autodesk Revit. It has been trialled in New Zealand and is currently linked to LCAQuick, a New Zealand based LCA tool. This integration allows practitioners to assign LCA material templates directly to building elements in Revit while visualising the model. It also enables users to export project data, including detailed material quantities and specifications, into spreadsheets to support LCA processes using other tools, helping to reduce both input time and data errors.

While the prototype is currently based on the New Zealand material database, its structure is adaptable and designed for future connection with international databases and LCA platforms. The tool is also freely available to the industry, aiming to lower barriers to adoption and encourage wider use.

Investigating the environmental impacts of Australian buildings beyond embodied emissions: a spatially explicit, cradle-to-gate multi-indicator analysis

***Dr. Narges Emami**, Dr. Raymundo Marcos Martinez, Dr. Natthanij Soonsawad, Dr. Heinz Schandl, Dr. Alessio Miatto*

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Building construction affects human and ecological health beyond greenhouse gas emissions. This study quantifies the spatially explicit material stocks and environmental impacts of Australia's 13.8 million buildings by integrating detailed spatial and material data.

We used the Geoscape Building dataset to extract 3D volumetric data and classified buildings into six types based on form and function. Each building was linked to construction archetypes by period and typology, then matched with material assembly data to estimate embodied materials. Environmental impacts from material production (A1–A3) were assessed using the ALCAS Carbon Neutral method, while transport impacts (A4) were estimated based on material origins. Land footprints were calculated by summing the areas of individual structures.

The embodied GHG emissions in Australian buildings are estimated at 1.2 billion tons of CO_2e. Emissions vary by building type, with residential buildings at 183 kg CO_2e/m^2, commercial buildings at 393 kg CO_2e/m^2, and industrial buildings at 262 kg CO_2e/m^2. Besides, other impacts include significant acidification, with 3.5 Mt of SO_2-eq, and considerable freshwater ecotoxicity, of 11,865 trillion CTUe.

The production and transportation of ceramics account for the largest share of embodied emissions at 25.8%, followed by concrete (21.2%) and steel (16.8%). Single-family homes, comprising 91% of Australian buildings, contribute an average of 66.3% to the total environmental footprint across all impact categories. Industrial buildings, characterized by their high reliance on metal components, rank as the second largest contributors (11.4% on average) to environmental impacts.

This study demonstrates how spatially explicit material usage and impact data can inform integrated strategies for urban material circularity. Improving the environmental performance of building materials requires a comprehensive assessment of multiple environmental impacts rather than focusing on single sustainability targets. Adequate consideration of the long-term impacts of building types and materials is essential for achieving sustainable, liveable and resilient cities.

Integrating Circularity Metrics into Life Cycle Assessment: A Framework Based on Published EPDs in the Building Sector

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Global Green Tag International

The transition to a circular economy (CE) in the building sector requires more than just reducing environmental impacts, it also involves designing for maintenance, durability, recyclability, reusability, disassembly potential for reuse/recycling and repairability.

Life Cycle Assessment (LCA) is widely used to measure environmental performance and assess impacts linked to material use decisions in supply chains. Environmental Product Declarations (EPDs), as LCA deliverables, are becoming more common and use verified real-world industrial data. However, circularity-related information in EPDs is often missing or inconsistent or not clearly mentioned. Building products EPDs follow standards like EN 15804, which are mainly focused on attributional LCA impact reporting.

Although Module D (end-of-life recovery benefits) is declared in EPDs which often presents itself as an area where reliability of data used can impact the continuous adoption of circularity metrics into LCA. Module D is also not included in cradle-to-gate (A1-A3) EPDs or those covering A1–A3 with optional modules A4 and/or A5. This research proposes a simple and practical framework to support the integration of CE metrics using existing EPDs, especially those published through the ECO Platform. The study reviews case study EPDs published in ECO Platform portal across product categories in the building sector, such as concrete, steel, timber, and flooring, to identify available CE data and existing gaps. An analytical approach is used to assess the presence, clarity, and completeness of circularity-related information. Key CE metrics such as recycled content, end-of-life recovery are mapped using verified industry data.

The proposed framework aims to supports LCA practitioners, architects, engineers, and manufacturers in better understanding product circularity and aligning with circular economy regulations. It also helps identify and apply circularity indicators already present in EPDs, integrating them with environmental impact data in a single workflow.

From Waste to Resource: Biochar as a Carbon-Reducing Strategy in Philippine Rice Farming

Ms. Bernadette Magadia **, *Dr. Rex Demafelis* , *Ms. Anna Elaine Matanguihan* , *Ms. Mica Angel Evangelista***

University of the Philippines Los Banos

Rice is a staple crop in the Philippines, producing large quantities of rice straw as a byproduct—approximately one kilogram of straw for every kilogram of wet palay. Despite its abundance, rice straw is often left to decom-pose in flooded fields, contributing significantly to methane emissions, a potent greenhouse gas. This study, in partnership with Straw Innovations Ltd., investigated a potential sustainable pathway for rice straw utilization through biochar production, aiming to reduce the carbon footprint of rice farming which provides basis for future integration into carbon market and supporting the advancement of climate-smart agricultural practices. Three pyrolysis-based conversion scenarios were modelled using process simulation software: (1) pyrolysis, (2) pyrolysis with heat recovery, and (3) pyrolysis with both heat and carbon dioxide (CO_2) recovery. Each con-figuration was evaluated for its carbon dioxide equivalent per kilogram $kgCO_2e/kg$ of biochar produced. The second scenario achieved the lowest carbon footprint at 0.731 $kgCO_2e/kg$ of biochar. This system maximizes heat efficiency while converting methane to CO_2 that would be released into the atmosphere. This reduced the carbon footprint of conventional rice farming by 50.99%. The conversion of rice straw into biochar presents a dual environmental advantage: it prevents methane emissions from straw decomposition in flooded fields and sequesters carbon in a stable form in biochar. Future studies should extend beyond life-cycle emissions analysis to assess the techno-economic viability of heat-integrated biochar systems. This consists of comprehensive evaluation of capital and operating expenses, logistical strategies for straw collection and transport, and financial return timelines for investing in heat-recovery infrastructure. Additionally, estimating potential earnings from carbon credit markets is crucial. Conducting pilot-scale demonstrations is necessary to reduce risks with full-scale deployment and to evaluate broader impacts, including changes in crop productivity, soil nutrient retention, and elimination of open-field straw burning and rice straw incorporated in flooded fields.

LCA of water delivery infrastructure and irrigation technologies employed in cherry production in the Okanagan Valley (Canada)

Ms. Alyssa Smart , Dr. Nicole Bamber , Dr. Melanie Jones , Dr. Johannus Janmaat , Dr. Nathan Pelletier

University of British Columbia

Representation of the processes associated with, and the environmental impacts of, irrigation in agricultural systems is often simplified in life cycle assessment (LCA) to consider only water and energy consumption. In this research, an alternative approach is employed to add more nuance to the irrigation supply chain as a contributor to a more comprehensive suite of environmental outcomes, using a case study of cherry production in the Okanagan Valley of British Columbia, Canada. A regionalized life cycle inventory of Okanagan water de-livery systems was developed based on primary data from local water purveyors, and an LCA was performed to determine the share of environmental burdens associated with irrigation water, including the water supply network. For the water delivery system, the LCA results highlighted the importance of water treatment for a wide range of impact categories - demonstrating the need for dedicated agricultural water delivery that, unlike municipal drinking water, does not need to be treated.

The water delivery model was used in combination with an LCA of Okanagan cherry production conducted by Sanderson et al. (2019). Irrigation contributed a significant portion to most impacts of cherry production. In addition, the local water delivery model yielded significantly different impacts of cherry production (ranging from ~1/3 to double), compared to the generic ecoinvent irrigation process employed by Sanderson et al. (2019). Employment of more efficient irrigation technologies, such as drip irrigation (compared to microsprinkler), de-creased impacts in these categories by 10-16%. When the increased nitrous oxide emissions associated with drip irrigation were considered, drip irrigation still outperformed microsprinkler in every impact category except climate change, where higher impacts due to nitrous oxide emissions from drip irrigation were counteracted by the decreased efficiency of microsprinkler systems. This study highlights the importance of using detailed, regionalized LCI data for agricultural irrigation systems.

Carbon footprint of global wheat production and opportunities for decarbonisation

Dr. Nazmul Islam, Dr. Adam C. Castonguay

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Wheat is a vital global staple food, contributing significantly to global food security by providing around 20% of the world's daily calories and protein intake. It is one of the key staple foods, consumed by 2.5 billion people in 89 countries, with an average annual per capita consumption of 65.6 kg, representing 37% of the average per capita cereal consumption. Such consumption also contributes to global greenhouse gas (GHG) emissions, and opportunities for decarbonisation need to be identified. A scenario-based life cycle assessment was conducted in this study for wheat cultivation and flour production systems across the top 10 wheat-producing countries, producing around 80% of the global wheat. The study considered wheat cultivation, grain transport, processing, and milling processes. Carbon storage opportunity cost from land use was also simulated by estimating the spatially explicit and annualised carbon stock loss resulting from land clearing for wheat production. The study evaluated the contribution of the global wheat cultivation and flour production system to global GHG emissions. Then it evaluated the mitigation potential based on some of the available and emerging approaches, such as green Ammonia in the fertiliser supply chain, and renewable energy integration in the supply chain. Published scientific articles, open-access databases, industry and international organisation reports, and LCA databases were used to compile a life cycle inventory, and GHG emissions and mitigation for each country were then evaluated. The functional unit was defined as 1 tonne of flour wheat at the mill gate. The study highlights the data gaps for exploring the decarbonisation pathway of the global wheat industry. The insights from this study could help decision-makers to identify and optimize intervention strategies for a sustainable and climate-smart global wheat production.

Pathways to Carbon Neutrality: A Comprehensive Baseline Carbon Account for the Agriculture Sector in Northern Rivers NSW

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The NSW government has implemented Net Zero Plan and Climate Change Policy Framework to achieve 50% reduction in emissions below 2005 levels by 2030, and to meet Australia's target of net zero emissions by 2050. Local governments play a crucial role in these initiatives, requiring tailored GHG emission account to support progress towards the net zero targets. This study modelled a range of data using the Greenhouse Accounting Frameworks at the local government scale to establish a baseline carbon account for agriculture in the Northern Rivers Region, NSW (Richmond Valley, Ballina, Lismore, Byron, Tweed, Kyogle, Clarence Valley). The carbon account includes direct (Scope 1) and indirect (Scope 2, 3) emissions. Scope 1 emissions, primarily from livestock, account for 55% of the total emissions (910,154 tons of CO_2 equivalent (tCO_2-e)), with beef production being the highest contributor due to enteric methane followed by dairy emissions. The average carbon footprint of beef was relatively high, 20.9 kg CO_2-e/kg live weight. Scope 2 emissions from electricity contribute 3%, while Scope 3 emissions for goods and services, and transportation make up 25%. Carbon sequestration in plantations offsets

-17% of the total emissions (-278,869 tCO_2-e), highlighting the role of trees in achieving net zero targets including the co-benefits. We emphasize the need for targeted mitigation strategies in high-emission sectors like beef and dairy, promoting sustainable practices to reduce their carbon footprint. Local governments and policy makers can use this baseline carbon account to develop strategies and incentives for reducing emissions, potentially leading to economic opportunities such as carbon credits and funding for emission-reducing projects. Annual updates of emissions are recommended to inform policies and tracking of emissions. The Northern Rivers Region can make substantial strides toward net zero goals by prioritizing enhanced agricultural methods, emission-cutting technologies, plantation efforts, sustainable land management, and a streamlined value chain.

Unlocking Rapid Scaling Product Carbon Footprint Declarations – Key Lessons from the Food Industry

Ms. Jee Wei Tay [1], ***Mr. Simon Quick*** [2]

1.Rebuilt

2.Pollen Digital

Product labels are essential to driving industry improvements, meeting regulatory and providing informed choice for end consumers. Whilst there has been growth in construction product labelling (EcoLabels, EPDs) over the last decade, their overall growth rate is too slow to achieve the magnitude of change necessary to meet the climate change challenge of the world. The critical production limitations on product carbon footprint labels are data complexity and labour inputs to Life Cycle Assessment and verification process.

Recent calls by industry, in particular SME players, to reduce costs and level access to product label development have increased but with little practical action. Given the urgency of solving for these constraints it is helpful to look to other industries for lessons of scaling solutions.

The food nutrition labelling industry has evolved from basic ingredient listings in 1990's largely limited to aca-demic research to a significant commercial industry with growth driven by regulatory requirements, consumer preference, health awareness and technological progress. These in turn led to reduced costs and increased access to the mandatory food nutrition labels. Early nutritional analysis was primarily conducted by academic and research institutions with little commercial intent and were expensive. Today, AI-driven cloud software systems allow ISO food labels to be generated directly by the manufacturer (or appointed consultants) for less than A$2,000 per product, in some cases as little as a few hundred dollars.

The global food market is 10 times the size of the construction materials market with similar complexity but has successfully managed commercial scaling to a level we see as desirable for construction products. In this paper we examine the enabling technological and regulatory factors which supported this transition in the food industry and suggest how these could be implemented in the construction industry to achieve equivalent success for all stakeholders.

A dual-functional unit LCA framework towards absolute impact reductions: the case of residential buildings

***Mr. Gerasimos Christoforatos*, Prof. Kim Pickering**

University of Waikato

Current sustainability assessment frameworks for buildings typically rely on gross floor area (GFA)-based functional units, while the core function of accommodating occupants is ignored outside urban-scale studies. This disconnect can potentially lead to suboptimal design strategies and higher absolute environmental impacts. To address this, we propose a dual functional unit framework for building LCA that introduces functional multidimensionality and better aligns relative performance metrics with absolute sustainability goals. A life cycle assessment (LCA) is conducted on eight detached houses, focusing on embodied global warming potential (GWP), with results normalized by both GFA and occupancy. The comparison reveals substantial performance shifts—with some buildings' relative performance shifting from +13.9% per GFA to –36.5% per occupant. A multi-criteria decision-making (MCDM) method is employed to integrate both functions, generating composite scores that prioritize buildings performing well across both. The framework supports evaluation of products with multiple functions and offers a practical route toward absolute sustainability by relating impacts to broader societal roles, such as accommodation.

Assessing the global economic impacts of floods and their potential propagation through international trade

***Dr. Slim Mtibaa*, Dr. Keitaro MAENO, Dr. Kamrul Islam , Dr. Masaharu Motoshita**

National Institute of Advanced Industrial Science and Technology

With globally interconnected economies through supply chains, the economic impacts of flooding—one of the most devastating natural disasters—pose significant concerns for both direct flood-affected countries and their trade partners, raising critical challenges for business continuity and supply chain resilience. Considering these interconnected risks, there is a pressing need for a global assessment of direct economic losses and their potential propagation through international trade to support the development of flood-resilient supply chains. Here, to assess the generic global flood risks, we evaluate direct economic losses across different sectors and propose indicators for assessing the indirect impacts of flood propagation through international trade. We demonstrate that the estimated global annual economic loss across agricultural, industrial, and service sectors is US$194 billion. China, India, the USA, Indonesia, and Egypt are significant sources of flood-related risks due to their considerable direct economic losses and diverse export partners, collectively accounting for more than 50% of the global direct economic loss. Meanwhile, emerging and developing countries in Asia and Africa and some developed countries with concentrated imports from high-risk-giving countries show significant potential to be affected by flood impacts indirectly; the relevance of indirect risk to these countries differs from the sector. These findings highlight the importance of trade diversification—particularly toward partners with lower flood risk—as a strategy to reduce vulnerability to indirect flood impacts and mitigate supply chain disruptions. Therefore, the methods and indicators developed in this study provide a foundation for informing investment decisions, supporting business continuity planning, and strengthening global supply chain resilience. in the face of growing climate risks.

Tackling embodied carbon in Australia’s built environment

Ms. Nicole Sullivan
thinkstep-anz

It has been 6 short years since embodied carbon became a topic of serious interest for Australia’s built environment. The decarbonisation of our electricity grid, voluntary adoption of renewables and known mechanisms for improving energy efficiency was good news for national carbon reduction. But the elephant in the room for buildings and infrastructure was embodied carbon – locked in from the start of an asset’s lifetime, never to be recovered.

In 2019, the GBCA helped to shape the WorldGBC report “Bringing Embodied Carbon Upfront”. In 2020 they launched “Green Star Buildings” with the ground-breaking “Upfront Carbon Reduction” credit. Across 2020 and 2021, I worked first with the GBCA and then thinkstep-anz on the landmark Australian report, “Embodied Carbon & Embodied Energy in Buildings”. It has been referenced countless times, clearly justifying action on Australia’s embodied carbon footprint.

NABERS jumped on board in 2021 and by 2022, we were supporting their development of their NABERS Embodied Carbon rating tool, which has been released over 2024 and 2025.

The Infrastructure sector also jumped in. In 2023 we worked with Infrastructure Australia to quantify the embodied carbon in Australia’s buildings and infrastructure pipeline. It was released in 2024, along with Infrastructure NSW and then the national Infrastructure and Transport Ministers releasing technical guidance for measuring embodied carbon for infrastructure.

ASBEC released an Issues Paper in 2024 outlining seven “decarbonisation dilemmas” for Australia’s built environment, followed by extensive consultation and then a Policy Roadmap in 2025.

thinkstep-anz has been part of all this work and more – leading, supporting and guiding to ensure that we quickly move Australia’s built environment to a lower-carbon future. The presentation will outline our trajectory and methods for influencing change at a national scale with the help of LCA and data-driven decision making.

Understanding the Challenges in Agricultural LCAs: A Case Study of Australian Onions

Dr. Haoran Lei [1]***, Mr. Ossie Lang*** [2]***, Ms. Emily Moore*** [1]***, Dr. Doris Blaesing*** [2]***, Mrs. Donna Lucas*** [2]***, Dr. Chanjief Chandrakumar*** [1]

1.thinkstep-anz, **2.** *RMCG*

Climate change is already affecting agriculture and food systems globally. At the same time, food systems con-tribute significantly to climate change due to their substantial contributions to greenhouse gas (GHG) emissions, water use, and resource use. It is therefore critical to understand the environmental impacts of food production including GHG emissions, uncovering hotspots to improve efficiency and mitigating environmental impacts. To that end, this project aims to develop industry-wide benchmarks for GHG emissions from onion production in Australia. Onion growing activity data has been collected for representative farms across major onion growing regions in Australia. GHG emissions for each case study farm are calculated using life cycle assessments (LCA). The functional unit of this LCA is 1 kg of onion and the system boundary is cradle-to-farm-gate.

In this presentation, we will primarily discuss the key challenges that we faced during this and similar LCA projects – especially grower engagement and data collection. Additionally, we will present preliminary results of our LCA - including hotspots. Overall, the outcomes of this project will provide useful insights for current and future LCA practitioners in the field of agriculture.

Life Cycle Environmental Impacts of Melons Production in Australia

Dr. Haoran Lei [1], ***Mr. Ian Appleton*** [1], ***Mr. Edwin Chu*** [1], ***Ms. Emily Moore*** [1], ***Mrs. Joanna Embry*** [2], ***Mr. Johnathon Davey*** [2], ***Dr. Chanjief Chandrakumar*** [1]

1.thinkstep-anz

2.Melons Australia

Fruits and vegetables are indispensable for a balanced and healthy diet. Production and consumption of fruits and vegetables contribute to multiple environmental impacts globally - including climate change, water depletion and soil degradation. On the other hand, increasing environmental impacts threaten the production of fruits and vegetables. However, there is limited amount of information on the environmental performance of fruits and vegetables grown in Australia and none for melons grown in Australia. To that end, using a life cycle approach, this study, for the first time, evaluates the environmental impacts of producing watermelons in Australia – including climate change. Farming activity data has been collected for selected farms across major melon growing states in Australia and environmental impacts of each case study farm are calculated using life cycle assessment (LCA). The functional unit of this LCA is 1 kg of watermelon and the system boundary is cradle-to-farm gate. This on-going study will present the preliminary results of the LCA for case study farms - including major hotspots.

Product Environmental Footprint Benchmarking of Apple Production in the Okanagan Valley, Considering the Use of Bark Mulch to Meet Benchmark Requirements – A Life Cycle Assessment Study

Mr. Jared Brown [1], ***Dr. Nicole Bamber*** [1], ***Dr. Kirsten Hannam*** [2], ***Dr. Nathan Pelletier*** [1]

1. University of British Columbia

2. Agriculture and Agri-Food Canada

The Product Environmental Footprint (PEF) methodology developed by the European Union (EU) is increasingly being used to benchmark the life cycle environmental impacts of agricultural products and is expected to soon condition access to EU markets. With Canada seeking to increase economic ties with the EU, it is crucial that PEF benchmarks are developed to ensure future market access for Canadian agricultural products. However, few benchmarks have been developed for Canadian tree fruits and none have been developed for the apple industry in British Columbia's Okanagan Valley. On this basis, an ISO-compliant attributional life cycle assessment was conducted to establish benchmarks for Okanagan apple production, using the Hortifootprint Category Rules based on PEF guidelines. A scenario analysis considering the use of bark mulch as a soil treatment on apple orchards was also conducted to determine if growers could use it to improve benchmark performance, given its potential to reduce nitrous oxide emissions, irrigation needs, and herbicide needs. The life cycle inventory was modelled in OpenLCA with integrations from the ecoinvent, Agri-Footprint, and Environmental Footprint databases. Primary data on orchard operations and apple yield were collected from ten apple growers to develop industry-average PEF benchmarks, while irrigation, herbicide, and yield data from bark mulch and control plots were collected from Agriculture and Agri-Food Canada for the scenario analysis. The expected significance of this research includes the development of the first PEF benchmarks in British Columbia's tree fruit industry and the first study to quantify several previously unmeasured impact categories on bark mulch use in Okanagan apple production, including water use and ionizing radiation. Preliminary results suggest that bark mulch plots required 56% less irrigation on average compared to control plots over two growing seasons, suggesting that life cycle water use for Okanagan apple production may be lower through bark mulch use.

Assessment of the Baseline Carbon Footprint of the University of the Philippines Los Baños

***Dr. Rex Demafelis*, Ms. Bernadette Magadia, Ms. Anna Elaine Matanguihan , Mr. Eros Paul Estante, Ms. Angelica Ariel Mawili**

University of the Philippines Los Banos

In response to the Race to Zero (R2Z) global campaign led by the UNFCCC Champions for Climate Action in 2021, the University of the Philippines Los Baños (UPLB) recognized the need to promote sustainability and reduce its environmental impact. UPLB committed to establishing a roadmap to become a net zero or low-carbon university. However, carbon footprint (CF) measurement was not yet integrated into UPLB's operation, presenting a challenge for initiating sustainability efforts. To address this, a series of training workshops were conducted across UPLB units and offices to equip them in measuring and reporting their CF. Additionally, a university CF calculator was developed and utilized, enabling units to assess their emissions. Through collaborative participation, UPLB successfully calculated its baseline CF for 2021.

The study followed the Life Cycle (LCA) methodology framework as prescribed in ISO 14040, and the GHG Proto-col Corporate Standard was used to determine the emissions scope to be included in the University's emissions. The CF accounting aimed to identify the key sources of greenhouse gas emissions and to provide recommendations for minimizing the University's environmental impacts. UPLB's baseline CF for 2021 was calculated at 10,833.25 MT CO_2e, with Scope 2 emissions (from electricity consumption) being the largest contributor at 76.8%. Scope 1 emissions (direct emissions) and Scope 3 emissions (indirect emissions such as material consumption, indirect fuel emission, waste generation, and employee and student commuting) contributed 10.5% and 12.7%, respectively. Based on these findings, the University was advised to prioritize energy efficiency in its operations by reducing electricity and fuel consumption, exploring cleaner energy sources, and implementing carbon offsetting strategies. The results of this study can serve as a model for other universities in the country to conduct carbon footprint assessments in pursuit of a shared goal of achieving net-zero emissions in higher education institutions.

Multi-Method for Assessing the Sustainability Performance of Highways – A case study in Germany

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Institute of Sustainability in Civil Engineering - RWTH Aachen

Early decisions taken by contractors and clients in roads construction will define the impacts in the future. During the life cycle of highways, issues arise such as CO_2 emissions. Therefore, from the start of projects, it is crucial to evaluate material choices, energy sources, costs and potential impacts on humans.

The SusInfra (Sustainability in Infrastructure) addresses these challenges by developing a tool that will assist clients and contractors in taking decisions about the sustainability performance of their project proposals, since the early stages. Within this project, a framework has been developed based on life cycle sustainability assessment (LCSA) together with multi-criteria methods to support prioritization of indicators and rate project proposals for their sustainability performance.

For the environmental dimension, the framework addresses three phases. Initially, the LCA methodology is applied to a standard highway in Germany with variations of resources to quantify potential environmental impacts. The second phase involves a hotspots analysis to identify the most relevant impact categories and critical parameters over the life cycle, which will enhance the tool practicability. Finally, a rating system is in development based on benchmarks for the main impact categories in relation to roads and evaluating projects' performances.
Similar methods were applied for the social and economic dimensions, based on the S-LCA and LCC. Main indicators were selected, the potential risks and hotspots were identified, followed by the development of a rating system.

The framework will support the transparency of results, comparison of different projects and facilitate the presentation of the potential impacts of German roads. Preliminary results of the framework will be presented at the conference, introducing a new path for evaluating the sustainability performance of highway projects. This approach also highlights the importance of presenting LCSA results in an integrated way to support decisions for the future of sustainable infrastructures.

Environmental Performance of Australian Universities – The Case Study of the Queensland University of Technology

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1. Queensland University of Technology

2. Leibniz University Hannover

The environmental impact of the operation of an Australian University, i.e. the Queensland University of Technology (QUT), in 2022 has been assessed by applying the recently published life cycle assessment guidelines for Higher Education Institutions. Overall, 16 environmental impact categories were considered based on ISO 14072. QUT's energy supply was identified as the most substantial impact overall, accounting for over 48% in each of eight impact categories. Airconditioning (with the use of the refrigerant R134a) has the highest impact on the *ozone depletion* category. Transport exhibits the second most significant impact in eight of the 16 impact categories, mostly due to international air travel by international students and staff. Infrastructure has the most significant impact in six categories but is probably underestimated due to lack of data. In addition, suggestions how to reduce QUT's environmental impact are discussed. Subsequently, recommendations to develop the LCA guidelines for HEIs further are presented.

Operationalising Life Cycle Assessment in Facility Management: Capturing Infrastructure Dynamics to Support AASB S1 and S2-Aligned Sustainability Reporting

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1. *Australian National University*
2. *Rajarata University of Sri Lanka*
3. *Massey University*

The increasing adoption of mandatory AASB S2 (Climate-related Disclosures) and voluntary S2 (General Requirements for Disclosure of Sustainability-related Financial Information), is reshaping expectations for how organisations assess and report sustainability. Facility management (FM) organisations, as the custodians of large and diverse building portfolios, are central to delivering on these requirements, particularly regarding Scope 1, 2, and relevant Scope 3 greenhouse gas emissions, climate-related risk & opportunities identification, and scenario-based transition planning (AASB S2 29). Hence, there is a gap compared to the conventional reporting methods that often overlook the significant environmental implications of infrastructure dynamics, such as the electrification of systems.

This paper proposes an integrated framework that links LCA outputs to disclosure categories under AASB S1 and S2 by adopting a qualitative research approach based on secondary data. The framework suggested including scenario analysis of FM workflows to measure, monitor, and communicate the full life cycle impacts of dynamic infrastructure changes. By capturing both embodied and operational carbon impacts across the asset lifecycle, LCA enables FM providers to track the emissions consequences of infrastructure interventions over time, supporting informed planning and climate-aligned asset management. Furthermore, the proposed framework connects the LCA outputs with materiality assessment (S1 17-19), a critical component of the sustainability disclosures. The latter will elaborate on the sustainability impacts of the dynamic asset management components of the FM companies.

Future work will pilot the LCA-integrated framework across diverse facilities. FM organisations can lead climate-aligned decision-making by embedding LCA into operations, supporting AASB S1 and S2 compliance while enabling sustainable FM in a low-carbon-based built environment trajectory.

A review of recycling allocation methods in life cycle assessments of food waste reduction strategies within a circular economy framework

***<u>Mrs. Rathnayake Mudiyanselage Nisansala Subodhani Ranundeniya</u>*, Dr. Peter Stasinopoulos , Prof. Nirajan Shiwakoti , Prof. Simon Lockrey**

RMIT University

Halving food waste (FW) by 2030 requires a shift from the current linear model to a circular model in food production systems. FW reduction strategies, such as prevention, redistribution, reuse for animals, and valorisation, aim to retain or recover the value of wasted food in alignment with circular economy principles. Life cycle assessment (LCA) is used to assess the environmental sustainability of these strategies, where recycling allocation plays a critical role. Currently, there is a lack of studies that systematically review recycling allocation methods across FW reduction strategies. To address this gap, this study critically examines the application of recycling allocation methods in LCAs of FW reduction strategies within a circular economy framework. This aim is achieved through a comprehensive review of 73 scholarly and grey literature articles published between 2012 and 2023. A total of 76 FW reduction strategies were recorded, with 100:0 and 0:100 as the main methods reported. FW prevention is typically treated as a closed-loop system (54%), with 0:100 method assigning impacts to the product generating FW. However, 43% of prevention strategies excluded recycling impacts. FW redistribution mainly follows 100:0 (67%), while 33% strategies exclude recycling impacts. In FW reuse for animals, all studies use 100:0 method. Seventy percent of valorisation strategies used 100:0, while 30% deviated by incorporating upstream burdens. A significant variation is observed in the adoption of recycling allocation methods within and across FW reduction strategies, limiting the comparability of LCA results. The 100:0 and 0:100 recycling methods do not provide flexibility in allocating upstream environmental burdens to FW. Therefore, it is recommended to explore the suitability of other recycling methods for assessing FW reduction strategies. Further, a common recycling allocation method is needed to improve consistency and comparability in FW reduction LCAs.

Nutritional life cycle assessment (LCA) of shifting to pulses from animal sourced foods: an Australian case study of hummus versus ham sandwich

Mrs. Adeline Lanham [1], ***Prof. Jolieke van der Pols*** [1], ***Dr. Marguerite Renouf*** [2]

1. Queensland University of Technology

2. Lifecycles

Increased consumption of pulses has been suggested in response to global concerns regarding the environmental impact of the food system. However, Australian data for the environmental and nutritional implications of this dietary shift has been lacking. We therefore assessed the environmental and nutritional impact of consuming hummus or ham on a sandwich using Australian data.

The environmental impact of ham (produced in Australia or imported from Europe) and hummus (produced commercially, or homemade with canned or dried chickpeas), within the meal context of a sandwich were evaluated using LCA. Impacts considered were climate change, water scarcity and eutrophication potential. Life cycle inventory data were adapted for the Australian context, from cradle to plate. The nutritional value of ham or hummus sandwiches were evaluated using the Nutrient Rich Foods Index (NRF9.3 - including nine beneficial nutrients and three nutrients to limit).

Initial results indicate that the environmental impact of a hummus sandwich was lower than a ham sandwich across all environmental indicators, regardless of the production methods. Quantitative environmental impact indicators for each of the ham and hummus scenarios will be presented at the conference. A sandwich with homemade hummus had the greatest positive nutritional value (NRF9=0.23 for boys (aged 14-18yo); NRF9=0.28 for girls (aged 14-18yo)), with less nutritional value from the commercial hummus (NRF9=0.17 for boys; NRF9=0.28 for girls), and from ham (NRF9=0.09 for boys; NRF9=0.11 for girls). The score for nutrients to limit was largest for a sandwich with ham (NRF3=-0.12 for boys; NRF3=-0.12 for boys) than homemade hummus (NRF3=-0.08 for boys; NRF3=-0.08 for girls) or commercial hummus (NRF3=-0.08 for boys; -0.02 for girls).

Using Australian specific data, this case study demonstrated that hummus, in comparison to ham, in a sandwich, has a lower environmental impact and healthier nutritional profile. Localised data should be used in LCA studies.

Reducing Emissions in Cold Chain Grocery Transport: A Life Cycle Assessment of Passive Cooling with PCMs

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Australian National University

The global demand for cold chain delivery systems is rapidly increasing, driven by the need to transport temperature-sensitive goods such as food, pharmaceuticals, and specialised equipment. Currently, most cold chain logistics rely on active electric refrigeration systems powered by the vehicle's engine, typically diesel. In the case of refrigerated food transport, up to 94.8% of a truck's total cradle-to-grave emissions are attributed to the use phase alone. This presents a significant opportunity to reduce emissions through alternative cooling strategies, such as passive systems using phase-change materials (PCMs). While prior studies have examined the potential of PCMs for cold chain applications—focusing on thermal performance, material selection, and configuration optimisation—their broader environmental implications remain under-explored. This study addresses this gap by conducting a comparative cradle-to-grave Life Cycle Assessment (LCA) of two delivery systems: one employing conventional mechanical refrigeration, and the other using PCM bricks within an unpowered, insulated compartment. The LCA will use a functional unit of one tonne of cold grocery delivered within a 10 km radius while maintaining temperature at 4 °C ± 2 °C, and will assess various PCMs, considering manufacturing, use, and end-of-life phases. Sensitivity analyses will be performed to account for variations in ambient temperature, fuel efficiency, PCM volume, refrigeration performance, and traveling distance. The study aims to identify conditions under which PCM-based systems can minimise overall emissions. Preliminary expectations suggest that while PCM systems may incur slightly higher emissions during manufacturing and disposal, they are likely to offer meaningful reductions in use phase emissions, contributing to more sustainable cold chain logistics.

Enabling Circularity in 3D Printing: Life Cycle Sustainability Assessment of Recycled PLA Gear Components

Mr. Mohammad Raquibul Hasan **, *Dr. Ian Davies, Dr. Alokesh Pramanik , Dr. Michele John, Prof. Wahidul Biswas***

Curtin University

This study evaluates the technical and life cycle sustainability of the use of post-consumer recycled polylactic acid (rPLA) in fused deposition modelling (FDM) for 3D-printed gear components. Five material compositions ranging from 0% to 100% rPLA were assessed for mechanical and functional performance, alongside a life cycle sustainability assessment (LCSA) integrating environmental (ELCA), economic (LCC), and social (SLCA) indica-tors for determining the sustainability score for each blend. Mechanical testing showed a slight reduction with higher rPLA ratios, but all blends retained functional gear performance. V50:R50 achieved the highest sustain-ability score (-1.29), offering a balanced trade-off. Findings support rPLA's viability in non-critical applications and highlight the need for quality assurance in circular additive manufacturing.

The Effect of Upcycling and Downcycling on Emission Factors: A Qualitative Framework for Circular Economy in Industrial Waste Treatment

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The transition to a circular economy presents significant opportunities for reducing environmental impacts through improved waste management practices. This work explores the qualitative effects of upcycling and downcycling on emission factors, focusing on the role of industrial waste treatment in supporting the circular economy. The primary question addressed is: How should emission factors in downstream waste management reflect the different scenarios of upcycling and downcycling within a circular economy framework?

In the context of circular economy strategies, upcycling and downcycling represent key waste management pathways with varying environmental consequences. Upcycling, where waste is repurposed into higher-value products, typically leads to reductions in emissions by decreasing the need for raw material extraction and lowering energy consumption. In contrast, downcycling, which involves converting waste into lower-value products, may result in higher emissions, especially when secondary products require more energy-intensive processing or have shorter lifespans.

This paper presents a conceptual framework to guide the understanding of how emission factors should be adjusted in LCA studies to account for these upcycling and downcycling processes. The framework emphasises the importance of considering the full life cycle of both the waste treatment process and the final products, particularly in the context of varying material quality and processing requirements. The paper also highlights the need for consistent and reliable data to accurately reflect the impacts of these circular economy strategies. By offering a theoretical approach to understanding emission factors in the circular economy, this paper aims to support future research and policy development, providing a basis for companies and researchers to better integrate upcycling and downcycling into sustainable waste management practices.

Life Cycle Assessment of Different Pathways for End-of-Life Management of LDPE Packaging Waste

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Low-Density Polyethylene (LDPE) is widely used in the building and construction sector for packaging, protecting materials, and facilitating their handling and transportation. However, its use in Australia typically follows a linear 'take-make-dispose' model that results in significant environmental impacts. Properly managing this waste resource is essential, as it can reduce the environmental impacts of construction activities. One key step is ensuring LDPE remains within the economy as long as possible through effective end-of-life (EoL) management to support a Circular Economy (CE). This study employed Life Cycle Assessment (LCA) to assess the Greenhouse Gas (GHG) emissions associated with three alternative EoL management scenarios for LDPE used as packaging for construction materials. These alternatives include waste-to-energy, mechanical recycling and chemical re-cycling and were compared to the business-as-usual practice of disposal in the landfill. The study used waste management and resource recovery system in Victoria, Australia. The findings show that mechanical recycling is the most favourable option, followed by chemical recycling. Considering the offset that can be achieved by the avoided virgin polymer production in these scenarios, they present significant advantages compared to disposal in the landfill. The suitability of these two pathways, however, depends on waste characteristics, with factors such as contamination, mixing with other waste, and the need for washing and sorting affecting both the choice of pathway and overall emissions. Additionally, among all activities within the life cycle, the production of LDPE packaging from virgin polymer accounted for over 50% of the total GHG emissions across all scenarios, highlighting the significance of this stage. The findings provide actionable recommendations for practitioners and policymakers in developing best practices for the life cycle management of LDPE packaging in construction, ultimately contributing to CE and reduced GHG emissions.

Future-oriented LCA of emerging SBC technology within transportation

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Lithium-ion batteries (LIBs) in the mobility sector are expected to increase with the electrification of transport. New technological innovations in electric vehicle (EV) LIBs include structural batteries that due to their mechanical stiffness and energy storage capacity can replace structural parts as well as parts of the battery in the vehicles. This offers potential for mass savings, advancing the state of the art in EV lithium-ion-based energy storage. Based on early and preliminary assessments, structural batteries are expected to be significant in improving the technical and environmental performance of EVs.

In this study, prospective LCA methodology was used to assess the environmental performance of structural battery composites (SBCs) at early stages (TRL 3). These SBCs are currently produced only at laboratory scale at Chalmers University of Technology in Sweden. The aim was to guide in technical development by providing early estimates of environmental impacts associated with SBC production, from a life cycle perspective.
Hotspot analysis identified contributing processes and helped explore improvement opportunities with environmental life cycle assessment. The effect of shifting to new technology generations as well as the effect of different scenarios, associated with parameters considered in production upscaling was also assessed. To complement this analysis, computer-aided design was used to explore the use of SBCs in vehicle components in an example application: EV quadricycles. Gains and tradeoffs were identified, providing useful information about eco-design.

The study generated insights into the possibility of advancements towards sustainable transportation. Challenges were highlighted related to data gaps and lack of information on technical requirements, as well as actual performance of SBCs in intended uses. Important factors in SBC technology development, production assessment and environmental life cycle assessment were identified. The prospective LCA provided recommendations for future research and development for the emerging SBC technology.

Life Cycle Assessment of Waste Tyre Recycling in Australia

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Deakin University

Australia produces approximately 537 thousand tonnes of waste tyres (WTs) each year, with only about 66% re-covered for civil engineering applications; the remainder is either landfilled or stockpiled. In civil engineering, tyre-derived granules and crumbs are limited to 5–10% binder substitution in road construction due to structural performance constraints. Additionally, substituting sand with granules in concrete increases the carbon footprint. These challenges underscore the need for more sustainable management strategies. To address this, the present study applies a Life Cycle Assessment (LCA) using SimaPro to compare pyrolysis to current practices, such as landfilling and crumb rubber production, in Australia. The assessment uses 1 tonne of WTs as its functional unit, with inventory data sourced from Tyre Stewardship Australia and published studies, adapted for Australian conditions. The results show that pyrolysis emits (255 kg CO_2 eq per tonne), which is lower than crumb rubber production (278 kg CO_2 eq per tonne) and landfilling (598 kg CO_2 eq per tonne) under the current electricity generation scenario. It is important to note, however, that crumb production will have a comparable GWP to WT pyrolysis due to the absence of direct greenhouse gas emissions. Looking ahead, the electrification of pyrolysis is expected to be the most sustainable pathway, given its lower electricity consumption compared to crumb production. Therefore, based on these findings, pyrolysis is recommended for treating WTs in Australia.

Comparative LCA of OTR tyre repair programme.

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Edge Impact

Edge Impact conducted a cradle-to-grave life cycle assessment (LCA) to evaluate the environmental benefits of a tyre repair program for off-the-road (OTR) tyres. The assessment compares the environmental impacts of tyres repaired up to two times with those disposed of after initial damage, examining variations in repair severity, number of repair locations, and end-of-life pathways.

The baseline LCA covered eight models of OTR tyres receiving minor repairs, while scenario analyses focused on exploring differences in repair frequency, severity, repair location, and EoL recycling rates. Sensitivity analyses examined the influence of transport distance to repair facilities and energy sources on overall impacts.

The results will inform the client's sustainability strategy and support the development of a third-party verified carbon calculator specific to the tyre repair process.

Integrating Life Cycle Thinking Principles in Transport Infrastructure Design and Maintenance

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Numerous extreme weather events around the world show the dramatic consequences of climate change. New approaches are needed to counter this trend. As part of the project SusInfra, a sustainability assessment tool will be developed to evaluate sustainability performance in road construction, with particular attention for CO_2-eq emissions. The concept of the sustainability assessment tool will be introduced, focalizing the assessment on the carbon footprint in which the CO_2-eq emissions across the entire life cycle of a highway in Germany are assessed and quantified by Global Warming Potential ($kgCO_2$-eq) indicator. These emissions will be quantified by numerous simulations using the LCA-Software "GaBi" (Sphera) with varying key input parameters. The Input parameters, such as materials, energy supply, transport distances, and machine usage, along with the impact category results are used as foundational data to identify patterns, which can then be used to optimize the planning process of roads. The tool delivers intermediate data for e.g. CO_2-eq emissions of specific processes and materials, ensuring that future innovations in processes or materials, documented e.g. in the form of LCAs or EPDs, can be specifically integrated into the tool by exchanging the intermediate data ensuring the tool remains relevant in the future. The sustainability assessment tool will provide reliable information e.g. on the climate impact of a road project from cradle to grave and enable the formulation of functional tenders aligned with the principles of "green public procurement" (GPP), incorporating environmental performance into the decision-making process for road construction projects.

Evaluating the Environmental Impact of Australian Hempcrete Using a Life Cycle Assessment Approach

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The global construction industry contributes significantly to greenhouse gas (GHG) emissions, with infrastructure accounting for 18% of GHG emissions in Australia. To meet climate targets and decarbonise the building sector, the use of eco-friendly building materials is essential. Hemp-based construction materials gain popularity due to their environmental benefits, which include a short crop growth cycle, the capacity for long-term carbon sequestration in the final product, and low thermal conductivity in service. Our research explores the environmental impact of hempcrete in construction, highlighting the role of life cycle assessment (LCA) research in understanding the environmental impacts of new biomaterials. This project assesses the environmental im-pacts of $1m^2$ of wall in residential housing. We expect hempcrete to outperform traditional materials in terms of fossil fuel depletion and global warming potential, and that long-term carbon sequestration in Australian hempcrete leads to a negative carbon footprint, with binder production contributing significantly to GHG emissions. The production of raw materials remains the primary source of environmental impacts, which biogenic carbon sequestration and carbonation of hempcrete can mitigate. However, the transport distance of raw materials, manufacturing processes, and the composition of binder and other materials in building aggregates may have a significant environmental impact that is not yet fully understood. LCA serves to better comprehend this material's carbon potential as a green building material. The results of this comprehensive LCA inform policy formulation, guide the development of the emerging hemp industry, and contribute to lower GHG emissions in Australia's construction sector.

A cradle-to-gin-gate GHG assessment of global cotton lint production and mitigation scenarios

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Globally, Cotton (*Gossypium hirsutum* L.) production contributes one-quarter to the total textile fibre industry. A scenario-based life cycle assessment (LCA) was conducted on data across 19 countries investigating global cotton lint production, which contributes ~95% of the global cotton lint production. The analysis centred on two key aspects; namely: (1) the contribution of cotton lint production to global greenhouse gas (GHG) emissions, and (2) the evaluation of mitigation strategies based on emerging technology (e.g., the use of Enhanced Efficiency Fertilisers (EEF) in cotton production, Green Ammonia in the fertiliser supply chain, and renewable energy integration in the ginning process) and existing practices (e.g., reduction of nitrogen application rates, energy efficiency increase for irrigation and ginning, and improved farm mechanisation systems such as electric tractor). The analysis was performed by considering the farm-to-gin gate boundary. The data sources included open-access databases, published scientific articles, industry reports, and LCA databases. The study compiled a life cycle inventory for cotton production from multiple sources, subsequently used to calculate GHG emissions and mitigation for each country. The functional unit was defined as 1 tonne of cotton lint at the gin gate. Limitations that arose from the analysis, such as the urea demand increase in response to yield increase, competing use of ammonia for fuel and fertiliser, high cost of renewable energy in developing countries, and additional cost of EEF, are also discussed. Key data gaps, in both developed and developing countries, are highlighted that need to be addressed before defining an effective, transparent, and reliable decarbonisation pathway for the global cotton industry.

GHG Emission Assessment of Industrial Hemp Cropping Across Australia Regions

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Industrial hemp (*Cannabis sativa* L.) is a low tetrahydrocannabinol (THC) crop legally grown for food, fibre, and industrial applications. It is well regarded for its versatility, ability to grow in a wide range of climates, and perceived environmental benefits, including lower water and fertiliser requirements compared to conventional grain crops. In Australia, both grain and fibre varieties are cultivated across several regions with varying soil and climate conditions. However, most claims about hemp sustainability rely on data from overseas, where pro-duction conditions differ significantly from those in Australia, establishing a pressing need for local evidence to support sustainable production. Currently, there is limited information on the environmental performance of domestic cropping practices, which poses risks for investment and industry development. Without robust local data, the industry may rely on unverified claims that are not applicable to Australian conditions. Thus, this study aims to conduct a greenhouse gas (GHG) assessment of hemp cropping in different Australian regions using life cycle assessment (LCA). The functional unit is defined as 1 tonne of grain, and the system boundary is set from cradle-to-farm gate. Primary data (fertilisers, pesticides, water, energy for irrigation and machinery) collected from research trials and a dedicated industry survey is combined with secondary data from AusLCI and Ecoinvent3. Preliminary results indicate that key contributors to emissions include energy related emission from irrigation and inorganic fertiliser especially urea production, both of which show regional differences. On-going work will model varietal differences and benchmark results against conventional grain crops. This work forms the initial stage of a broader cradle-to-gate assessment of hemp oil in comparison with other industrial crop-based oils.

Unveiling Hydrogen's Hidden Footprint: A Comparative LCA of Green Hydrogen Production Pathways in India

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Green hydrogen as an energy carrier is key to transition to sustainable energy systems and global decarbonization. However, since environmental impacts vary with technology and energy source, an life cycle assessment (LCA) is essential to holistically assess and compare hydrogen production pathways. This study conducts LCA of hydrogen generation employing grid, solar-powered battery energy storage systems (Li-ion and lead-acid), solar photovoltaics, and wind as electricity sources for electrolysis technologies. A cradle-to-gate framework is applied using OpenLCA 2.3 with the ecoinvent database and ReCiPe Midpoint (H) and Endpoint (H/A) methods, assessing 18 midpoint and 3 endpoint environmental indicators.

Results indicate that SOE shows the highest climate (5.44, 3.11 kg CO_2-eq) and AEM the highest water depletion (37, 19 L) impacts when powered by solar or wind. but the lowest (57.49 kg CO_2-eq, 213 L) when powered by the SOE grid. Conversely, AWE exhibits the lowest climate impact (4.28, 1.12 kg CO_2-eq) under renewables, but its impact rise sharply to (74.77kg CO_2-eq) when grid-supplied, second only to PEM at (74.99 Kg CO2-eq). Endpoint analysis reveals grid-powered hydrogen has greater overall impacts, dominated by human health, followed by resource depletion and ecosystem quality. These findings emphasize the decisive role of renewable integration in achieving sustainable hydrogen pathways, particularly for emerging economies like India.

Life Cycle Assessment (LCA) of the use of renewable sourced hydrogen for fuel cell electricity generation

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The world is currently undergoing a massive energy transition from fossil fuel energy sources into carbon-free and renewable energy sources. In Australia, the same as many other countries, the development of a low-carbon energy system is of priority. Hydrogen has gained interest in recent years for the role it can play in the global clean energy transition.

As hydrogen is not freely available in nature, it has to be extracted from existing fuels or chemical compounds. The current study focuses on estimating the global warming potential (GWP) from the production of green hydrogen, where water molecules are electrochemically split to produce oxygen and hydrogen, and stored to subsequently produce electricity from the hydrogen using fuel cells.

The life cycle assessment (LCA) is performed by evaluating the various scopes of emissions involved in the manufacture and operation of the system. The main system components are the electrolyser for hydrogen production and the fuel cells for electricity generation, with renewable energy sources from solar PV and wind turbines evaluated. It was found that the system with wind only had the least GWP (22.14 kg CO_2 eq/ MWh) followed by solar only (37.7 kg CO_2 eq/ MWh), then wind and solar combination (56.59 kg CO_2 eq/ MWh) and finally the integrated wind, solar and battery system (87.05 kg CO_2 eq/ MWh). The capacity factor and lifetime of the solar PV farm and wind farm affected the process GWP the most, as increasing the capacity factor was found to significantly reduced the process GWP.

Decarbonising Electricity for Recycling: Impacts on Municipal Waste Glass Recovery in Victoria

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Australia's electricity generation remains dominated by coal, which accounted for 46 percent of output in 2023. With the Australian Energy Market Operator's "Step Change" scenario targeting 82% renewables by 2030, this study examines how electricity decarbonisation may influence emissions from municipal waste glass recycling. Piloted in Yarra City Council, Melbourne, the study compares life cycle emissions from two systems: mixed kerbside recycling bin (MKRB) and separate municipal waste glass bin (SKGRB), both supplying recycled glass for asphalt production. A hypothetical scenario was modelled in which 50% of coal-fired electricity in Victoria's 2022 mix was replaced with zero-emission renewables. Under this cleaner mix, emissions from the sorting stage fell 26% in the SKGRB system and 37% in the MKRB system, due to higher electricity intensity in the latter. The total emissions for one ton of asphalt decrease to 93.58 kg CO_2-eq for SKGRB and 131.29 kg CO_2-eq for MKRB. This corresponds to reductions of 1.35 kg CO_2-eq and 23.15 kg CO_2-eq per ton of asphalt. Findings highlight the importance of coordinating recycling strategies with electricity transition planning to ensure consistent climate benefits.

Incorporating LCA into healthcare decision making

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Healthcare represents nearly 11% of global GDP and 4.4% of global greenhouse gas emissions, creating a paradoxical situation where healthcare provision contributes to climate-related health impacts. With 63 countries pledging low-carbon health systems, and Australia targeting health system decarbonisation through its National Health and Climate Strategy, there is growing interest in integrating Life Cycle Assessment (LCA) into Health Technology Assessment (HTA). HTA is currently used internationally to decide which drugs and interventions to fund based on economic cost and health outcomes. This paper examines the methodological challenges of incorporating environmental impacts into cost-effectiveness analyses (CEAs), the primary method used in HTAs worldwide.

There are several challenges. In terms of LCA they include which methodology to use, such as environmentally extended input output (EEIO) or process-based LCA, and attributional or consequential LCA. From a CEA perspective they include how to integrate emissions into CEA models, and whether to monetise emissions or use them as decision modifier. Current limitations to the integration include insufficient LCA data for healthcare interventions and a skill shortages among practitioners familiar with both LCA and healthcare more broadly and health economics specifically.

Life cycle assessment of emerging PFAS removal technologies in drinking water treatment in Sweden

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Contamination of drinking water with per- and polyfluoroalkyl substances (PFAS) is a growing public health concern because the substances are associated with immune dysfunction, reproductive and hormonal effects, liver damage and certain cancers. Regulatory standards are increasingly stringent — for example, Sweden's Drinking Water Directive sets limits for the year 2026 at 4 ng/L and 100 ng/L for the total concentration of a group of four and twenty-one PFASs, respectively. Conventional water treatment methods are insufficient for PFAS removal, prompting the development of advanced technologies such as granular activated carbon (GAC), ion exchange (IEX), nanofiltration (NF), reverse osmosis (RO), foam fractionation (FF), and electrochemical oxidation (EO).

These technologies can vary not only in removal efficiency but also in their environmental and resource foot-prints. Trade-offs between energy use, material inputs and byproduct management mean that performance alone is not a sufficient criterion for technology selection. This study applies life cycle assessment (LCA) to evaluate the environmental impacts of two treatment trains designed to remove PFAS at a municipal water treatment plant in Sweden.

The assessment aims to identify key environmental hotspots and identify trade-offs across technologies, with particular attention to energy consumption, emissions and waste generation. By evaluating these systems holistically, the study supports evidence-based decisions for selecting sustainable PFAS treatment solutions under evolving regulatory conditions. The findings are intended to guide utility managers in aligning public health protection with environmental responsibility.

Does reusable mean less environmental impact? A systematic review of the environmental impacts of medical plastics, challenges, and gaps

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Background: The application of medical plastics, such as disposable medical plastics, is increasing and causing different challenges during disposal. The individual and collective environmental impact of these plastics is rarely investigated.

Objective: This review aims to summarize the environmental impacts of selected medical plastics in the health-care systems using Life Cycle Assessment (LCA) at different life cycle stages.

Method: Five databases, PubMed, MEDLINE, Google Scholar, Science Direct, and CINAHL, were used for the search. The environmental impact of 46 plastic products was summarized at different life cycle stages. The Global warming potential and selected environmental impact indicators were reviewed and analysed for the single and reusable item medical plastics.

Result: A total of 46 single-use and 17 reusable medical products were assessed for their global warming potential per item. Nine reusable items were analysed based on their functional units. A significant variation was observed among the single-use items, with the range of the global warming potential for the selected products being 0.013-109 kg CO2 eq. of Single-use operation room bed cover recorded the highest while surgical masks recorded the lowest carbon footprint per item. Similarly, for reusable medical products, the range was 0-19.8 kg CO2 eq., with the reusable operation room bed covers recorded as the highest and a multi-use blade recorded the lowest carbon footprints. According to the hotspot analysis, production was the most important source of the global warming potential for single use medical plastics whereas cleaning, disinfection, and sterilization were the main contributors for reusable products.

Conclusion: The review of the environmental impacts of different medical plastics shows significant variability across products and various stages of the life cycle stages of the products, and an evidence-based decision must be made carefully when comparing the products.

Papers

LCAutomate: Development of an automation code for LCA unit process creation, LCIA calculation, and graphical representation

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Abstract

There is a growing body of research on the simplification of LCA – methods to increase the efficiency of detailed, process-based LCA, removing barriers to performing LCA whilst maintaining an acceptable degree of rigor. If done appropriately, this could lead to greater uptake and implementation of LCA methodology and better, evidence-based decision support. Automated calculation of LCIA results and automated LCI data generation were two areas of particular potential for simplification. Many LCA tools are being developed that aim to automate LCI generation, but few have focused on automated LCIA calculation. Automated calculation (also requiring serial unit process creation) is particularly important in the case of large datasets, especially if they contain replicates of the same process – such as survey results from multiple farmers in the same industry, or time-series results from the same facility. For this reason, The UBC PRISM Lab (www.prismlab.weebly.com) has developed a Python-based LCA automation tool called LCAutomate, that interfaces with the openLCA software, using the Application Programming Interface (API) provided by Green Delta. This tool automates the LCA process from unit process creation to the calculation of LCIA results, including uncertainty assessment, contribution analysis, and graphical visualization - providing 10-fold time savings. Development of this tool in the Python environment allows for further integration with methods such as statistical analysis, and future integration of LCA with machine learning and other operations research methods. We demonstrate the utility of this automation software using a case study of a week-over-week dynamic LCA of Canadian egg production. This illustrates the potential for substantial time savings when analysing large datasets, which would otherwise be prohibitively time- and labour-intensive.

Automating the LCI data entry and LCIA processes, rather than the generation of LCI data, allows for time savings without sacrificing the collection of large high-quality primary datasets.

Keywords: automation; high-throughput LCA; automated LCA; primary data; dynamic LCA

Introduction

Among the many challenges associated with performance of high-quality, rigorous life cycle assessment (LCA) studies, the amount of effort required to implement LCA at scale in a high-throughput manner represents a large bottleneck that may hinder sustainable development (Lettner and Hesser, 2020). In response to this challenge, there is a growing body of literature dedicated to the simplification of LCA to improve the efficiency of detailed, process-based LCA whilst maintaining an acceptable degree of rigor (Naser et al., 2023). Automated generation of life cycle inventory (LCI) data, and calculation of life cycle impact assessment (LCIA) results, in particular, have been identified as key foci for potential simplification (Kiemel et al., 2022). While progress has been made towards this goal (for example, Haun et al. (2022)), rarely do such efforts focus on automating LCA from the perspective of large, high-quality primary data sets containing replicates of the same process, such as those resulting from collection of agricultural survey data from a large number of farmers producing the same product for the same markets, or time series data characterizing production operations at a single facility. Rather, automated LCA often refers to automatically generating or simulating LCI data from other sources (Schneider et al., 2023), rather than constructing entire models from primary data.

In light of this gap, the Priority Research for Integrated Sustainability Management (PRISM) Lab at the University of British Columbia, in partnership with software development consultancy Logisymetrix, sought to develop LCAutomate, a Python-based LCA automation tool. This tool facilitates high-throughput LCA modelling based on high-quality, primary data through the automated generation of linked unit process datasets and product systems, performance of LCIA calculations, and compilation of results to facilitate further analyses. It does not "generate" LCI data, since the collection of high-quality LCI data is essential to perform high-quality LCA studies. As a case study, this tool was used to support development of 340 individual LCA models for a dynamic LCA of the Canadian egg industry, as described in the conference paper (for this conference) "Partially dynamic life cycle assessment of Canadian egg production, differentiated by housing system and hen feather colour". The purpose of this dynamic LCA case study was to provide a better understanding of how impacts change over time, specifically to identify optimal lay cycle lengths for laying hens (i.e., the amount of time that laying hens are housed before depopulation) and identify temporally-relevant interventions for sustainability improvement strategies.

Material and methods

LCAutomate was created in an iterative manner through partnership between the UBC PRISM Lab and the Quebec-based consultancy Logisymetrix. It was developed with the following goals: the tool must be able to make efficient use of large, primary data sets; it must be developed in a modular manner such that the tool may be used in its entirety, or in individual constituent parts; and it must be sufficiently generalizable such that it may be applied to a primary data set of any size and structure, requiring any number of processes be automatically generated.

The user begins by creating a template process (or collection of linked processes) in openLCA, as well as supporting files (Excel or otherwise) to indicate which processes will be replicated, and what values (LCI data, allocation, data quality, etc.) will be entered (Tables 1-2). The first file is to indicate which process is the "top" process (i.e., producing the functional unit), which life cycle processes need to be replicated (e.g., for each farm or time step in a dynamic LCA), and which files contain that information (Table 1). Table 2 is an example of such a replication file which indicates all LCI values for the processes that need to be replicated (e.g., for the different time steps in a dynamic LCA).

Table 1 File Information

Top	Process name	Process Universally Unique Identifier (UUID)	Replication File
x	**Egg-enriched cage layer**		Egg_Enriched_white.xlsx
	Egg-enriched white manure management	c0c2a65c-1d0c-416a-b1f1-c78708f29fbf	Egg_Enriched_white_Manure_Management.xlsx

Table 2. Sample Excel table (from file Egg_Enriched_white.xlsx – as indicated in Table 1) for LCI data to be replicated in processes created in LCAutomate.

Provider	**Flow**	**Direction**	**Unit**	**20 weeks of age**	**21 weeks of age n weeks of age**
Energy consumption mix – Enriched	Energy consumption mix	Input	MJ	40.61	60.91
Feed mill-layers	Feed - layer	Input	tonnes	5.88	3.57
Pullets-conventional	Pullets-conventional	Input	Items	5395.10	2070.43
market for tap water | tap water | Cutoff, U	tap water	Input	kg	0.13	0.20
Transportation consumption mix – Enriched	Transportation consumption mix	Input	T*km	4749.60	1895.23
	Egg-enriched cage layer	Output	Kg	1000	1000
Egg-enriched-mortality management	Mortality-enriched cage layer	Output	Kg	2.91	10.16
Egg-enriched manure management	Poultry Manure	Output	kg	3104.27	1884.66
	Spent hens	Output	tonnes	9.17	3.52

The openLCA Application Programming Interface (API) provided by Green Delta serves as the inter-face between the Python-based LCAutomate code and the openLCA software. LCAutomate is imple-mented in a standard Data Science Workflow to enable both user-friendliness (particularly for non-coders), for modularity of running portions of the code independently as desired, and for integration with powerful analysis tools. The Workflow is composed of a series of data nodes and transformation nodes. Figure 1 represents a simplified diagram of the data and transformation nodes associated with the LCAutomate program.

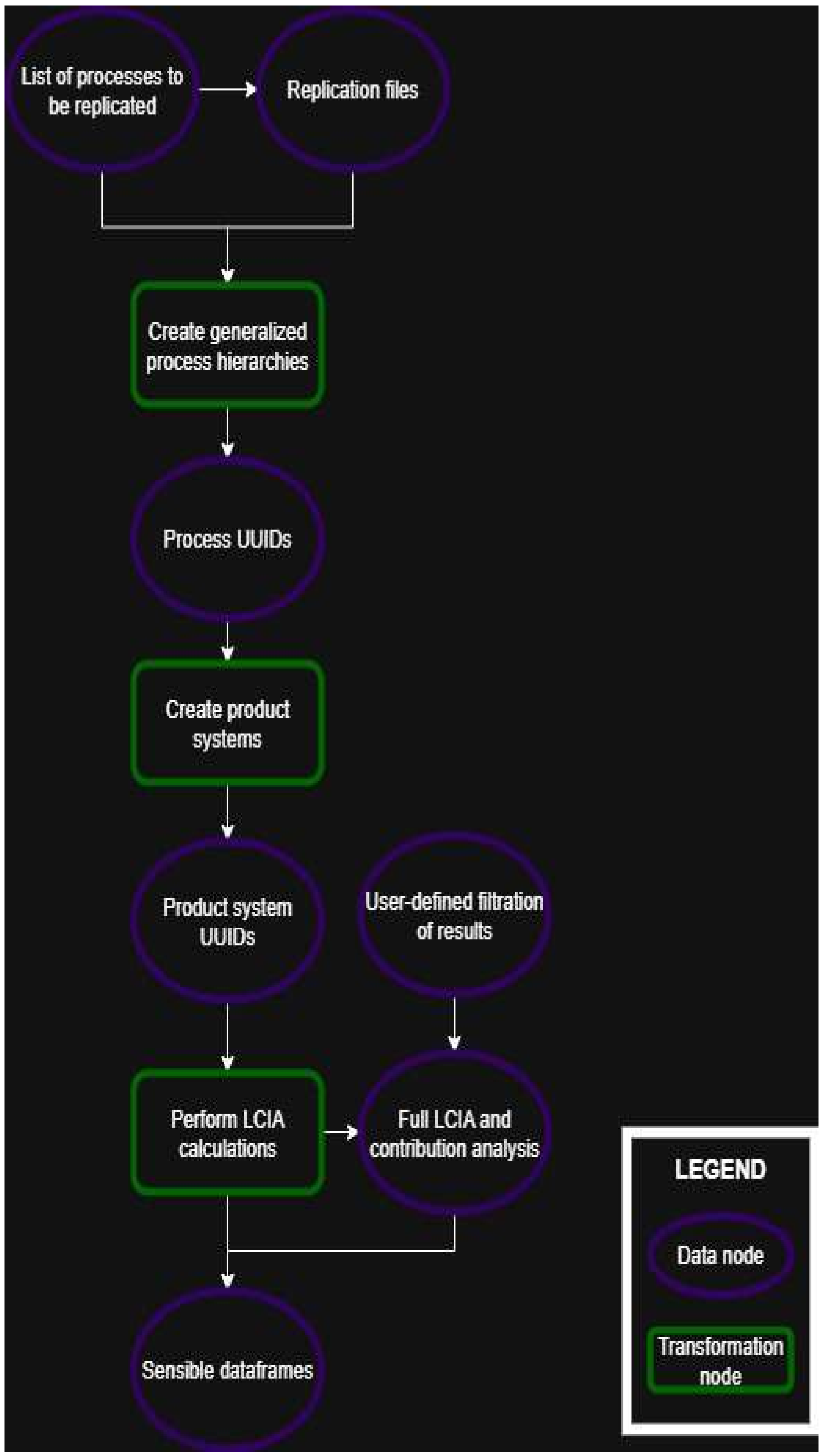

Figure 1. Data and process nodes associated with the Data Science Workflow for the LCAutomate software.

The openLCA Application Programming Interface (API) provided by Green Delta serves as the inter-face between the Python-based LCAutomate code and the openLCA software. LCAutomate is implemented in a standard Data Science Workflow to enable both user-friendliness (particularly for non-coders), for modularity of running portions of the code independently as desired, and for integration with powerful analysis tools. The Workflow is composed of a series of data nodes and transformation nodes. Figure 1 represents a simplified diagram of the data and transformation nodes associated with the LCAutomate program. The user-defined template files are the first data nodes, which are inputs to the first transformation node: Create generalized process hierarchies. This code provides the functionality for the user to automate the creation of any combination of processes (foreground, upstream, and downstream) linked together in a supply chain. These processes are then created in openLCA, producing a list of UUIDs for the newly created processes. Then, in the Create product systems transformation node, product systems are automatically created for each replicated collection of linked processes (producing the data node of product system UUIDs). In the Perform LCIA calculations node, these product systems are then used in the calculation of LCIA results, using an impact assessment method defined by the user.

The openLCA API was consulted to determine how to accurately define these fields within a Python environment to facilitate automatic generation of unit process datasets. It also provided protocols necessary for generation of product systems from the created, linked unit process datasets, and for auto-mated LCIA calculation and results export according to defined calculation parameters (i.e., target amounts, allocation procedures, and LCIA method).

When using the openLCA graphical user interface, the user can filter the LCIA results to view the pertinent information for their research needs. This user-defined filtration process is lost when exporting the calculation results from openLCA, therefore it has been implemented as a data node in the LCAutomate program. These LCIA results are defined to be exported from openLCA as hierarchical JSON files (representing hierarchies of linked processes in a supply chain – but not presented in a user-friendly format). These exported JSON files are subsequently processed using custom-built code for ingesting files into a Jupyter Notebook workbench, in which data can be extracted from the files and combined into data frames using the pandas Python package. Once the exported results are ingested into manipulable data frames, it becomes possible to visualize the results (e.g., LCIA graphs, contribution analyses, etc.), and to apply any number of data science techniques to the LCIA results available through other Python packages. Robust error detection is also built into LCAutomate, providing user-friendly error messages, rather than those generated automatically in Python.

To test the functionality of LCAutomate, the complete automation framework was applied to a case study for the development of weekly LCA models used in a partially dynamic LCA of the Canadian egg industry, as described in the conference paper "Partially dynamic life cycle assessment of Canadian egg production, differentiated by housing system and hen feather colour". For this analysis, LCAutomate was used to generate a total of 680 unit process datasets, representing egg production and linked manure management processes for the estimation of life cycle environmental impacts of Canadian lay cycles of different lengths across different housing systems and hen feather colours. From these process-es, 340 product systems were generated, and LCIA results were automatically estimated.

To determine the potential time savings offered by LCAutomate, the amount of time required to generate 10 linked LCA models from the Canadian egg case study using LCAutomate was recorded and compared to the amount of time required to generate the same 10 models by hand. While this was only performed using a small subset of the models generated for the dynamic LCA of the

Canadian egg industry, it was assumed that use of LCAutomate would result in time savings that scale with the size of the primary data set underpinning the analysis.

Results and discussion

The LCAutomate software package has been made available on the Logisymetrix Gitlab page (https://gitlab.com/logisymetrix-home/openlca). It is open-source, and freely available for public use and testing. The software was successfully used to conduct the case study dynamic LCA of Canadian eggs, resulting in the creation of 340 distinct LCA models and sets of LCIA results characterizing Canadian egg production in different housing systems, with different hen feather colours, for different lay cycle lengths. Sample results are presented in Figure 2 (for details on the LCA study and LCIA results, see "Partially dynamic life cycle assessment of Canadian egg production differentiated by housing system and hen feather colour"). From the starting point of the template files, the entire automation pro-cess took just over an hour to complete.

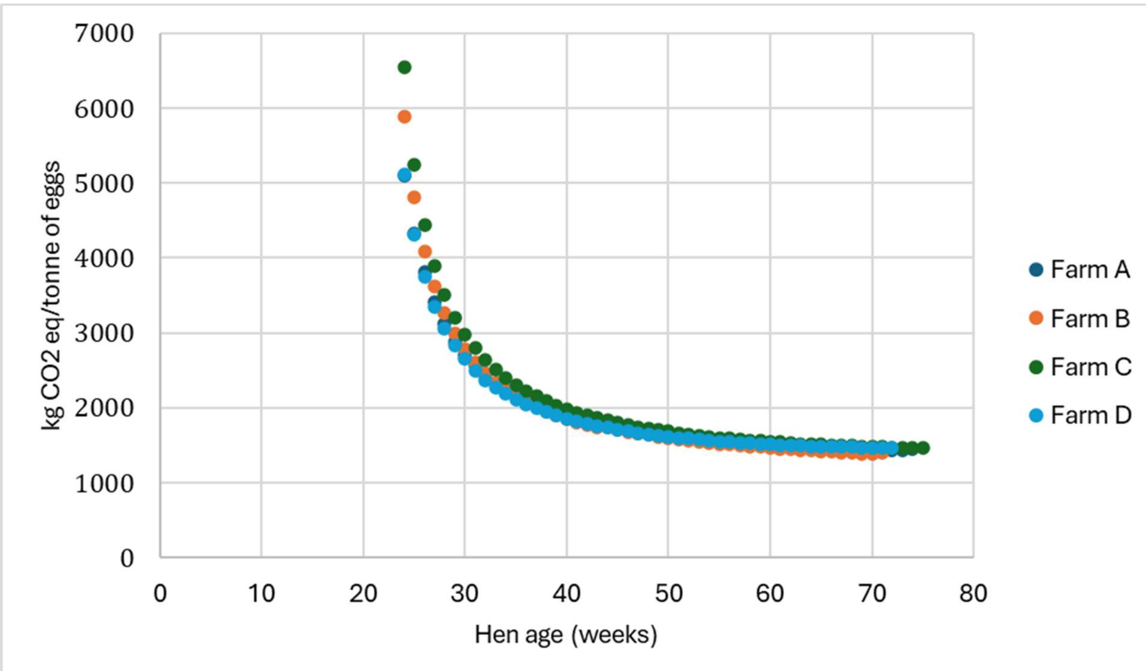

Figure 2. Carbon footprint per tonne of eggs produced for lay cycles of each length on four enriched colony farms in Canada. Each dot represents an individual, complete LCA model generated using LCAutomate (i.e., 217 models in total). All dots begin at a cycle length of five weeks to make the observed trend clearer.

To generate 20 unit process datasets, 10 product systems, run LCIA results on all 10 product systems, export the results and ingest the exported JSON files to the workbench to the point of a data frame including the total impacts with LCAutomate took approximately 3 minutes and 15 seconds. In comparison, manual creation of the same processes and product systems, and calculation and export of LCIA results from a common starting point took approximately 24 minutes and 55 seconds. Use of LCAutomate therefore reduced the time requirement for model generation and LCIA calculation by approximately 86%. The fact that such drastic time savings may be realized over a relatively small number of LCA models generated indicates that the potential time savings from the use of LCAutomate are enormous. Over larger datasets (such as the complete data set used for dynamic LCA of the Canadian egg industry), it is not unreasonable to assume that LCAutomate has reduced the time required to serially generate complete LCA models and LCIA results by a significantly larger proportion, because this analysis does not account for additional "indirect" time savings – that is, those that may be realized by al-lowing LCAutomate to run in the background while other tasks are completed by the LCA practitioner. Such serial data entry processes are also extremely error-prone when performed by a human rather than a machine, thus compounding the time savings for error correction. When considering these indirect time savings alongside the direct savings afforded by use of LCAutomate, it is clear that LCAutomate provides substantial value in increasing productivity and accuracy as a high-throughput LCA modelling tool.

Conclusion

LCAutomate is a powerful tool to support the automation and integration of LCA with high-volume da-ta sources, such as Internet of Things (IoT) sensors from barn monitoring systems, or on-field gas ex-change sensors (or any other non-agricultural data sources), using any necessary custom-built code for data extraction. Using the Python coding environment enables the integration of LCIA results with sophisticated operations research, such as machine learning, artificial intelligence, and optimization algorithms. In addition to these powerful integration benefits, the time savings alone allow for the analysis of LCA models for complex dynamic LCAs such as the case study presented here, and LCAs of individual farms (or other individual enterprises), rather than aggregate national or regional averages. In this work, time savings of approximately 10-fold were observed when modelling a dynamic LCA of egg farms. Allowing the field of LCA to make use of such large datasets and powerful analysis tools will open up new possibilities for data-driven sustainability decision-making.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada/Egg Farmers of Canada Industrial Research Chair in Sustainability, and the Canada Foundation for Innovation John Evans Leadership Fund.

References

- Haun, P., Müller, P., Traverso, M., 2022. Improving automated Life Cycle Assessment with Life Cycle Inventory model constructs. Journal of Cleaner Production 370, 133452.
- Kiemel, S., Rietdorf, C., Schutzbach, M., Miehe, R., 2022. How to Simplify Life Cycle Assessment for Industrial Applications—A Comprehensive Review. Sustainability 14, 15704.
- Lettner, M., Hesser, F., 2020. Asking Instead of Telling — Recommendations for Developing Life Cycle Assessment Within Technical R&D Projects, in: Progress in Life Cycle Assessment 2019.
  - Springer Cham.
- Naser, A.Z., Defersha, F., Pei, E., Zhao, Y.F., Yang, S., 2023. Toward automated life cycle assessment for additive manufacturing: A systematic review of influential parameters and framework design. Sustainable Production and Consumption 41, 253–274.
- Schneider, D., Jordan, P., Dietz, J., Zaeh, M.F., Reinhart, G., 2023. Concept for Automated LCA of Manufacturing Processes. Procedia CIRP 116, 59–64. https://doi.org/10.1016/j.procir.2023.02.011

Life cycle carbon footprint analysis for supporting decision-making in scaling up circular economy innovations

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Abstract

Transitioning to a circular economy requires evidence-based evaluation of emerging alternatives and innovations. Life cycle assessment (LCA) provides a robust framework for quantifying environmental impacts and supporting decision-making in this context.

A study was carried out to evaluate five processes developed by the Institute for Frontier Materials (IFM) at Deakin University for producing pigments from textile waste. Life cycle carbon footprint analysis and financial cost modelling exercise conducted here informs decision-making on scaling the most environmentally and economically viable process to industrial production, supporting strategic technology selection and market positioning.

This study applies LCA methodology to assess the cradle-to-gate carbon footprint of the five pigment production processes scaled from pilot to industrial level: (1) pigment paste via vacuum filtration, (2) pigment paste via vacuum filtration with radiation treatment, (3) pigment powder via spray drying, (4) pigment powder via spray drying with radiation treatment, and (5) pigment powder via jet milling with radiation treatment.

The results indicate that, among paste-based processes, vacuum filtration combined with radiation treatment yields the lowest environmental impacts. In contrast, for powder-based processes, jet milling with radiation treatment shows the highest environmental sustainability, reducing the carbon footprint by over 50% compared to the spray drying pathway.

The case study illustrates how LCA can effectively guide complex decisions in scaling up innovative technologies with minimal environmental burdens. It underscores the critical role of LCA in providing practical, evidence-based insights to advance circular economy transitions and offers a framework for industries seeking environmentally sustainable production pathways.

A multi-criteria evaluation integrating life cycle carbon footprint assessment and cost modelling was undertaken to compare the environmental and economic performance of the five pigment production processes. However, due to commercial confidentiality, cost data and associated results are not presented in this paper, and only the LCA and cost modelling outcomes are presented as results.

Keywords: Circular economy, Life cycle assessment, Innovation, Pigment production, Carbon footprint, Environmental impacts

Introduction

Life cycle assessment (LCA) is an internationally standardised method for quantifying the environmental impacts of product systems across their entire value chain. It is increasingly applied in the context of the circular economy, where it serves to identify environmental "hotspots" and assess whether strategies such as reuse, recycling, and product life extension can effectively reduce impacts under realistic conditions (Schöggl et al., 2024). In the textile sector, LCA studies demonstrate that reuse and recycling can offer significant climate benefits compared to landfill or incineration. However, these outcomes are highly sensitive to assumptions such as collection efficiency and energy mix (Lee and Martínez, 2023). To address this, sector-specific reviews emphasise the importance of transparent scenario building and uncertainty analysis when evaluating emerging recycling pathways.

At the process level, textile recycling operations reveal distinct environmental hotspots. Drying and milling, for instance, are often the largest contributors to greenhouse gas emissions in pigment and material production. Fernandez (2022) highlights that spray drying is highly energy-intensive and significantly influences cradle-to-gate carbon footprints. Therefore, selecting lower-energy processing routes or redesigning production systems can yield substantial environmental improvements. These challenges are compounded by the global scale of textile waste generation, which exceeds 90 million tonnes annually. Natural fibre waste presents difficulties due to its limited recyclability (Sandin and Peters, 2018). At the same time, conventional pigment production processes remain resource- and energy-intensive, contributing considerably to greenhouse gas (GHG) emissions and other environ-mental impacts (Ardente et al., 2019). Recent research suggests that valorising textile waste into functional products such as pigments offers a promising pathway, simultaneously reducing landfill disposal while decreasing reliance on virgin raw materials (Padhye and Wang, 2022).

This project evaluates the life cycle carbon footprint and cost performance of the five innovative pro-cesses that convert textile waste, particularly natural fibres, into coloured microparticles for use as pigments. Only the LCA outcomes are reported in this paper due to commercial confidentiality related to the cost performance data. Beyond addressing the challenge of textile waste, these processes offer a potential pathway to reduce dependence on resource-intensive conventional pigment production.

The study aims to provide a comprehensive assessment of the techno-economic and environmental viability of these pigment production processes for scaling up to industrial-level production. Hence, directly supporting the practice of a circular economy by providing the evidence base for valorisation. By quantifying the techno-economic and environmental impact of converting textile waste (a low-value, high-volume stream destined for landfill) into a high-value pigment, this assessment evaluates the viability of a new circular pathway. It ensures that the new process is environmentally sound and identifies the optimal technology to do so, moving beyond simple downcycling and displacing virgin material production.

Materials and methods

1.1 Mapping the process

The five distinct processes developed to produce coloured microparticles from waste textiles are presented in Table 1. Each process was mapped before the calculations and analysis, including the sequence of operations, process conditions, and the corresponding inputs and outputs. Figures 1-5 show the process mapping for each process.

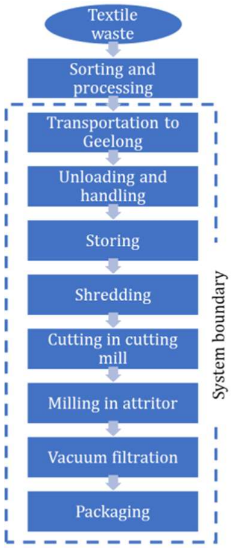

Figure 1- Process mapping for process P1-A

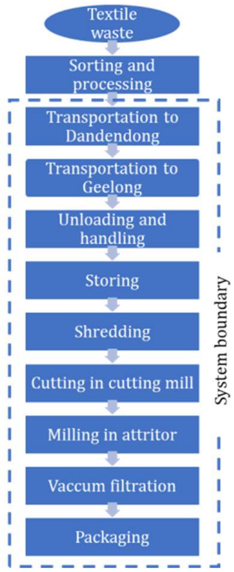

Figure 2- Process mapping for process P2-A

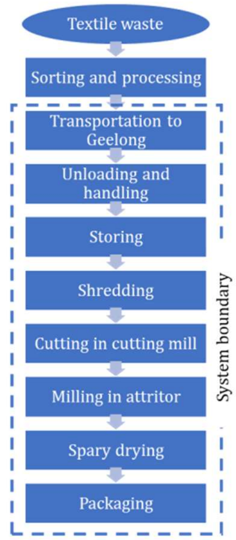

Figure 3 - Process mapping for process P1-B

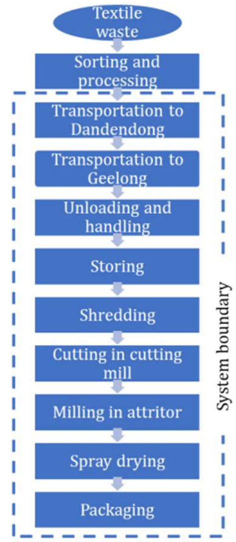

Figure 4 - Process mapping for process P2-B

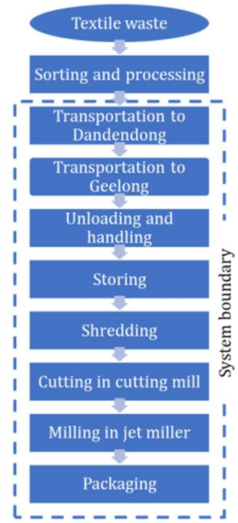

Figure 5- Process mapping for process P3-B

The pigments were produced in two forms: paste and powder. The process begins with transporting textile waste from recyclers to the pigment production facility (PPF). At the PPF, the textile waste is first shredded and then granulated into snippets, which are then milled into fine particles using an attritor. Depending on the production pathway, these fine particles are either vacuum filtered to obtain pigment paste or spray dried to obtain pigment powder. The final products are then packaged in drums for storage and distribution. The exception is the process P3-B, which bypasses this step and uses jet milling to convert granulated snippets directly into powder.

Table 1- Main variations of the 5 processes used to produce pigments

Process ID	Output	Summary description
P 1-A	Paste	Paste using vacuum filtration following wet milling
P 2-A	Paste	Paste using vacuum filtration following wet milling + radiation pre-treatment
P 1-B	Powder	Powder using spray drying following wet milling
P 2-B	Powder	Powder using spray drying following wet milling + radiation pre-treatment
P 3-B	Powder	Powder using jet milling + radiation pre-treatment

1.2 Life cycle carbon footprint analysis

The life cycle carbon footprint assessment was conducted to quantify the greenhouse gas (GHG) emissions associated with the five distinct pigment production processes. A cradle-to-gate system boundary was applied, with the analysis focused on the GWP100 indicator in accordance with ISO 14067 standards, which provide guidelines for quantifying and communicating product carbon footprints. The functional unit was defined as producing 1 kg of pigment in bulk form at the pigment production facility (PPF) gate, ready for shipment. All material and energy flows were calculated with reference to this unit. To ensure consistency, it was assumed that all activities within the study boundary occurred within a single facility, thereby eliminating the need for transportation between process steps. As the proposed PPF has not yet commenced operations, process-specific primary data were not available. Instead, inventory data were derived from laboratory-scale investigations and supplemented with assumptions to approximate industrial conditions.

Certain processes were excluded from the analysis, including activities undertaken by textile recyclers before transporting the waste to the PPF, the distribution and application of the final pigment, and the production and disposal of capital goods. These exclusions were made to maintain focus on the core production processes most relevant to scaling up the technology.

The cradle-to-gate life cycle impact assessment (LCIA) evaluated the contribution of each process to climate change through its GHG emissions. Results were normalised to the functional unit of 1 kg of pigment and subsequently interpreted to identify key emission hotspots, enabling conclusions and recommendations to support decision-making on sustainable pigment production.

Data collection focused on process-specific information. Process data captured the technical and operational characteristics of each production pathway, including input–output ratios, machinery used, machinery specifications and capacities, processing conditions such as processing time, and resource consumption such as electricity, water, and chemicals. All processes were modelled as batch operations, reflecting the design of the proposed pigment production facility (PPF).

Results

1.1 Emissions comparison of all processes

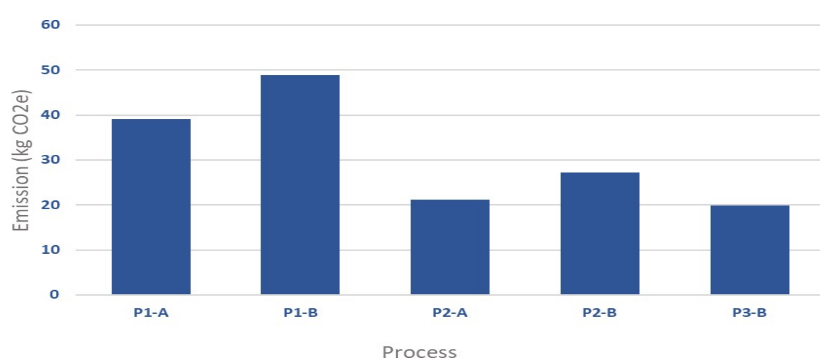

Figure 6 - Life cycle carbon footprint of each process

The comparative analysis of GHG emissions across the five pigment production processes reveals substantial variations in environmental performance (Figure 6). The processes P1-A and P1-B exhibit the highest carbon footprints. Among them, P1-B shows the lowest environmental performance, with emissions of 48.90 kgCO_2e per kilogram of pigment produced. Although P1-A performs slightly better, its emissions remained higher than those of the alternative processes.
In contrast, the radiation-enhanced processes demonstrate improved environmental outcomes. P2-A and P2-B generated 21.23 kgCO_2e and 27.15 kgCO_2e per kilogram of pigment, respectively. The most sustainable option is P3-B, which achieved the lowest emissions at 19.94 kgCO_2e per kilogram of pigment. P1-A produces pigment in paste form through vacuum filtration, whereas P1-B yields pigment powder via spray drying, an energy-intensive operation that significantly elevates the overall carbon footprint. The superior performance of P2-A, P2-B, and P3-B results primarily from the integration of radiation pre-treatment, which reduces milling time by 50%. This optimisation leads to considerable electricity savings and corresponding reductions in GHG emissions.

Summary of analysis

The summarised analysis obtained from the cradle-to-gate carbon footprint assessment is given in the section below. Table 3 below depicts the comparative ranking of the five processes based on environ-mental impact and cost. The cost modelling was conducted as a techno-economic analysis considering cost factors such as CAPEX for machinery, OPEX for energy, labour and materials. Due to commercial confidentiality, only the ranking from the financial cost modelling is given in Table 2.

Table 2 – Ranking of paste and powder-based processes

Pro-cess ID	**Process Type**	**Process description**	**Rank based on environ-mental impact**	**Rank based on cost**
P 1-A	Paste-based	Paste using vacuum filtration following wet milling	2	2
P 2-A		Paste using vacuum filtration following wet milling + radiation pre-treatment	1	1
P 1-B	Powder-based	Powder using spray drying following wet milling	3	3
P.2-B		Powder from spray drying following wet milling + radiation pre-treatment	2	2
P.2-B		Powder using jet milling + radiation pre-treatment	1	1

Comparative analysis of paste-based output processes

The processes P1-A and P2-A produce paste-based outputs. In both processes, milling emerges as the dominant contributor to carbon emissions, accounting for around 93% and 85% of the total kgCO2e, respectively. While cutting and vacuum filtration also contribute noticeably to both processes, their impact remains significantly lower than milling. The PPF's operations, including transportation, storage, shredding, and handling textile waste, result in minimal emissions, contributing negligibly to the overall carbon footprint in both processes. Ranking of paste-based processes based on the environ-mental performance is given in Table 2. Based on the environmental impact and the cost-effectiveness, the P2-A process is more sustainable for paste production due to its lower environmental impact and cost.

Comparative analysis of powder-based output processes

P1-B and P2-B processes involve spray drying, while process P3-B includes jet milling. In process P3-B, spray drying is not involved, and jet milling directly produces powder-based pigments. P1-B, P2-B, and P3-B have total emissions of 48.86 kgCO2e, 27.15 kgCO2e, and 19.94 kgCO2e, respectively. The textile waste is subjected to gamma radiation treatment in processes P2-B and P3-B, which has resulted in a reduction in milling time and hence a significant reduction in total emissions.

In all three processes, P1-B, P2-B, and P3-B milling consistently stand out as the most significant contributors to carbon emissions, accounting for 87%, 78%, and 90% of the total kgCO2e, respectively. While cutting and spray drying also contribute to the emissions, their shares are much lower across the processes. Other processes, including transportation, unloading and handling, storage, and shredding, have minimal carbon emissions in all three processes. Ranking of powder-based processes is given in Table 2. The environmental impact of the P2-B and P3-B processes is significantly lower compared to the P1-B process. The P3-B process incorporates jet milling as a substitute for both milling in an attritor and the spray drying process. Substituting milling in attritor and spray drying with jet milling enables the pro-duction of powder-based outputs with lower emissions and lower cost. Overall, P3-B indicates more sustainability in terms of both environmental impact and cost-effectiveness.

Sensitivity analysis

This study is based on high-level estimations and assumptions as the data availability is limited at this stage of the project. Exact data on industrial scale equipment and infrastructure was not available at this stage and therefore, the scale up was simulated based on high level assumptions. Considering the uncertainties of the data, a sensitivity analysis was performed as described below. Sensitivity analysis was conducted to evaluate how variations in key operational and system parameters influence the total environmental impact of each process. The assessment focused on three main considerations:

(1) parameters related to the attritor (electricity consumption, operational efficiency, and runtime),
(2) transportation distances between processing sites, and
(3) the decarbonization factor associated with the electricity grid.

For each case, the analysis determined the percentage change required in each parameter to cause a 1 % variation in the total environmental impact. This method allows the identification of parameters with the greatest leverage on overall system performance, guiding priorities for environmental optimization.

Sensitivity analysis of the attritor

The attritor represents one of the most energy intensive stages in the processing sequence. Its performance is primarily governed by three operational parameters; electricity consumption, operational efficiency, and runtime which collectively determine the overall energy demand and emission profile of the process. Evaluating the sensitivity of these parameters highlights which factors most strongly influence environmental performance and therefore warrant operational attention. The corresponding results are summarized in Table 3.

Table 3. Sensitivity analysis of key parameters of attritor for each process

Process	**Electricity consumption for attritor**	**Operational efficiency of the attritor**	**Runtime of the attritor**
P1-A	1.08%	0.98%	4.55%
P1-B	1.15%	1.05%	4.83%
P2-A	1.17%	1.01%	22.27%
P2-B	1.27%	1.10%	24.22%
P3-B	1.10%	0.95%	20.92%

Note: P1-A and P1-B operate with a runtime of 2 hours, whereas P2-A, P2-B, and P2-C operate with a runtime of 4 hours.

Electricity consumption and operational efficiency exhibit high sensitivity, as minor changes in these parameters produce noticeable variations in total impact. Runtime shows intermediate sensitivity, meaning longer operating durations moderately influence overall emissions. Optimizing energy use and maintaining high machine efficiency are therefore the most critical levers for environmental improvement in milling operations.

Sensitivity analysis of the transportation distances

Transportation between Ravenhall, Dandenong, and Geelong was analysed to determine how changes in distance influence total environmental impact. This is to consider the effect of change of processing sites on the environmental impact. The sensitivity results are presented in Table 4.

Table 4. Sensitivity analysis of transportation distance for each process

Process	Distance from Raven-hall to Dandenong	Distance from Raven-hall to Geelong	Distance from Dandenong to Geelong
P1-A	-	304.01%	-
P1-B	-	321.97%	-
P2-A	205.19%	-	112.79%
P2-B	223.13%	-	122.64%
P3-B	192.73%	-	105.95%

As shown in Table 4, transportation parameters demonstrate low sensitivity, indicating that variations in transport distances cause only limited changes in total environmental impact.

Effect of decarbonization factor

Since electricity is a key energy source for all processes, variations in grid carbon intensity directly affect total emissions. To assess this influence, two complementary analyses were carried out: a parameter sensitivity evaluation presented in Table 5, and a 50 % grid decarbonization scenario illustrated in Figure 6.

Table 5. Sensitivity analysis of decarbonization for each process

Process	Decarbonization Factor
P1-A	1.00%
P1-B	1.07%
P2-A	1.03%
P2-B	1.16%
P3-B	1.03%

As shown in Table 5, the grid emission factor exhibits high sensitivity, meaning that even small variations in grid decarbonization cause noticeable changes in total environmental impact. This outcome highlights the strong dependence of system performance on the carbon intensity of electricity supply. The second scenario modelled a 50 % reduction in the grid emission factor to represent future low-carbon energy conditions.

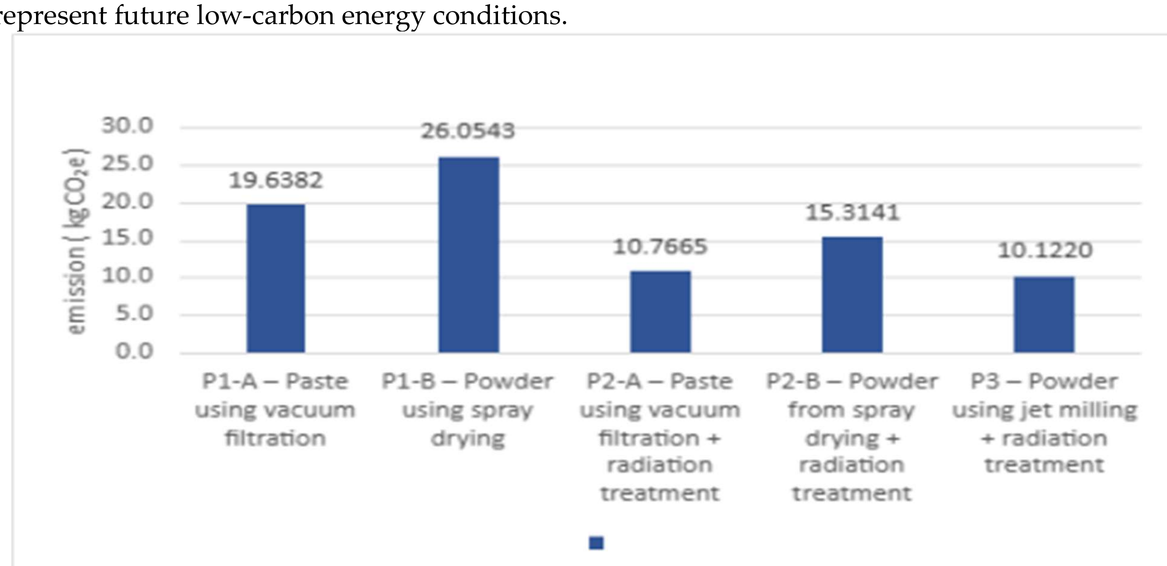

Figure 6: Emissions with 50% decarbonization

The 50 % decarbonization scenario results in significant reductions in absolute emissions. However, the relative ranking of processes remains unchanged, indicating that operational efficiency continues to be the dominant factor determining environmental performance, even under cleaner grid conditions.

Discussion

The multicriteria evaluation framework developed in this study enabled a structured comparison of environmental and financial trade-offs across five pigment production processes derived from textile waste. The results highlight a divergence in environmental performance between untreated and pre-treated processes, particularly when comparing P2-A and P3-B scenarios to their conventional and un-treated counterparts. This finding aligns with recent literature emphasising the role of advanced pro-cessing technologies in reducing the carbon footprint of textile waste valorisation (Khan et al., 2023).

The findings also directly validate the environmental hotspots identified in the literature, where milling and drying are cited as primary contributors to the carbon footprint of material production. Across all five scenarios in this study, milling emerged as the single largest source of emissions, accounting for up to 93% of the total $kgCO_2e$ in certain processes. Similarly, the inclusion of energy-intensive spray drying rendered process P1-B the highest-emitting option overall, underscoring the critical impact of this unit operation.

The superior performance of P3-B, the most sustainable option, demonstrates the significant environ-mental benefits of process intensification. By utilising jet milling, this innovative pathway effectively replaces two separate, energy-intensive stages, wet milling in an attritor and subsequent spray drying, with a single, more efficient operation that directly produces a powder output. This consolidation and the complete avoidance of spray drying are the primary reasons for its leading environmental performance among all alternatives studied. This analysis therefore provides clear, evidence-based guidance: for paste production, radiation pre-treatment with vacuum filtration (P2-A) is the preferred route, while for powder production, radiation pre-treatment combined with jet milling (P3-B) is the most sustainable pathway.

The study also demonstrates that financial cost modelling is a critical complement to environmental analysis. While several low-emission scenarios also demonstrated competitive costs, the framework uncovered cases where environmental benefits came at significantly higher financial costs. This insight is particularly relevant for early-stage innovations where funding, market readiness, and return on in-vestment can influence scaling decisions.

In this study, analysing trade-offs associated with cost and environmental analysis was not necessary, as the ranking as depicted by Table 3 presents results that are mutually aligned in selecting a process that has effective cost and environmental performance. However, decision methods such as multi-criteria decision analysis (MCDA)(Montibeller & Franco, 2010) and decision prioritisation techniques such as analytical hierarchy process(Canco et al., 2021) and fuzzy logic(Wu & Xu, 2020) can be used when decision outcomes don't align and trade-offs need to be analysed based on the priority set by the decision maker.

Finally, the multicriteria approach presented is broadly transferable to other circular economy innovations. Its transparency and adaptability can help practitioners and policymakers evaluate competing options in sectors such as construction materials, plastics, and bio-based products, where similar trade-offs exist.

Key assumptions and holistic decision-making

It is important to acknowledge that these findings are predictive, as they rely on laboratory-scale data extrapolated to an industrial context. Key assumptions regarding the energy efficiency of industrial-scale machinery, the regional electricity grid mix, and material yields introduce a degree of uncertainty. Therefore, these results should be viewed as a robust comparative guide for decision-making, with the recommendation that the analysis be validated with primary operational data in the future. A full validation with primary operational data and a quantitative uncertainty analysis is a recommended next step before final commercial investment.

Furthermore, while this cradle-to-gate carbon footprint assessment provides a clear environmental ranking, the selection of a process for industrial scale-up involves other critical factors. For instance, although P3-B is the most environmentally sustainable option, a comprehensive business decision would also need to weigh the potentially high capital investment required for specialised jet milling equipment against long-term operational savings. Additionally, technical considerations, such as the ability to consistently achieve target particle sizes and other quality specifications at scale, must be thoroughly evaluated to ensure the commercial viability of the chosen pathway.

Conclusion

This study demonstrated the effectiveness of a multicriteria approach combining life cycle carbon foot-print analysis and financial cost modelling to support decision-making in scaling up circular economy innovations. Evaluating five pigment production processes converting textile waste into functional pigments reveals that,

- Radiation pre-treatment significantly improves environmental performance, reducing milling time and electricity consumption.
- P2-A is the most sustainable paste-based process, and P3-B is the most sustainable powder-based process, achieving the lowest GHG emissions and greater cost efficiency among the alternatives.

The findings provide a clear, evidence-based pathway for selecting pigment production technologies that minimise GHG emissions and maximise cost efficiency. The approach presented can be adopted by other early-stage circular economy innovations to support robust, evidence-based transitions from pilot to commercial scale.

The findings also confirm that integrating environmental and financial criteria can inform the selection of optimal processing technologies, enabling stakeholders to balance trade-offs and enhance circular outcomes. Further trade-off analysis can be done using the analytic hierarchy process for multicriteria decision analysis.

Future work could extend the analysis to incorporate additional environmental indicators (e.g., toxicity) to enable even more comprehensive sustainability assessments as well as include social and technical performance dimensions, offering a more holistic approach. While cost and trade-off analyses were conducted in the study, detailed cost results are not presented here due to confidentiality.

Acknowledgements

The authors gratefully acknowledge the support of the IFM, Deakin University, and the project partners, including Sustainability Victoria, Textile Recyclers Australia, and RIP Curl.

References

- Schöggl, J. P., et al. (2024). Life cycle assessment in circular design process: A systematic review. Journal of Cleaner Production, 451, 131-145t: https://www.sciencedirect.com/science/arti-cle/pii/S0959652625015380

- Lee, S., Martínez, P., 2023. Quantifying the environmental impacts of textile reuse and recycling routes via LCA. Resources, Conservation & Recycling, 191, 106777. https://doi.org/10.1016/j.resconrec.2022.106777
- Fernandez, L., 2022. Energy implications of drying and spray-drying operations in chemical pro-cessing: an LCA perspective. Chemical Engineering Research and Design, 180,456–468. https://doi.org/10.1016/j.cherd.2022.03.015
- Sandin, G., Peters, G.M., 2018. Environmental impact of textile reuse and recycling – A review. *Jour-nal of Cleaner Production*, 184, 353–365. https://doi.org/10.1016/j.jclepro.2018.02.266
- Ardente, F., Mathieux, F., Recchioni, M., 2019. Environmental assessment of pigments and dyes: A review of emerging alternatives. *Journal of Cleaner Production*, 231, 1322–1336. https://doi.org/10.1016/j.jclepro.2019.05.306
- Padhye, R., Wang, L., 2022. Advances in textile waste valorization for sustainable materials. *Re-sources, Conservation & Recycling*, 181, 106246. https://doi.org/10.1016/j.resconrec.2022.106246
- International Organization for Standardization, 2018. ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification. ISO, Geneva, Switzerland.
- Khan, M.I., Wang, L., Padhye, R., 2023. Textile waste management in Australia: A review. Resources, Conservation & Recycling Advances 18, 200154. https://doi.org/10.1016/j.rcradv.2023.200154
- PAS 2050, 2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution, London. ISBN 9780580644743.
- Montibeller, G., & Franco, L. (2010). Multi-Criteria Decision Analysis for Strategic Decision Making. In Handbook of Multicriteria Analysis (Vol. 103, pp. 25–48). https://doi.org/10.1007/978-3-540-92828-7_2
- Canco, I., Kruja, D., & Iancu, T. (2021). AHP, a Reliable Method for Quality Decision Making: A Case Study in Business. Sustainability, 13, 13932. https://doi.org/10.3390/su132413932
- Wu, H., & Xu, Z. (2020). Fuzzy Logic in Decision Support: Methods, Applications and Future Trends. INTERNATIONAL JOURNAL OF COMPUTERS COMMUNICATIONS & CONTROL, 16. https://doi.org/10.15837/ijccc.2021.1.4044

Life cycle optimization of Canadian egg production for least environmental impacts and best animal welfare outcomes

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Abstract
In many regions around the world, egg industries are navigating a transition away from conventional cage production systems to alternative systems, driven primarily by animal welfare concerns. Alternative systems may, however, be characterized by differences in environmental impacts, and trade-offs across different kinds of animal welfare outcomes. Simultaneous improvement of both animal welfare and environmental performance therefore represents a set of potentially conflicting objectives that must be reconciled to support long-term sustainable development of egg production. In this study, reconciliation of these objectives was explored using a life cycle optimization-based approach and a case study of the Canadian egg industry. The environmental impacts of Canadian egg production in non-organic housing systems were quantified using environmental life cycle assessment, while animal welfare impacts were estimated using a recently developed animal welfare life cycle impact assessment method. These impacts were subsequently incorporated into a multi-objective optimization model solved using the weighted sum approach to determine the optimal distribution of egg production across alternative housing systems, given estimated differences in environmental and animal welfare impacts. Fifteen optimization scenarios were investigated, representing different sets of stakeholder preferences for improved environmental and animal welfare outcomes. Across all scenarios, the optimal solution was to produce all eggs in enriched colony systems, indicating these systems adequately minimize negative environmental impacts, while also maximizing positive welfare impacts. The results may provide valuable decision support for the Canadian egg industry, while also presenting a novel framework combining environmental LCA, animal welfare assessment, and mathematical optimization. This framework may be leveraged to provide decision support in the presence of potentially competing objectives with respect to environmental and animal welfare impacts, and may be extended in the future to also incorporate economic objectives to help better support evidence-based decision making for sustainable development of egg industries worldwide.

Keywords: Life cycle optimization; Animal welfare; Poultry; Egg

Introduction

The Canadian egg industry, and many others around the world, are currently in a transitionary period in which production in conventional cage housing systems is being phased out in favour of production in alternative systems, including enriched cage, single and multi-tier non-cage, and free range systems (National Farm Animal Care Council, 2017; Vogeler, 2021). While this transition is largely driven by perceived wide-spread animal welfare benefits that will results from the discontinued use of conventional cages (Caputo et al., 2023), it may also have large impacts on other sustainability attributes. Generally, (though not always), environmental impacts are higher in alternative systems than in conventional cages due to lower levels of resource-use efficiency, particularly with respect to feed use which is a large contributor to many environmental impacts (Turner et al., 2022a). How this transition occurs, including the new proportions of egg production attributable to each non-organic housing system may therefore have significant implications for both environmental and animal welfare outcomes in industrial egg production systems. In light of these impacts, it is imperative that the housing system transition be navigated in such a manner that simultaneously accounts for both the animal welfare and environmental impacts of alternative systems, particularly given the potential for trade-offs between environmental and animal welfare impacts.

One method for understanding these potential trade-offs and synergies is the development of mathematical optimization models to optimize the distribution of egg production in different housing system types in accordance with relative preferences for different environmental and animal welfare objectives. Mathematical optimization may be used to explore a number of potential transition scenarios that align with various sets of stakeholder priorities and preferences for different objectives, accounting for differences in expected environmental and animal welfare outcomes of different housing systems. Development of an optimization framework to investigate the optimal distribution of production in non-organic housing systems may provide useful decision support for Canadian egg farmers currently navigating this transition, while also providing value as a consumer-facing tool to help consumers in understanding potential trade-offs between systems. This original study describes development and application of such a framework.

Material and methods

Estimation of environmental and animal welfare impacts of Canadian, non-organic egg production

The environmental impacts per tonne of eggs produced in Canadian, non-organic egg production systems were estimated in line with the methods described by Turner et al. (2022), with updates. Major updates included the use of new life cycle inventory models describing production of Canadian field crops, use of updated, IPCC Tier 2 emissions models for estimation of emissions associated with manure management systems (IPCC, 2019), and use of the CML-IA baseline life cycle impact assessment method (Mikosch et al., 2022). Updated results are available in Turner (2025). The animal welfare im-pacts per tonne of eggs produced in Canadian, non-organic egg production systems were estimated in line with the methods described by Turner et al. (2023).

Optimization problem definition

Objective functions

Across the environmental and animal welfare impacts estimated, a total of 18 possible impact categories could be used in the defined optimization problem (i.e., 11 midpoint environmental impacts, and 7 midpoint animal welfare impacts). To reduce the complexity of the optimization problem, redundant impacts were identified based on correlations between estimated impacts for environmental impact categories, and structural similarities in characterization models for animal welfare impacts. On this basis, a total of 8 different impact categories were retained to use as objective functions for optimization. Of these, four represented environmental impacts (i.e., acidification, eutrophication, global warming potential, and human toxicity), and four represented animal welfare impacts (i.e., mortality, morbidity/injury, and fulfilment of basal, and additional behavioural needs). Since the two behavioural impacts included were sought to be maximized rather than minimized, as for all other impacts included, these two objectives were multiplied by -1 such that all impacts included as objective functions were minimized during optimization.

Constraints

Constraints were defined in accordance with anticipated changes in market share of non-organic Canadian egg production attributable to each housing system. In total, three different sets of constraints were defined to represent current market conditions, as well as projected future market conditions. In the first scenario, an inequality constraint was defined such that the proportion of hens housed in conventional cage systems could not exceed the proportion currently housed in this type of system. This constraint was defined in accordance with the Canadian Code for Care and Handling of Laying Hens, which dictates that new construction of conventional cage systems is currently banned in Canada (National Farm Animal Care Council, 2017). In this scenario, the maximum upper limit market share for conventional cage housing was set at 48%, in line with data for 2023 ((Egg Farmers of Canada, 2024). For the second scenario, an inequality constraint was defined such that the maximum proportion of hens housed in conventional cage systems was 24% (i.e., half of the current market share). This scenario was intended to represent 2030 market conditions as the halfway point between the current conditions, and 2036 market conditions in which it is estimated no hens will be housed in conventional cage housing systems (National Farm Animal Care Council, 2017). In the final scenario, an equality constraint was defined such that the market share for conventional cage systems was zero, while market shares for all other housing systems were unconstrained. This scenario was intended to reflect market conditions in 2036, representing the expected complete phase out of conventional cage egg production in Canada. Across all scenarios, the potential market share for all alternative housing systems were assumed to be unconstrained, and no minimum market share was assumed for any alternative systems. A complete summary of the three scenario constraints is available in Table 1.

Table 1. Three different constraint scenarios for multi objective optimization of Canadian egg production for environmental and animal welfare outcomes, and the market year those constraints are intended to represent

Scenario	Market year	Maximum conventional cage market share (%)
1	2024	48
2	2030	24
3	2036	0

Weighted sum solver

A weighted sum approach was used to solve the defined optimization problems. All necessary conditions to ensure pareto optimality are met by the optimization problems defined in this analysis. Use of a weighted sum approach requires definitions of weights associated with each objective function, rep-resenting the relative importance of each objective within the optimization. Definition of the weights associated with each objective may have substantial impacts on the optimal solution identified, particularly when there may be competing objectives as may be the case with the animal welfare and environmental impacts associated with egg production in different housing systems.

Little information is available regarding preferences for different product characteristics among Canadian egg consumers. (Doyon et al., 2023) found a disproportionately high percentage of consumers reporting purchasing non-cage and free range eggs relative to the Canadian market share of these systems. (Rahmani et al., 2019) found that consumers may exhibit strong preferences for eggs with reduced GHG emissions, with this preference potentially being stronger than that for improved animal welfare outcomes when these reductions were substantial (i.e., >20%). These data, however, were collected from Spanish consumers and may not be transferrable to Canadian consumers given regulatory differences between Canadian and European egg producers. Similarly, it is suggested by (Doyon et al., 2023) that Canadian consumers may have a stronger preference for lower environmental impacts than improved animal welfare outcomes, although this suggestion comes with the caveat that the preference may also be driven by lower market prices for consumers purchasing eggs with lower environmental impacts (i.e., caged eggs) compared to those with potentially improved animal welfare outcomes (i.e., cage free eggs).

Taken together, it is clear that there is little definitive information in the literature regarding the relative strength of preferences among Canadian egg consumers for improved environmental and animal welfare impacts. On this basis, multiple sets of weights were defined for each objective function representing different levels of compromise between objectives. In total, five different sets of weights for optimization were defined. A complete overview of the weights for each objective in each scenario is given in Table 2. On this basis, fifteen distinct optimization problems were defined representing different combinations of three constraint scenarios and five objective weight scenarios.

Table 2. Weights used for multi-objective optimization of the distribution of non-organic Canadian egg production in different housing systems with 8 objective functions.

	GHG emissions	Acidification	Eutrophication	Human toxicity	Mortality	Morbidity /Injury	Basic behaviour all needs fulfilled	Additional behavioural needs fulfilled	Sum environmental weights	Sum animal welfare weights
S1	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.5	0.5
S2	0.49	0.05	0.14	0.07	0.08	0.08	0.04	0.04	0.75	0.25
S3	0.49	0.05	0.14	0.07	0.04	0.04	0.08	0.08	0.75	0.25
S4	0.16	0.02	0.05	0.02	0.25	0.25	0.125	0.125	0.25	0.75
S5	0.16	0.02	0.05	0.02	0.125	0.125	0.25	0.25	0.25	0.75

Results and discussion

Across all 15 optimization scenarios investigated, it was found that the optimal solution was to produce all non-organic Canadian eggs in enriched cage systems. In order to obtain a different optimal mix, it was determined that a strong preference (i.e., a weighting factor of 0.9) for fulfillment of basic behavioural needs had to be used in the optimization, which resulted in the optimal mix of production systems being 100% free range. That 100% enriched cage production was identified as the optimal solution in almost all models tested indicates that enriched cage systems represent an optimal compromise between these objectives. In practice, this solution is not substantially different than what may be expected in the Canadian egg industry over time, as enriched cage production has seen substantially larger growth in market share since the implementation of the ban on conventional cages compared to other alternative, non-organic systems (Egg Farmers of Canada, 2024). From an environmental perspective, such a shift would result in generally negligible changes (i.e., <0.5%) to the current national average environmental impacts per tonne of eggs produced in Canada. The majority of impacts would decrease slightly, while freshwater aquatic ecotoxicity and terrestrial ecotoxicity impacts would be expected to increase by <0.2% relative to the current national average. Notably, these results are very similar to those presented by Turner et al. (2022b), who indicate that 100% enriched production could lead to the largest reductions in average environmental impacts per tonne of eggs produced.

From an animal welfare perspective, such a shift would generally be expected to have a positive animal welfare impact for all those hens transitioning from conventional cage housing to enriched housing for most animal welfare impacts. For those hens, this transition would be expected to result in a lower risk of mortality, better support for basal and additional behavioural needs, and generally better positive affective state. There may, however, be some trade-offs for hen transitions from conventional cage systems, as this transition may also result in a moderately high risk of morbidity and injury as well as risk of being the victim of injurious behaviours, and, as a result, a larger contribution from negative affective state. For those non-organic hens currently housed in other alternative housing systems, including non-cage and free range systems, a transition to enriched housing would engender more trade-offs. Such a transition would generally be expected to provide hens with a lower risk of mortality, morbidity/injury, and of experiencing injurious behaviours. In contrast, this shift would also generally be expected to result in slightly worse outcomes for supporting additional behavioural needs, and smaller contributions to positive affective state. Smaller contributions to negative affective state may be expected for those hens transitioning from single-tier non-cage and free range housing systems, but not necessarily those from multi-tier aviary systems.

Conclusion

This analysis develops and applies a novel framework for optimization of the distribution of Canadian, non-organic egg production across different housing systems, taking into account differences in estimated life cycle environmental, and animal welfare impacts. This framework indicates that, regardless of stakeholder preferences for improved environmental or animal welfare impacts, all Canadian egg production should occur in enriched colony systems as they represent an optimal compromise between these sustainability impacts. Additionally, this framework may be easily modified to take into account additional objective weighting scenarios based on primary data describing stakeholder preferences for different sustainability attributes, and additional sustainability attributes, such as economic factors. While the optimum solution identified in this analysis demonstrated a high degree of robustness to different combinations of stakeholder priorities and constraints, it is possible that incorporation of additional sustainability considerations, such as economic outcomes, could result in different optimal solutions.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada/ Egg Farmers of Canada Industrial Research Chair in Sustainability, the Canada Foundation for Innovation John Evans Leadership Fund, and Egg Farmers of Canada.

References

- Caputo, V., Lusk, J., Tonsor, G., Staples, A., 2023. The transition to cage-free eggs.
- Doyon, M., Bergeron, S., Saulais, L., Labonté, M.-E., Provencher, V., 2023. Do consumers value animal welfare and environmental attributes in egg production similarly in fresh eggs and prepared meals? Animals 13, 324.
- Egg Farmers of Canada, 2024. Annual Report 2024.
- IPCC, 2019. IPCC Guidelines for National Greenhouse Gas Inventories Intergovernmental Panel on Climate Change (2019).
- Mikosch, N., Dettmer, T., Plaga, B., Gernuks, M., Finkbeiner, M., 2022. Relevance of impact categories and applicability of life cycle impact assessment methods from an automative industry perspective. Sustainability 14, 8837.
- National Farm Animal Care Council, 2017. Code of Practice for the Care and Handling of Pullets and Laying Hens, National Farm Animal Care Council.
- Rahmani, D., Kallas, Z., Pappa, M., Gil, J.M., 2019. Are consumers' egg preferences influences by animal-welfare conditions and environmental impacts? Sustainability 11, 6218.
- Turner, I., 2025. Investigating sustainability improvement potential in the Canadian egg industry through integration of life cycle assessment, animal welfare, and operations research. University of British Columbia.

- Turner, I., Heidari, D., Pelletier, N., 2022a. Life cycle assessment of contemporary Canadian egg production systems during the transition from conventional cage to alternative housing systems: Update and analysis of trends and conditions. Resources, Conservation and Recycling 176, 105907.
- Turner, I., Heidari, D., Widowski, T., Pelletier, N., 2023. Development of a life cycle impact
Turner, I., Heidari, D., Widowski, T., Pelletier, N., 2023. Development of a life cycle impact
assessment methodology for animal welfare with an application in the poultry industry. Sustainable Production and Consumption 40, 30–47. https://doi.org/10.1016/j.spc.2023.06.010
- Turner, I., Heidari, D., Pelletier, N., 2022b. Environmental impact mitigation potential of increased resource use efficiency in industrial egg production systems. Journal of Cleaner Production 354, 131743. https://doi.org/10.1016/j.jclepro.2022.131743
- Vogeler, C.S., 2021. Politicizing farm animal welfare: A comparative study of policy change in the United States of America. Journal of Comparative Policy Analysis: Research and Practice 23, 526–543.

Partially dynamic life cycle assessment of Canadian egg production, differentiated by housing system and hen feather colour

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Abstract

Temporal changes in life cycle inventory data and impact assessment results are often overlooked in environmental life cycle assessment (LCA). Dynamic LCA (dLCA) has been proposed as a solution to this issue, though applications in agricultural systems remain relatively limited, particularly with respect to livestock production systems. Given anticipated increases in demand for livestock products and their substantial resource/environmental impacts, identification and dissemination of sustainability best management practices in this sector is desirable. DLCA may be a useful tool for this, highlighting specific hotspots to target within livestock systems that may otherwise be obscured when viewing production cycles using data that is averaged over time and space. This analysis presents the first partially dynamic LCA of a livestock system using a case study of the Canadian egg industry. Three partially dynamic LCA models were built: one representing production in enriched colony cages, and two representing production in aviary systems with white and brown feathered birds. Each incorporates dynamic inventories based on weekly productivity, mortality, and feed consumption data collected from Canadian egg farmers. The analysis yielded two key results. First, it illustrated how the environmental impacts of Canadian egg production change as the lay cycle progresses. Second, for those results beyond the standard 52-week lay cycle currently utilized in Canada, it facilitated comparisons of estimated impacts over extended lay cycles to previous analyses, in which the impacts of lay cycle extension were explored using LCI data derived from predictive models, as opposed to primary data. These results may subsequently be used in future analyses to determine optimal lay cycle lengths from an environmental perspective, which may differ from the currently utilized, relatively short cycle lengths and/or optimal cycle lengths from an economic perspective. This may also provide additional nuance to discussions regarding the sustainable development of the Canadian egg industry.

Keywords: Dynamic life cycle assessment; Poultry; Egg; Lay cycle length

Introduction

The concept of managing resource use and practices with respect to not only the current moment in time, but the future as well, is an inherent component of sustainability, and is included in many conceptualizations of the topic (Horton and Horton, 2019). In spite of this, some suggest that LCA does not sufficiently account for time horizons during assessment (Lueddeckens et al., 2020). Levasseur et al. (2010) propose dynamic LCA (dLCA) as a means to better incorporate the time dimension into LCA calculations. While dLCA has been applied in many industrial sectors, its use in the agri-food sector has been relatively limited, with the majority of applications focusing on end-of-life treatments of food waste (Bahramian et al., 2024), and soil organic carbon dynamics (Shen et al., 2023). Comparatively, applications of dLCA to livestock systems are relatively rare (Hietala et al., 2021).

This original study reports a partially dynamic LCA of the Canadian egg industry, incorporating dynamic life cycle inventory data (da Costa et al., 2024), but not dynamic characterization factors. This analysis makes use of primary data collected from Canadian egg farms operating extended lay cycles (i.e., >52 weeks of lay) describing production, mortality, and farm-level resource use on a weekly time step to develop weekly LCA models of Canadian egg production. This analysis provides insight into how the environmental impacts of Canadian egg production change over time, while also providing additional insight into the wide-scale adoption of extended lay cycles in the Canadian egg industry, a practice that was previously estimated to be detrimental to the sustainability of the industry based on secondary data (Pelletier and Doyon, 2023). This analysis also represents a real-world application of LCAutomate, a program developed for fast, automated generation of LCA unit processes, life cycle impact assessment calculations, and results processing based on large amounts of high quality primary data.

Material and methods

The goal of this analysis was to perform a cradle-to-farm gate attributional, partially dynamic LCA of Canadian egg production, differentiated by both housing system type, and hen feather colour. The functional unit, reference flow, system boundaries, and exclusions were defined consistently with previous LCA studies of the Canadian egg industry (Turner et al., 2022). Allocation between co-products at the laying flock (i.e., eggs and spent hens) was done using an internal causality-based approach based on metabolic partitioning within laying hens, as described by Arulnathan et al. (2022). Impacts related to land use changes, and soil organic carbon dynamics were excluded due to high levels of uncertainty in the magnitude and longevity of these effects, as were impacts associated with production, maintenance, and decommissioning of infrastructure and capital equipment, disposal of packaging, antibiotics, cleaners, and poultry enteric fermentation. Future analyses may consider including impacts related to land use changes given continued anticipated growth in the Canadian egg industry (Egg Farmers of Canada, 2024).

Primary survey data were collected from twenty-two Canadian egg farmers operating lay cycles between 53 and 66 weeks. Collected data included the age of hens at placement and depopulation, hen feather colour and specific bird strain (if possible), housing system type, number of hens placed at the beginning of the lay cycle, weekly productivity and mortality, daily feed consumption per bird, and the proportion of eggs graded into each of the possible Canadian egg grading brackets. Farmers were not asked to report weekly data on water or energy consumption, as these data are prone to data quality issues, and generally make small contributions to the life cycle environmental impacts of Canadian egg production (Turner et al., 2022). Similarly, data on manure production and removals were not collected, as these data are also prone to data quality issues; manure excretion data were therefore estimated based on a standard excretion rate scaled to weekly feed conversion efficiencies (Pelletier, 2017). Nitrogen (N) and Phosphorus (P) excretion was estimated using a nutrient mass balance model assuming that hen body mass is 2.2% N and 0.6% P, and that eggs are 1.7% N and 0.21% P, as per Koelsch (2007), and taking into account feed formulation nutrient composition (Pelletier, 2017). Emissions from manure management systems were estimated using an IPCC Tier 2 approach, while emissions associated with application of manure to agricultural land were estimated using a Tier 1 approach (IPCC, 2019). P losses were modelled using the SALCA-P emission model (Emmenegger et al., 2018). Weekly estimates of life cycle environmental impacts per cumulative tonne of eggs produced throughout lay cycles were estimated at the midpoint using the CML-IA Baseline impact assessment method (Mikosch et al., 2022).

Results and discussion

Contrary to previous analyses of extended lay cycles, the primary data collected during this analysis did not indicate dramatic reductions in feed conversion efficiency as hen age increased, even beyond the 52 week lay cycles normally practiced in Canada. In the previous analysis, substantial losses to feed conversion efficiency were predicted as a result of large decreases in productivity as hens aged based on data derived from breed-specific management guides. The primary data used in this analysis, however, showed no such large losses to productivity, with percent productivity (i.e., the percentage of hens laying one egg per day) remaining >90% beyond 52 weeks of lay in enriched colony systems (Figure 1). While percent productivity did not exhibit the same degree of robustness for brown and white hens housed in aviary systems, percent productivity in these systems was still >80% beyond 52 weeks of lay. These primary data therefore suggest that Canadian egg farmers are substantially outperforming productivity metrics given by hen genetics companies, and are also generally outperforming their counterparts in the United States operating at similar lay cycle lengths (Turner et al., 2023).97

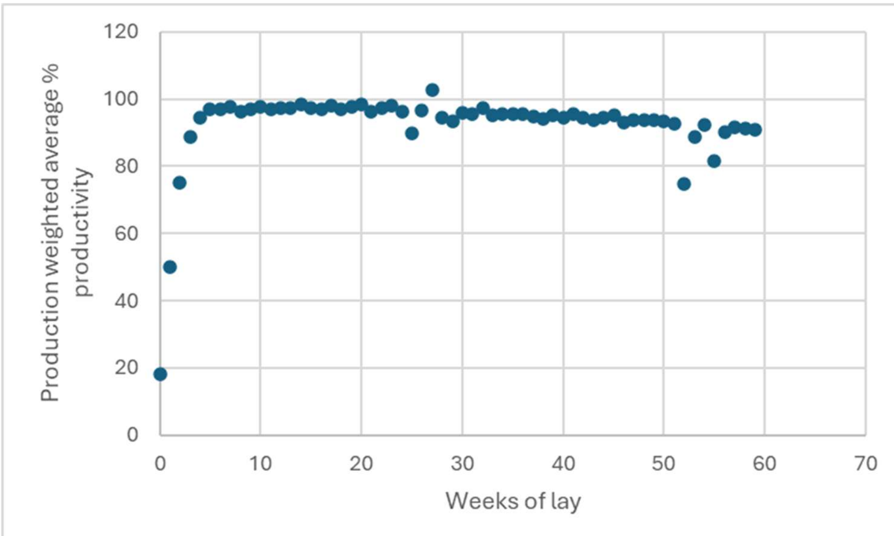

Figure 1. Production weighted average percent productivity (i.e, percentage of hens laying 1 egg per day) for hens housed in enriched colony systems

As anticipated based on the observed trends in productivity and feed conversion efficiency, estimated life cycle environmental impacts per tonne of eggs produced were generally observed to decrease as the lay cycle continued. This trend was observed regardless of the impact category assessed, and for all three of enriched, and white and brown hens housed in aviary systems. Though productivity was estimated to decrease as hens age in figure 1, these decreases in productivity were offset by increased egg mass as hens age, leading to a relatively constant mass of eggs produced Estimated life cycle greenhouse gas emissions per tonne of eggs produced in enriched housing systems for lay cycles of each length are presented in Figure 2. Only a single impact category from a single housing system is shown, including only a subset of farms for increased clarity, as a similar trend was observed for all the dLCA models developed. That estimated impacts do not increase as cycle length increases beyond the standard 52 week lay cycle length regularly practiced in Canada is directly contradictory to previous analyses of extended lay cycles in Canada, which predicted steady increases in impacts as lay cycles extended beyond 52 weeks. Contrary to the previous analysis, which concluded it would be detrimental to the environmental sustainability of the Canadian egg industry to enact lay cycle extension, this analysis indicates that there may be no such detriment. Further, when other sustainability aspects are considered (such as economic impacts), it may be possible that lay cycle extension could be an efficacious strategy for sustainable development of the Canadian egg industry – particularly due to improved economic outcomes for farmers as hens tend to lay larger eggs as they continue to age. Increased scrutiny is warranted, however, before lay cycle extension can be suggested as a sustainable development strategy for the Canadian egg industry given the differences in conclusions resulting from the use of secondary data (as in the previous analysis) compared to primary data (as in this analysis), and to consider how other sustainability attributes (such as animal welfare outcomes) may be impacted by increasing cycle length (Arulnathan et al., 2024). The results of this study may also be influenced by the functional unit chosen. If a functional unit based on number of eggs produced was chosen rather than a mass-based functional unit, it is possible that impacts would increase with cycle length as the estimated increases in egg mass as hens age would no longer offset the observed decreases in productivity.

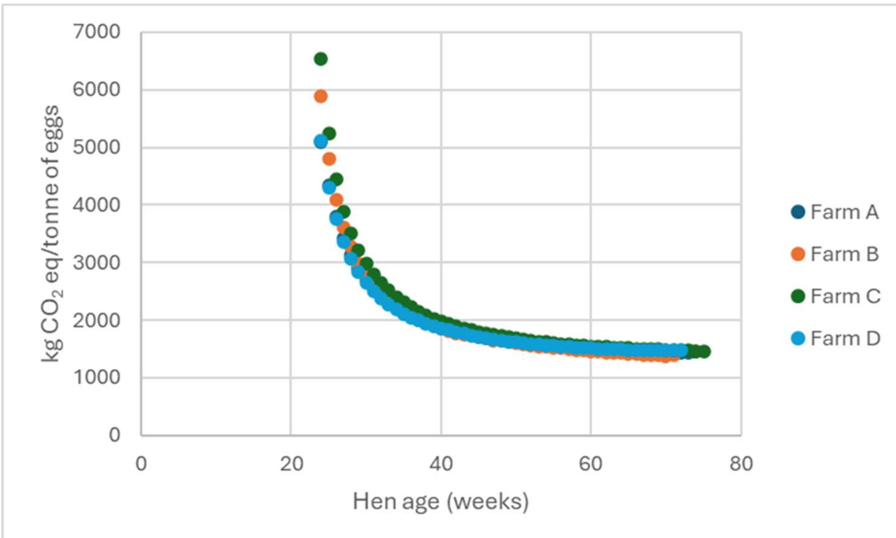

Figure 2. Life cycle GHG emissions per tonne of eggs produced in enriched housing systems on four Canadian farms across different lay cycle lengths. Each dot represents an individual, complete LCA model generated using LCAutomate. All dots begin at a hen age of twenty-four weeks to make the observed trend clearer.

Conclusion

Contrary to previous analyses, this analysis suggested that lay cycle extension beyond the standard 52 weeks regularly practiced in Canada does not result in large increases to environmental impacts per tonne of eggs produced. The opposite trend observed in this analysis may be attributed to the observation that Canadian egg farmers seem to be substantially outperforming productivity metrics suggested by hen management guides, with lay persistency being maintained well beyond 52 weeks of age in both enriched and aviary housing systems. The results of this analysis highlight the importance of the use of high-quality primary data to underpin sustainability assessment and sustainability decision making. Use of such large data sets may be facilitated through the use of automation tools, such as the AutoLCA tool used in this analysis and described in detail by submission ID 74. In the future, the results of these analyses may be integrated alongside economic indicators into a multi-objective optimization model to determine the optimal lay cycle length from an environmental and economic perspective for Canadian egg production in enriched and aviary housing systems.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada/Egg Farmers of Canada Industrial Research Chair in Sustainability, the Canada Foundation for Innovation John Evans Leadership Fund, and Egg Farmers of Canada.

References

- Arulnathan, V., Heidari, M.D., Pelletier, N., 2022. Internal causality in agri-food systems: Solving allocation problems based on feed energy utilization in egg production. Journal of Environmental Management 309, 114673.
- Arulnathan, V., Turner, I., Bamber, N., Ferdous, J., Grassauer, F., Doyon, M., Pelletier, N., 2024. A systematic review of potential productivity, egg quality, and animal welfare implications of extended lay cycles in commercial laying hens in Canada. Poultry Science 103, 103475.
- Bahramian, M., Hynds, P.D., Priyadarshini, A., 2024. Dynamic life cycle assessment of commercial and household food waste: A critical global review of emerging techniques. Science of the Total Environment 921, 170853.
- da Costa, T.P., da Costa, D.M.B., Murphy, F., 2024. A systematic review of real-time data monitoring and its potential application to support dynamic life cycle inventories. Environmental Impact Assessment Review 105, 107416.Egg Farmers of Canada, 2024. Annual Report 2024.
- Emmenegger, M.F., Délerce-Mauris, C., Porté, C., 2018. Models integrated in Ecoinvent LCI calculation
- tool for crop production.
- Quantis. Hietala, S., Heusala, H., Katajajuuri, J.-M., Järvenranta, K., Virkajärvi, P., Huuskonen, A., Nousiainen, J., 2021. Environmental life cycle assessment of Finnish beef – cradle-to-farm gate analysis of dairy and beef breed beef production. Agricultural Systems 194, 103250. https://doi.org/10.1016/j.agsy.2021.103250
- Horton, P., Horton, B.P., 2019. Re-defining sustainability: Living in harmony with life on Earth. One
- Earth 1, 86–94.
- IPCC, 2019. IPCC Guidelines for National Greenhouse Gas Inventories Intergovernmental Panel on
- Climate Change (2019).
- Koelsch, R., 2007. Estimating manure nutrient excretion [WWW Document]. URL (accessed 4.15.25).
- Levasseur, A., Lesage, P., Margni, M., Deschěnes, L., Samson, R., 2010. Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. Environmental Science and Technology 44, 3169–3174. https://doi.org/10.1021/es9030003
- Lueddeckens, S., Saling, P., Guenther, E., 2020. Temporal issues in life cycle assessment—a systematic review. International Journal of Life Cycle Assessment 25, 1385–1401. https://doi.org/10.1007/s11367-020-01757-1
- Mikosch, N., Dettmer, T., Plaga, B., Gernuks, M., Finkbeiner, M., 2022. Relevance of impact categories and applicability of life cycle impact assessment methods from an automative industry perspective. Sustainability 14, 8837.
- Pelletier, N., 2017. Life cycle assessment of Canadian egg products, with differentiation by hen housing system type. Journal of Cleaner Production 152, 167–180 https://doi.org/10.1016/J.JCLEPRO.2017.03.050
- Pelletier, N., Doyon, M., 2023. Long life layers - an environmental, economic, and animal welfare cost/benefit analysis. Egg Farmers of Canada.
- Shen, Z., Hamelin, L., Tiruta-Barna, L., 2023. Converting carbon vulnerable lands to wood plantations for use as building materials: Overall environmental performance and time-dependent assessment of carbon dioxide removals. Journal of Cleaner Production 388, 136040.
- Turner, I., Arulnathan, V., Pelletier, N., Ibarburu, M., Gates, R., 2023. Egg industry LCA - 2021 update.

- Turner, I., Heidari, D., Pelletier, N., 2022. Life cycle assessment of contemporary Canadian egg production systems during the transition from conventional cage to alternative housing systems: Update and analysis of trends and conditions. Resources, Conservation and Recycling 176, 105907.

A proposed framework to incorporate digital technologies with LCA in sustainable construction

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Abstract
The construction sector remains a significant contributor to global greenhouse gas emissions and material resource depletion. In response to escalating environmental concerns, Life Cycle Assessment (LCA) has gained prominence as a reliable methodology for quantifying and mitigating environmental impacts across the lifecycle of built assets. This study critically reviews the integration of digital technologies with sustainability practices. A mixed-methods approach, combining bibliometric analysis and a structured questionnaire was employed to evaluate current adoption levels and practices. Although digital tools such as BIM, Digital Twins, and IoT exhibit strong potential to enhance sustainability in the construction sector, their implementation remains limited and fragmented. Notable challenges include the lack of interoperable systems and fragmented data standards throughout the project lifecycle stages. In response to these barriers, the paper introduces a holistic framework designed to enhance data interoperability among digital tools and across lifecycle phases. The framework combines static and dynamic data sources, supports scenario analysis, and feeds results into interactive dashboards to inform decision-making. It aligns with international standards and is adaptable to certification benchmarks. While the framework shows strong potential for practical adoption, further pilot testing and regional customisation are needed. This study calls for coordinated industry collaboration to build digital capacity, establish standardised protocols, and mainstream LCA into routine workflows to support the transition towards net-zero and circular built environments.

Keywords: Sustainability, Digitalisation, Life Cycle Assessment, BIM, Digital Twin, Circular Economy

Introduction

The building and construction sector is responsible for approximately 37% of global CO_2 emissions, making it highly vulnerable to climate change impacts such as material degradation and operational disruptions (United Nations Environment Programme, 2023). Emissions from key construction materials are particularly significant, with cement contributing 8% and steel 7–9% of global CO_2 emissions (United Nations Environment Programme and Construction, 2024). The limitations of conventional construction practices and the urgency of climate goals have necessitated a paradigm shift within the construction industry. Traditional methods are increasingly inadequate for meeting the growing complexity and scale of sustainability targets (Banihashemi et al., 2024).

Digital transformation has emerged as a strategic response to these challenges. The adoption of advanced technologies such as Building Information Modelling (BIM), Digital Twin (DT), and Internet of things (IoT) present powerful tools for enhancing environmental performance and enabling data-driven decision-making throughout the asset lifecycle. These tools support real-time monitoring, enhancing data interoperability, scenario analysis, and performance optimisation. Their integration significantly strengthens the application of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), which are vital methodologies for evaluating both environmental and economic impacts throughout the whole lifecycle. Global initiatives such as EU's Renovation Wave and ISO standards (ISO 14040/14044) play a crucial role in promoting standardisation and broader adoption of digital tools. These initiatives enable scalable and adaptable sustainability solutions across diverse building types and climatic conditions (Sáez-de-Guinoa et al., 2022, Ohueri et al., 2024).

LCA has become a core component of green building certification systems such as LEED, BREEAM, and Green Star, helping drive the uptake of sustainable design and construction practices (Lützkendorf and Lorenz, 2015). Globally, there are now more than 600 green building rating systems, also referred to as environmental assessment or sustainability certification frameworks, which are used to evaluate the environmental performance of buildings (Li et al., 2023). However, limited data transparency by certification organisations and the fragmented policy landscape of the building sector remains a major challenge. Many certification schemes operate voluntarily and provide limited access to data on certified buildings, making it difficult to assess the environmental performance of the global building stock comprehensively (Marchi et al., 2021). The absence of a unified global sustainability framework reinforces the need for standardised design and material used to reduce environmental footprints more effectively (Teh et al., 2020)

Alongside environmental assessments, LCC provides a long-term perspective on the economic sustain-ability of projects, incorporating capital, operational, maintenance, and end-of-life costs. It creates a clearer picture of the actual financial impact of a project (Biolek and Hanák, 2019). This provides stakeholders with valuable insights to make better-informed decisions by comparing alternatives based on the total lifecycle costs. A notable example is The Edge building in Amsterdam with a high BREEAM rating of 98.36% which is one of the world's most sustainable office buildings integrates IoT sensors, AI-driven analytics, and digital twin technology to optimise energy use and indoor environmental quality. This integration led to savings in energy, maintenance, and operational costs, with an expected re-duction of 70% in energy consumption, 42% decrease in water usage and zero-waste operations (Marwa, 2025, Lemeš, 2025)

Achieving such outcome depends heavily on the engagement and alignment of stakeholders across all phases of the construction lifecycle. According to PAS 2080:2023, different stakeholders possess varying levels of influence over whole life carbon stages as shown in ***Figure 1***. It also highlights the critical role of society, end-users, and occupiers in shaping long-term operational behaviours and sustainability demands (BSI, 2023). Effective lifecycle carbon reduction requires consistent engagement, shared ac-countability, and integrated collaboration (Arogundade et al., 2023).

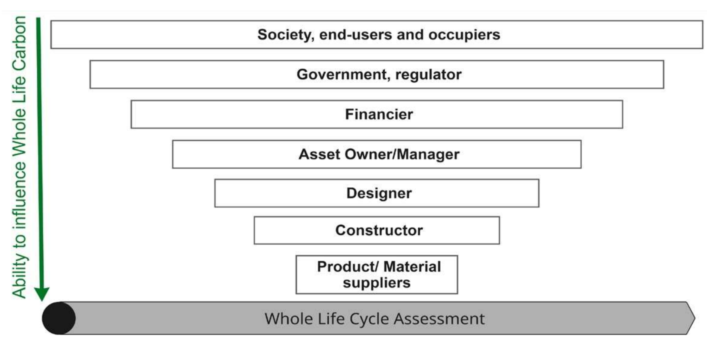

Figure 1: Stakeholder influence across whole life cycle (Edited from PAS 2080:2023)

This research aims to enhance data interoperability, automate environmental assessments, and support carbon emission reduction across the construction life cycle. It investigates current research trends and identifies gaps in the integration of digital technologies with sustainability practices. Based on these insights, a practical and holistic framework is proposed to improve data exchange, strengthen data visualisation, and support informed decision making, ultimately contributing to more efficient and sustain-able construction practices.

Material and Methods

This study adopts a two-phase mixed-methods approach to investigate the integration of Life Cycle Assessment (LCA) with emerging digital technologies in the construction sector. The first phase involved a systematic literature review (SLR), following PRISMA protocols. ***Figure 2*** summarises the review pro-cess. The search strategy included specific keywords such as "Life Cycle Assessment (LCA)," "Embodied Carbon," "Sustainability," "Digital Twin," "BIM," "Life Cycle Costing (LCC)," and "Construction." These terms were selected to align precisely with the study's scope, focusing on the intersection of sustainability and digitalisation in the built environment. This review critically identifies key research trends and knowledge gaps in the existing literature. These findings established a robust conceptual foundation for the second empirical phase of the study.

Building directly upon the knowledge gaps and insights identified from the bibliometric analysis, a structured questionnaire was designed to capture professional insights on the use of digital tools for sustainability. Questionnaire were provided in the supplementary material section (Appendix 1). In the second phase, 102 targeted professionals with demonstrated expertise in sustainability and digital technologies within the construction sector were selected. The sample comprised engineers, researchers, architects, consultants, and project managers, ensuring a broad representation of roles and experience levels. The study combines academic and industry insights to highlight the current state of digital integration within LCA and identify key barriers to adoption. This approach strengthens the credibility of the findings and supports the development of a comprehensive framework to improve interoperability and decision-making in the built environment.

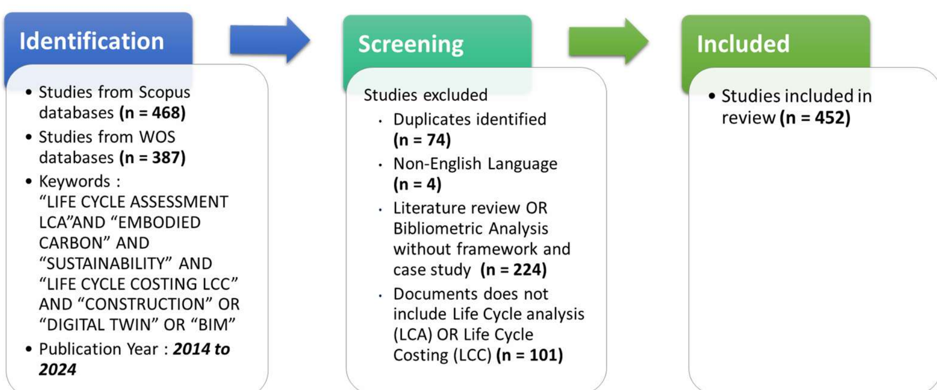

Figure 2 : (PRISMA) flowchart of the literature review process

Results, Analysis and Discussion

Qualitative Bibliometric Analysis

There is a consistent increase in research publications in recent years which underscoring the growing academic and industry focus on the intersection of digitalisation and sustainability within the construction sector. This growth highlights a shift in focus towards integrating digital technologies with environ-mental assessment. Despite the significant progress, the field remains in its formative stages.

A predominant share of research has centred on the integration of BIM-LCA analysis. As highlighted in ***Table 1***, 85% of studies prioritise BIM-LCA integration, primarily focused on early design and construction stages However, the limited extension of BIM applications across the full asset lifecycle reveals a significant methodological gap. Without broader application, these approaches unable to capture long-term environmental and operational benefits. In contrast, other emerging technologies such as DT, IoT, RFID, and Geographic Information Systems (GIS) remain underrepresented. Only 6% of LCA/LCC studies integrate DT, while 9% involve IoT, RFID, or GIS. These technologies offer advanced capabilities in real-time monitoring, automation, and predictive analytics, all of which are critical for dynamic, data-driven sustainability strategies. This underutilisation reveals an opportunity to develop a more dynamic and adaptive approaches.

Furthermore, most of the research carried out is based on technical studies or case-specific implementations which limiting its scalability and broader applicability. The findings show a lack of holistic frameworks that integrate multiple digital tools across all lifecycle stages. Future research should move be-yond BIM-centric approaches to explore multi-tool interoperability, enabling system-wide improvements and long-term environmental outcomes.

Table 1 : Publication reflected on digital tools with sustainability assessment integration

No.	Digital tools integrate with LCA and/or LCC	Percentage (%)
1	BIM	85%
2	DT	6%
3	IoT, RFID, and GIS	9%

Questionnaire Survey Data

The questionnaire was designed to gather insights on sustainability, digitalisation, and technology adoption within the construction sector. The respondent pool was diverse, with engineers forming the largest group (39%), followed by researchers, architects, and sustainability consultants. Smaller proportions included managers, government representatives, and suppliers. Furthermore, there were 18% of participants categorized under "Other," encompassing roles such as quantity surveyors, financial managers, and safety professionals. This diversity ensured representation from both technical and non-technical domains.

In terms of industry experience, the survey covered a broad spectrum of professional tenures. The big-gest group of respondents, 37% which had more than 10 years of experience, highlighting the significant representation of experienced industry professionals. Participants with 1–3 years of experience ac-counted for 24%, followed by those with 4–6 years (19%) and 7–10 years (17%). Only a small segment, 3%, indicated less than 1 year of experience. This balance distribution ensured insights from professionals with varying levels of engagement and familiarity in the construction industry.

Table 2: Demographic information of questionnaire participants

Characteristics	Participants	Percentage
Profession	Engineer	39%
	Researcher	11%
	Architect	10%
	Sustainability consultant	8%
	Manager	6%
	Government Officer	3%
	Supplier	5%
	Other (Quantity Surveyor, Financial Manager, Safety professional)	18%
Years of experience	Less than 1 Year	3%
	1-3 years	24%
	4-6 years	19%
	7-10 years	17%
	More than 10 years	37%

Adoption of Digital Tools by Construction Industry Experts

Survey findings reveal varying levels of digital tool adoption across the construction sector, reflecting both opportunities and challenges in integrating emerging technologies into industry workflows. The question asked in the survey : "*Are you involved in the use of any of the following technologies in your work or research?*" Respondents were allowed to select more than one option. As summarised in ***Table 3***, BIM emerged as the most widely adopted tool, with 41% of respondents reporting its use. BIM is primarily applied in the design and planning stages for 3D modelling, clash detection, and cost estimation, and remains a foundational tool in digital construction. Followed by the IoT with the adoption rate of 24%, predominantly among engineers and researchers. IoT enables sensor-based monitoring, real-time feedback, and data capture for improved decision-making. Besides that, DT technology while offering significant potential for lifecycle monitoring and dynamic data integration, recorded a lower adoption rate of 19%. DT usage was also concentrated among researchers and engineers, indicating limited diffusion into broader industry practice.

Table 3: Summary distribution of participants response on key digital technologies

No.	Technologies	Responses (%)
1	Digital Twin (DT)	19%
2	Building Information Modelling (BIM)	41%
3	Internet of things (IoT)	24%
4	Other (Eg. AI, Prefabrication, Nature Based solution)	4%
5	None of the above	13%

Notably, 13% of respondents reported not using any of the listed digital technologies, which may indicate that the integration of widely recognised digital tools within the industry is still in progress. Government officers and sustainability consultants indicated minimal engagement with digital tools, potentially due to the indirect nature of their roles in project execution. However, they are critical stakeholders overseeing the whole lifecycle of a project, from planning to operation. The low adoption of advanced tools such as DT and IoT highlights ongoing challenges, particularly in integrating real-time data systems into existing processes. The absence of data visualisation platforms and decision-support tools presents a further barrier. Without user-friendly, interpretable outputs, many professionals struggle to translate data into actionable insights.

Adoption of Sustainable Tools by Construction Industry Experts

Despite the growing focus on sustainability, the survey findings indicate that LCA tools are not widely adopted in the construction industry. *Table 3* summarises the survey responses' findings on using various LCA tools in the construction industry. As shown in the table, only 16% of respondents reported using LCA tools, while 11% used Life Cycle Costing (LCC) and 6% used Life Cycle Inventory (LCI). Alarmingly, 67% of respondents indicated that they do not practise any form of life cycle-based assessment.

Table 4: Survey Participant responses on using LCA tools

No.	Adoption of Life Cycle Assessment Tools	Responses (%)
1	Life Cycle Inventory (LCI)	6%
2	Life Cycle Assessment (LCA)	16%
3	Life Cycle Costing(LCC)	11%
4	Not Practicing	67%

In this study, the Life Cycle Inventory (LCI) is not considered a standalone tool but a core dataset within the Life Cycle Assessment (LCA) framework. The LCI phase involves systematically collecting and quantifying data throughout a product or building's lifecycle. These datasets form the foundation for subsequent environmental impact assessment under LCA. References to "LCI tools" therefore refer to the use of LCI databases and software that support data compilation and integration within broader LCA work-flows.

These results highlight a significant gap in adopting life cycle thinking within the construction sector. While LCA provides a structured method to evaluate environmental impacts across all project life cycle from material extraction to end-of-life disposal. Its integration into day-to-day decision-making remains limited. It is crucial to address the barriers hindering their widespread adoption.
To address these challenges, greater emphasis is needed on embedding life cycle approaches into planning, procurement, and operational frameworks. Institutional support, clearer guidelines, and investment in user-friendly tools could significantly enhance uptake. Bridging this implementation gap is essential for advancing sustainable outcomes that deliver long-term environmental, economic, and social value.

Proposed conceptual framework

Based on the findings from the systematic literature review and survey responses, this study proposes a conceptual framework that integrates digital tools with life cycle assessment (LCA) to support sustain-able decision-making in construction as illustrates in *Figure 3*. It aims to improve integration, usability, and scalability to support widespread industry adoption.

The framework consists of three core components: digital tools, life cycle assessment, and the decision-making phase. BIM models provide static design and construction data, while Digital Twins and IoT sensors supply real-time, dynamic information throughout the asset lifecycle. The Bentley iTwin platform enhances interoperability by integrating these data sources through a common data environment, enabling automated data flow, real-time synchronisation, and improved decision-making across lifecycle stages (iTwin Platform, 2025).

The LCA–LCC module builds on this data environment by separating environmental and economic assessments. Inventory data from Bentley iTwin can be complemented by inputs from Life Cycle Inventory (LCI) databases and Environmental Product Declarations (EPDs). These datasets are then transferred into life cycle assessment (LCA) to evaluate environmental impacts using the One Click LCA platform, while life cycle costing (LCC) supports cost optimisation using the same or parallel data inputs (Pasanen, 2024). To enhance analytical robustness, probabilistic and comparative analyses were conducted using R Studio to support scenario evaluation, sensitivity testing, and statistical interpretation of LCA and LCC results. Within the proposed framework, R Studio serves as the analytical engine for performing scenario-based modelling and data interpretation. This approach automates impact calculations and aligns with international sustainability standards, including ISO 14040 and ISO 14044, as well as global green building certification systems such as LEED, BREEAM, Green Star, and Green Mark In the final stage, outputs are translated into interactive data visualisation dashboards using platforms such as Power BI. These dashboards facilitate stakeholder understanding by presenting LCA and LCC outcomes in an accessible, real-time format. Importantly, the insights generated are also fed back into the Digital Twin platform, creating a closed-loop system that supports continuous performance monitoring and optimisation. This feedback mechanism enhances the dynamic nature of the Digital Twin by updating operational parameters based on scenario analysis and sustainability benchmarks. The framework further enables alignment with green building certification systems, supporting transparent, data-driven decision-making and advancing scalable, industry-ready sustainability practices.

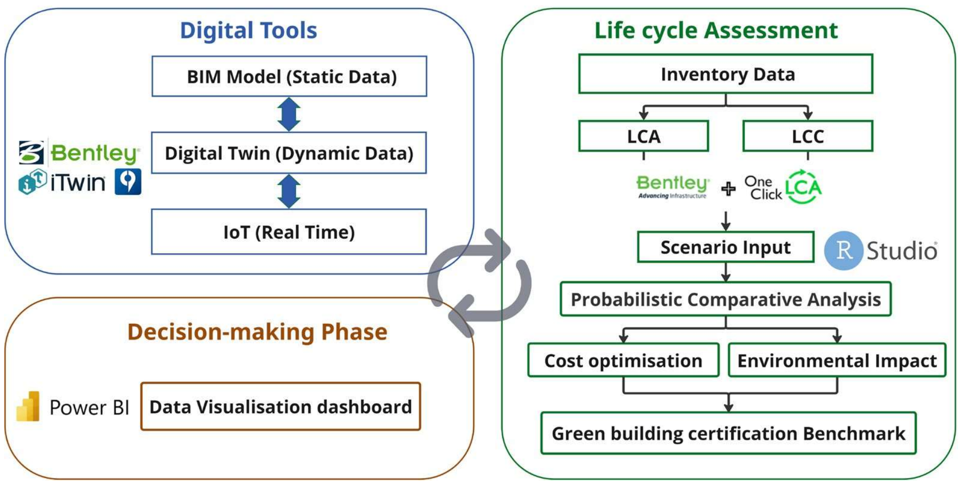

Figure 3: Flowchart for the proposed conceptual digital aided LCA framework

Conclusion and Future Direction

This study provides a critical evaluation of the current state of digital integration within and presents a practical digital-aided framework to enhance sustainability outcomes in the construction industry. Findings from both bibliometric analysis and industry survey responses, the study confirms that BIM is increasingly adopted and mandated for various construction projects. However, remains largely static and concentrated in early design stages. In contrast, the adoption of advanced technologies such as DT and IoT are still emerging. Its present underexplored potential for dynamic, real-time feedback mechanisms but are hindered by fragmented digital ecosystems and inadequate regulatory incentives. These findings align with trends observed in prior studies and underscore systemic barriers to widespread implementation.

The proposed digital-aided LCA framework directly addresses these challenges by improving data interoperability, enabling real-time monitoring, and automating assessment workflows. It aligns with international standards and supports informed decision-making across the asset lifecycle. By taking a system-wide perspective, the framework demonstrates strong potential for practical application and contributes to a scalable strategy for improving sustainability performance.

Several limitations in this study need to be acknowledged. The survey sample was not able to represent the perspectives of all stakeholder groups, and the analysis of certain technologies was constrained by data availability. Social dimensions of sustainability, such as equity, community effects, and labour concerns, were not examined. The research provides an overview in broad terms and is not indicative of regional diversity in the adoption of sustainable and digital practices. Such diversity will be explored in future studies and the development of frameworks to provide scalability and flexibility in different contexts.

Future research should focus on piloting the framework in real-world settings, developing adaptive models for different regional contexts. Effective data collection and visualization are critical to support informed decision-making, enabling continuous assessment and adaptive management throughout project lifecycles. This study underscores the need to explore strategies for building digital capacity across the construction sector. Advancing this agenda will require the development of integrated digital platforms, real-world validation through pilot projects, and cross-disciplinary collaboration. A coordinated effort involving policymakers, industry practitioners, and researchers is essential to standardise protocols and mainstream LCA into routine decision-making. These efforts are key to unlocking the full potential of digitalised LCA as a catalyst for achieving net-zero emissions and circular economy outcomes in the built environment. Acknowledgements This research was supported by Griffith University through Australian Government Research Training Program (RTP). We also acknowledge the participants who contributed to this study by completing the questionnaire, which was conducted under ethical approval (GU Ref No: 2024/634). The authors express gratitude to all survey participants and experts for their valuable input.

References

- Arogundade, S., Dulaimi, M., Ajayi, S., Saka, A. & Ilori, O. 2023. Decarbonization Of Construction Projects: A Review And Interpretive Structural Modelling Of Carbon Reduction Drivers. Journal Of Engineering, Design And Technology, Ahead-Of-Print.
- Banihashemi, S., Meskin, S., Sheikhkhoshkar, M., Mohandes, S. R., Hajirasouli, A. & Lenguyen, K. 2024. Circular Economy In Construction: The Digital Transformation Perspective. Cleaner Engineering And Technology, 18.
- Biolek, V. & Hanák, T. 2019. Lcc Estimation Model: A Construction Material Perspective. Buildings, 9, 182. Bsi 2023. Pas 2080:2023. Itwin Platform, B. S. 2025. Available: https://www.bentley.com/software/itwin-platform/ [Accessed 2025].
- Lemeš, S. 2025. Importance Of Measurements For Circular Economy And Green Transition.
- Li, X., Feng, W., Liu, X. & Yang, Y. 2023. A Comparative Analysis Of Green Building Rating Systems In China And The United States. Sustainable Cities And Society, 93, 104520.
- Lützkendorf, T. & Lorenz, D. 2015. Sustainable Design, Investment And Value. Design Economics For The Built Environment: Impact Of Sustainability On Project Evaluation, 137-151.
- Marchi, L., Antonini, E. & Politi, S. 2021. Green Building Rating Systems (Gbrss). Encyclopedia, 1, 998-1009.
- Marwa 2025. The Edge Amsterdam .. Where Solar Innovation Touches The Sky - Soular Innovations. Soular Innovations.
- Ohueri, C. C., Masrom, M. A. N. & Seghier, T. E. 2024. Digital Twin For Decarbonizing Operating Buildings: A Systematic Review And Implementation Framework Development. Energy And Buildings, 320, 114567.
- Pasanen, P. 2024. Bentley Systems & One Click LCA Integration [Online]. One Click LCA. Available: https://oneclicklca.com/en/resources/press-release/bentley-systems-announces-availability-of-life-cycle-assessment-and-embodied-carbon-calculation-capabilities-for-infrastructure [Accessed 2025].

- Sáez-De-Guinoa, A., Zambrana-Vasquez, D., Fernández, V. & Bartolomé, C. 2022. Circular Economy In The European Construction Sector: A Review Of Strategies For Implementation In Building Renovation. Energies, 15, 4747.
- Teh, D., Khan, T., Corbitt, B. & Ong, C. E. 2020. Sustainability Strategy And Blockchain-Enabled Life Cycle Assessment: A Focus On Materials Industry. Environment Systems And Decisions, 40, 605-622.
- United Nations Environment Programme, G. A. F. B. & Construction 2024. Global Status Report For Buildings And Construction - Beyond Foundations: Mainstreaming Sustainable Solutions To Cut Emissions From The Buildings Sector.
- United Nations Environment Programme, Y. C. F. E. A. 2023. Building Materials And The Climate: Constructing A New Future.

From Waste to Resource: Biochar as a Carbon-Reducing Strategy in Philippine Rice Farming

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Abstract

Rice is a staple crop in the Philippines, producing large quantities of rice straw as a byproduct—approximately one kilogram of straw for every kilogram of wet palay. Despite its abundance, rice straw is often left to decompose in flooded fields, contributing significantly to methane emissions, a potent greenhouse gas. This study, in partnership with Straw Innovations Ltd., investigated a potential sustainable pathway for rice straw utilization through bio-char production, aiming to reduce the carbon footprint of rice farming which provides basis for future integration into carbon market and supporting the advancement of climate-smart agricultural practices.

Three pyrolysis-based conversion scenarios were modelled using process simulation software: (1) pyrolysis, (2) pyrolysis with heat recovery, and (3) pyrolysis with both heat and carbon dioxide (CO_2) recovery. Each configuration was evaluated for its carbon footprint equivalent per kilogram of biochar produced. The second scenario achieved the lowest carbon footprint at 0.731 kg CO_2-e per kilogram of biochar. This system maximizes heat efficiency while converting methane to CO_2 that would be released into the atmosphere. This reduced the carbon footprint of conventional rice farming by 50.99%. The conversion of rice straw in-to biochar presents a dual environmental advantage: it prevents methane emissions from straw decomposition in flooded fields and sequesters carbon in a stable form in biochar. Future studies should extend beyond life-cycle emissions analysis to assess the techno-economic viability of heat-integrated biochar systems. This consists of comprehensive evaluation of capital and operating expenses, logistical strategies for straw collection and transport, and financial return timelines for investing in heat-recovery infrastructure. Additionally, estimating potential earnings from carbon credit markets is crucial. Conducting pilot-scale demonstrations is necessary to reduce risks with full-scale deployment and to evaluate broader impacts, including changes in crop productivity, soil nutrient retention, and elimination of open-field straw burning and rice straw incorporated in flooded fields.

Keywords: LCA Supporting Global/National/Industry Responses, LCA-based Carbon (GHG) Accounting Supporting Net Zero, Neutrality Pathways and Certification Responses, LCA Supporting Circularity and Circular Economies Responses, Agriculture and Bio-based Production Ap-plications and Innovations, Prospective and Dynamic LCA studies, Biochar, Rice straw

Introduction

Rice plays a central role in the Philippines' agriculture and food security, with production reaching 20.06 million metric tons of wet palay in 2023 (PSA, 2023). However, this scale of production also results in substantial agricultural waste, primarily in the form of rice straw. For every kilogram of wet palay harvested, an equivalent amount of rice straw is generated (IRRI, 2020), amounting to roughly 20 million metric tons annually. Despite its abundance, rice straw is underutilized, and conventional disposal methods such as open field burning and anaerobic decomposition remain widespread. These practices are major contributors to greenhouse gas (GHG) emissions, including methane, nitrous oxide, and carbon dioxide (Gadde et al., 2009; Bidhan et al., 2025), which pose environmental and climate concerns.

In 2020, the Philippines recorded methane emissions amounting to 70,155 Gg CO_2e, which accounted for approximately 34% of the country's total greenhouse gas emissions. Within the agriculture sector, methane contributed 38,434 Gg CO_2e, representing about 71% of the sector's total emissions of 54,080 Gg CO_2e. This means that methane from agricultural activities was responsible for around 54% of the country's overall methane emissions and about 19% of total greenhouse gas emissions. Given this substantial contribution, exploring the conversion of unused rice straw into biochar offers a sustainable approach to managing rice straw (PCCC, 2021).

Produced through pyrolysis—a thermal process in low-oxygen conditions—biochar retains approximately 50% of the original carbon content (Lehmann and Joseph, 2015; Hammond et al., 2011). Due to its high cellulose and lignin content, rice straw is a suitable feedstock for biochar, allowing for efficient carbon stabilization and reduced GHG emissions compared to traditional disposal methods. Controlled pyrolysis reactors, operating at 400°C–600°C, are increasingly being used at industrial scales with integrated heat recovery systems to improve sustainability (Wan Mahari et al., 2021; Fambri et al., 2024).

Assessing the environmental benefits of rice straw biochar production requires quantitative evaluation using Life Cycle Assessment (LCA) tools like SimaPro. Meanwhile, Aspen Plus serves as a platform to simulate and optimize pyrolysis conditions. This study aims to investigate different rice straw pyrolysis scenarios using Aspen Plus, quantify their respective carbon footprints, and determine the most environmentally sustainable configuration in terms of minimizing net GHG emissions.

Material and methods

Goal and Scope and Functional Unit

Transforming rice straw into biochar presents a promising mitigation strategy by offering a sustainable method of biomass valorization. A life cycle assessment (LCA) was carried out in SimaPro v9.5.0.2 to quantify the carbon footprint of each biochar production scenario and identify the scenario with the lowest emissions. The study also assessed the potential percentage reduction in emissions from rice farming when the system boundary is extended to include biochar production. It is important to note that this integration does not imply the application of biochar to soil, but rather the inclusion of biochar production within the system boundary beyond the traditional rice farming process. Table 1 outlines the study objectives along with their corresponding functional units.

Table 1. Study objectives and their defined functional unit System Boundary and Impact Assessment

Goal	**Functional Unit**
1.Compare the carbon footprint at different biochar production scenarios	kg CO2 / kg
2.Estimate the potential reduction in the overall carbon footprint of rice farming achievable by integrating biochar production system	biochar kg CO2 / ha

This study evaluates three scenarios for biochar production. Scenario 1 involves the pyrolysis of rice straw to generate biochar. Scenario 2 includes both pyrolysis and a heat recovery system, while Scenario 3 incorporates pyrolysis, heat recovery, and carbon dioxide recovery. The main goal is to compare the carbon footprints of these scenarios, and determine which scenario has the least carbon footprint. Figures 1, 2, and 3 present the system boundary for each scenario.

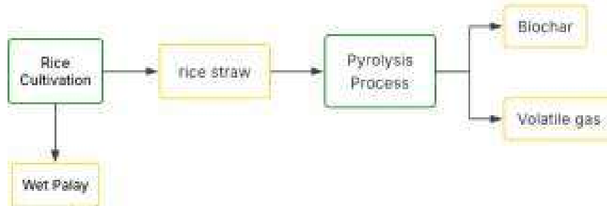

Figure 1. System boundary of Scenario 1 Biochar production

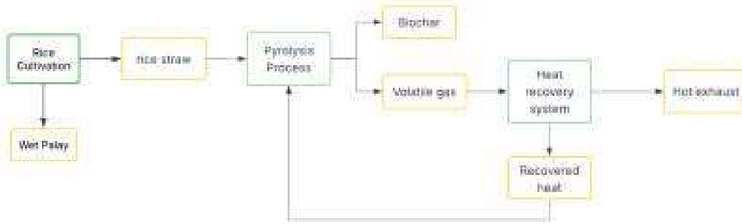

Figure 2. System boundary of Scenario 2 Biochar production.

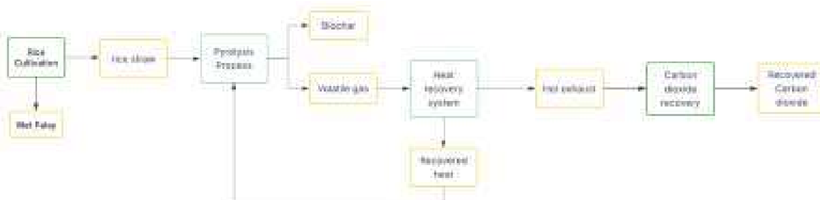

Figure 3. System boundary of Scenario 3 Biochar production

For the analysis of percentage reduction in emissions of rice farming, the system boundary covers the entire process from rice cultivation and harvesting up to biochar production, with the same three biochar scenarios applied. Figure 4 and 5 shows the system boundary of conventional rice farming system and rice farming system integrated with biochar production, respectively.

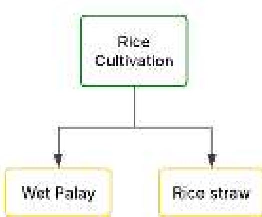

Figure 4. System boundary of conventional rice farming system.

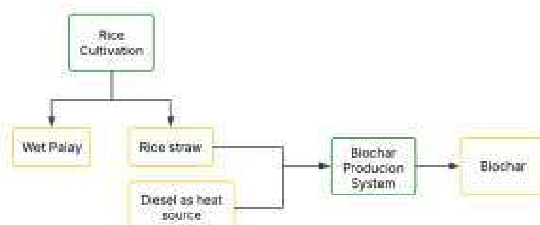

Figure 5. System boundary of conventional rice farming system integrated with biochar production.

The rice straw used as feedstock came from Victoria, Laguna, reflecting local farming conditions. Environmental impacts are calculated using the IPCC 2021 GWP100 V1.02 method, which estimates the global warming potential of greenhouse gases over a 100-year period.

Aspen Plus application

In the first simulation scenario, the modelled system includes rice straw as the sole biomass input, sourced from agricultural fields, and considers the burning of diesel to supply the thermal energy necessary for the pyrolysis reaction. An inert nitrogen (N_2) stream is continuously introduced to maintain an oxygen-limited environment, ensuring anaerobic conditions essential for pyrolysis. Prior to thermal decomposition, the rice straw undergoes a drying stage to reduce moisture content, enhancing pyrolysis efficiency. The overall pyrolysis process modelled under this scenario requires an external energy input of approximately 445.23 MJ to thermochemically convert 350 kg of rice straw per hour.

In the second scenario, the system boundary is expanded to include both the pyrolysis process and an integrated heat recovery system. In this configuration, the volatile gases (S3) produced during pyrolysis are combusted to generate the thermal energy required for the pyrolysis reaction itself, there-by reducing dependence on external fuel sources. Combustion of the volatile gases is carried out at 1000°C with sufficient air input, converting the chemical energy stored in the gases into usable thermal energy in the form of hot exhaust (Bowen and Purdy, 1983). As a result, this heat integration significantly lowers the system's external energy requirement to approximately 111.94 MJ for processing 350 kg of rice straw per hour. Lastly, the third scenario includes the pyrolysis, heat recovery and carbon dioxide recovery systems. The carbon dioxide recovery system here is added to recover the carbon dioxide in the exhaust gas instead of emitting it to the atmosphere which adds up to the carbon dioxide emissions. The system includes the use of solvent methyl diethanolamine (MDEA), absorption and stripper column, for CO_2 recovery system. The addition of additional systems in each scenario were conducted to deter-mine the carbon footprint reduction efficiency of adding systems in the biochar production pathway, to recommend the possible biochar production which has the least carbon footprint being created.

Life Cycle Inventory

Table 2 presents the inventory data for each biochar production scenario evaluated in the life cycle assessment. The system inputs include harvested rice straw, thermal energy required for the process, and nitrogen gas used to maintain a low oxygen environment during pyrolysis. Also shown are the gaseous outputs at each scenario.

Table 2. Life cycle inventory in each biochar production scenarios.

	Biochar Production Scenario		
	1	**2**	**3**
Input			
Rice straw (kg)	350	350	350
Heat (MJ)	445.23	111.94	617.22
N2 purge (kg)	200	200	200
Output			
Biochar (kg)	167.59	167.59	167.59
Volatile gas			
CO2 (kg)	87.82	128.73	19.93
CH4 (kg)	9.49	1.50E-22	0
CO (kg)	9.47	0.003	0.001

Recovered CO_2 (kg)	-	-	108.79

Results and Discussion

Assumptions and Limitation

The carbon footprint analysis in this study is derived from process simulations conducted using As-pen Plus v14. The rice straw properties used in the simulation, including proximate and ultimate analyses, are based on data specific to Philippine conditions, as reported by Migo-Sumagang et al., 2020. The pyrolysis process is modelled at an operating temperature of 500°C, with a biomass feed rate of 350 kg per hour. This temperature was selected following process optimization results indicating that carbon sequestration in the resulting biochar is maximized at this condition.

Basis of Pyrolysis Temperature in terms of amount of carbon sequestration

The pyrolysis process was assessed across a temperature range of 300°C to 600°C to evaluate its impact on carbon sequestration efficiency. This range aligns with the typical operating conditions for slow pyrolysis, as defined by Pandey et al., 2020. Simulation results revealed that carbon retention in biochar peaked at 500°C. Beyond this point, higher temperatures led to a decline in the proportion of carbon stabilized in the biochar. As a result, 500°C was identified as the optimal pyrolysis temperature for this study.

The aim of optimizing pyrolysis conditions is to maximize carbon sequestration—defined as the fraction of biomass carbon retained in a stable form within the biochar rather than released as green-house gases such as CO_2, and CH_4. Stabilizing this carbon is essential to minimizing the net emissions from biomass disposal. The U.S. Biochar Initiative (USBI) reports that pyrolysis can typically retain about 50% of the original carbon content. In this study, simulations showed a carbon retention rate of approximately 57%.

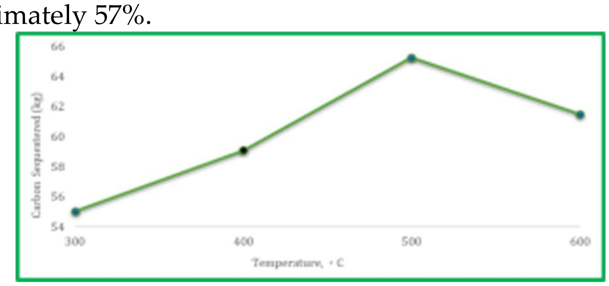

Figure 6. Effect of the temperature to the amount of carbon sequestered in biochar.

Carbon footprint of Biochar

The results show that scenario 1, which involves only the pyrolysis of rice straw to biochar, has the highest carbon footprint at 1.62 kg CO_2 per kg of biochar produced. In contrast, scenario 2, which integrates pyrolysis with a heat recovery system, results in the lowest carbon footprint of 0.731 kg CO_2/kg biochar. Scenario 3, which includes pyrolysis, heat recovery, and a carbon recovery system, yields a carbon footprint of 1.09 kg CO_2/kg biochar.

Among the three configurations, scenario 2 resulted in the lowest carbon footprint, achieving a 54.88% reduction compared to Scenario 1. Although, scenario 3 incorporates a carbon recovery system, the additional heat required to operate it offsets some of its environmental benefits, leading to a smaller reduction of 32.71% relative to scenario 1.

The performance of scenario 2 is primarily due to its heat recovery system, which combusts volatile gases such as methane (CH_4), carbon monoxide (CO), and hydrogen (H_2) to provide the necessary thermal energy for the pyrolysis process. This combustion step effectively converts these high-impact greenhouse gases into carbon dioxide (CO_2), a less potent GHG, thereby significantly reducing direct emissions and lessen the heat requirement of the system. In contrast, Scenario 1 lacks such a system, allowing volatile gases from pyrolysis to be released directly into the atmosphere, resulting in much higher direct emissions.

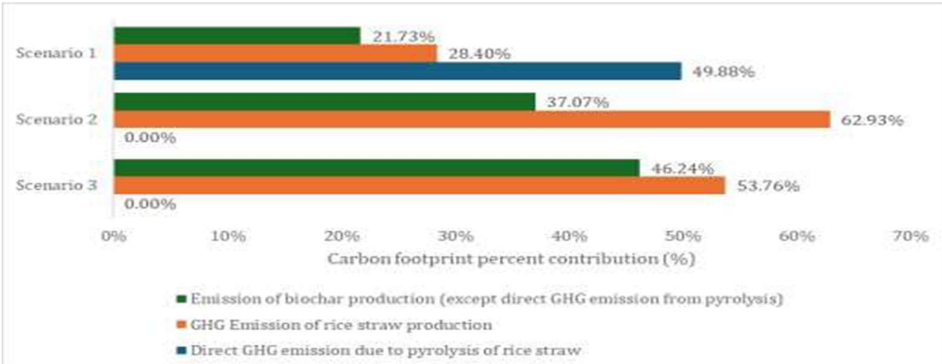

Figure 7. Percent distribution of emission in each scenario.

The results further highlight that in scenario 1, the main carbon footprint hotspot came from the direct emissions of rice straw pyrolysis, which contribute approximately 49.88% of total emissions. However, in scenarios 2 and 3, the primary contributor shifts to the production of rice straw, accounting for 62.93% and 53.76% of total emissions, respectively. This shift occurs because the direct GHG emissions from pyrolysis become negligible once heat recovery (scenario 2) and carbon recovery systems (scenario 3) are implemented. Nevertheless, the added utilities in scenario, particularly the in-creased heat requirement, negate the benefits of reduced direct emissions. Moreover, the higher proportion of emissions from rice straw production in Scenario 2 is due to the offsetting effect of the reduced share of emissions from biochar production, which is mainly driven by diesel consumption. As a result, Scenario 2 remains the most effective configuration in minimizing overall carbon footprint. Figure 7 shows the percent breakdown of carbon footprint in each scenario.

Carbon footprint of Rice farming integrated with Biochar production system

The study demonstrates a significant reduction in carbon footprint when rice farming is integrated with a biochar production system. This is evident when compared to the conventional carbon footprint value of 0.78 kilograms of carbon dioxide per kilogram of rice, based on a previous study conducted in Victoria, Laguna. That baseline was calculated using a yield of 5,589.81 kilograms of wet palay per hectare, equivalent to 4,385.67 kilograms CO_2 per hectare.

Figure 8 presents the carbon footprint per hectare of rice farming integrated with different biochar production scenarios. Figure 9 also illustrates the percentage reduction in emissions achieved. The results show that integrating rice farming with Scenario 2, which includes pyrolysis with a heat recovery system, achieves the highest reduction in carbon footprint at 50.99%.

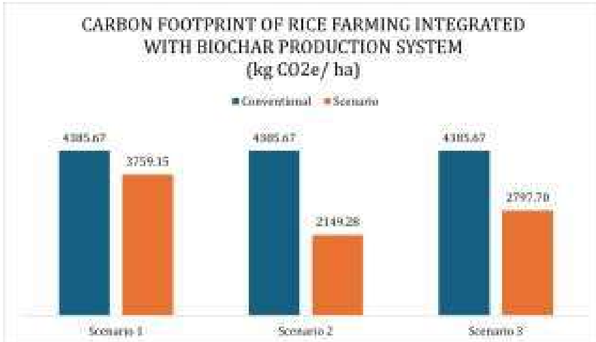

Figure 8. Carbon footprint of rice farming with biochar production in kg CO2/ha.

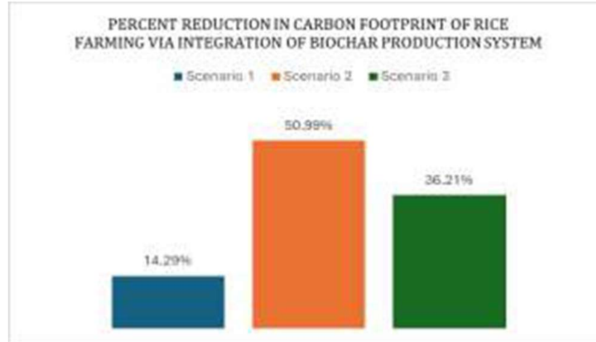

Figure 9. Percentage reduction in carbon footprint achieved by each scenario compared to conventional rice farming.

Conclusion

The study demonstrates a significant reduction in carbon footprint when rice farming is integrated with a biochar production system when compared to the conventional carbon footprint value of 0.78 kilograms of carbon dioxide per kilogram of wet palay, based on a previous study conducted in Victoria, Laguna. That baseline was calculated using a yield of 5,589.81 kilograms of wet palay per hectare, equivalent to 4,385.67 kilograms CO_2 per hectare. The life-cycle assessment carried out in this study makes it clear that the climate benefit of rice-straw biochar depends on where the system boundary is drawn and how energy loops are closed. When the boundary stops at stand-alone pyrolysis (Scenario 1), the carbon footprint is 1.62 kg CO_2 eq per kilogram of biochar due to emission of uncombusted methane. Extending the boundary to include on-site combustion of those volatiles in a heat-recovery loop (Scenario 2) decreases the carbon footprint to 0.731 kg CO_2 eq per kilogram of biochar and, when coupled to the upstream paddy, cuts farm-level emissions by 50.99% relative to the conventional baseline measured in Victoria, Laguna. Adding post-combustion carbon recovery (Scenario 3) lowers CO_2 emitted to atmosphere, but due to the extra heat required, the net benefit falls to a 36.21%. These results underline two enduring LCA insights: first, allocation of co-products and recycled energy streams can reverse apparent hotspots, and second, deeper process integration does not automatically translate to lower impacts once the energy penalty of additional unit operations is internalised.

Future research should go beyond environmental accounting and evaluate the techno-economic feasibility of such systems. This includes mapping capital and operational costs, optimizing logistics for straw collection and transport, determining the payback period for heat-recovery investments, and estimating revenue from potential carbon credits. Pilot-scale trials will be essential to de-risk large-scale implementation and assess additional factors such as effect on the crop yields, effect on the nutrient retention in soil, and the reduction of open-field straw burning and incorporation of rice straw in flooded fields.

Overall, the results show that scenario 2 heat-integrated biochar systems, which combust methane-rich volatiles onsite using a heat-recovery loop, as a high-impact climate mitigation strategy for rice-producing regions. This approach directly addresses both methane emissions, open-field burning of rice straw and incorporation of rice straw in flooded fields. When implemented alongside carbon credit schemes and localized pilot programs, it offers a scalable pathway for rice-farming communities to contribute to national net-zero targets.

Acknowledgements
This project is financially supported by UK Research and Innovation (UKRI)-Innovate UK and implemented in collaboration with Straw Innovations Ltd. and Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA). The project's central objective is the valorization of rice straw, an agricultural byproduct of rice cultivation. This initiative is designed to achieve the dual goals of mitigating the carbon footprint associated with rice farming and creating supplementary revenue streams to enhance the livelihoods of local farmers.

References

- Palay Situation Report, January to December 2023 | Philippine Statistics Authority | Republic of the Philippines [WWW Document], 2024. URL https://psa.gov.ph/content/palay-situation-report-january-december-2023
- Gadde, B., Bonnet, S., Menke, C., Garivait, S., 2009. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environmental Pollution, Special Issue Section: Ozone and Mediterranean Ecology: Plants, People, Problems 157, 1554–1558. https://doi.org/10.1016/j.envpol.2009.01.004
- Bidhan, N., Md Moudud, A., Subrata, P., Md Durrul, H., Mohammad Afzal, H., Sharmin, I., 2025. Unlock-ing the potential of rice straw: Sustainable utilization strategies for Bangladesh. Circular Economy 4, 100126. https://doi.org/10.1016/j.cec.2025.100126
- Philippine Climate Change Commission, 2021. Executive summary. In: Recabar, S., Evangelista, A., Ebora, J., Alonzo, A., Leyba, A., Francisco, J. (Eds.), *2010 Philippine Greenhouse Gas Inventory Report*.
- Lehmann, J., Joseph, S. (Eds.), 2015. Biochar for Environmental Management: Science, Technology and Implementation, 0 ed. Routledge. https://doi.org/10.4324/9780203762264
- Hammond, J., Shackley, S., Sohi, S., Brownsort, P., 2011. Prospective life cycle carbon abatement for py-rolysis biochar systems in the UK. Energy Policy 39, 2646–2655. https://doi.org/10.1016/j.enpol.2011.02.033
- Wan Mahari, A., Azwar, E., Foong, S.Y., Ahmed, A., Peng, W., Tabatabaei, M., Aghbashlo, M., Park, Y.-K., Sonne, C., Lam, S.S., 2021. Valorization of municipal wastes using co-pyrolysis for green energy pro-duction, energy security, and environmental sustainability: A review. Chemical Engineering Journal 421, 129749. https://doi.org/10.1016/j.cej.2021.129749
- Fambri, G., Lombardi, G., Badami, M., Chiaramonti, D., 2024. Energy Assessment of a Slow Pyrolysis Plant for Biochar and Heat Cogeneration. Chemical Engineering Transactions 109, 571–576. https://doi.org/10.3303/CET24109096
- Migo-Sumagang, M.V.P., Van Hung, N., Detras, M.C.M., Alfafara, C.G., Borines, M.G., Capunitan, J.A., Gummert, M., 2020. Optimization of a downdraft furnace for rice straw-based heat generation. Re-newable Energy 148, 953–963. https://doi.org/10.1016/j.renene.2019.11.001
- Bowen, M.D., Purdy, K.R., 1983. Pyrolysis system with hot gas circulation. EP0070710A2.
- Pandey, D., Daverey, A., Arunachalam, K., 2020. Biochar: Production, properties and emerging role as a support for enzyme immobilization. Journal of Cleaner Production 255, 120267. https://doi.org/10.1016/j.jclepro.2020.120267
- Biochar Slows Climate Change | US Biochar Initiative [WWW Document], n.d. . USBI. URL https://biochar-us.org/biochar-slows-climate-change

LCA of water delivery infrastructure and irrigation technologies employed in cherry production in the Okanagan Valley (Canada)

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Abstract

Representation of the processes associated with, and the environmental impacts of, irrigation in agricultural systems is often simplified in life cycle assessment (LCA) to consider only water and energy consumption. In this research, an alternative approach is employed to add more nuance to the irrigation supply chain as a contributor to a more comprehensive suite of environmental outcomes, using a case study of cherry production in the Okanagan Valley of British Columbia, Canada. A regionalized life cycle inventory of Okanagan water delivery systems was developed based on primary data from local water purveyors, and an LCA was performed to determine the share of environmental burdens associated with irrigation water, including the water supply network. For the water delivery system, the LCA results highlighted the importance of water treatment for a wide range of impact categories - demonstrating the need for dedicated agricultural water delivery that, unlike municipal drinking water, does not need to be treated.

The water delivery model was used in combination with an LCA of Okanagan cherry production conducted by (Sanderson et al., 2019). Irrigation contributed a significant portion to most impacts of cherry production. In addition, the local water delivery model yielded significantly different impacts of cherry production (ranging from ~1/3 to double), compared to the generic ecoinvent irrigation process employed by (Sanderson et al., 2019). Employment of more efficient irrigation technologies, such as drip irrigation (compared to microsprinkler), decreased impacts in these categories by 10-16%. When the increased nitrous oxide emissions associated with drip irrigation were considered, drip irrigation still outperformed microsprinkler in every impact category except climate change, where higher impacts due to nitrous oxide emissions from drip irrigation were counteracted by the decreased efficiency of microsprinkler systems. This study highlights the importance of using detailed, regionalized LCI data for agricultural irrigation systems.

Keywords: life cycle assessment, agriculture, cherries, water use, irrigation, regionalization

Introduction

Freshwater resources are essential for aquatic and terrestrial ecosystems, however 70% of anthropogenic freshwater consumption is for agricultural irrigation, both globally (Foley et al., 2010) and at the regional level within the Okanagan Valley in the province of British Columbia, Canada (Van Der Gulik et al., 2010). To assess irrigation efficiency as a potential solution to address water scarcity issues (ISO, 2014), one must consider the problem of freshwater use in the Okanagan using life cycle assessment (LCA), in order to account for trade-offs throughout the supply chain, as well as a full suite of relevant environmental impacts. In the last decade, life cycle thinking has been incorporated into the ISO standards for water footprinting methods, making LCA a well suited tool for water use-related impact assessment (ISO, 2014). LCA has been applied to quantify the resource trade-offs and environmental implications associated with water delivery and irrigation in agri-food systems in diverse contexts. For example, Abeliotis et al. (2013) found that electricity used for irrigation pumping was the major contributor to environmental impacts of bean production in Greece. However, life cycle inventory (LCI) data characterizing the supply chains of water delivery systems and irrigation technologies that support agricultural activities is currently lacking in Canadian LCA literature. In addition to the upstream impacts associated with the delivery of water, irrigation on farms also potentially influences field-level emissions from agricultural soils, including carbon dioxide (CO_2) emissions from bicarbonate in irrigated water (Hannam et al., 2016), and varying nitrogenous emissions from different irrigation technologies (Deng et al., 2018; Fentabil et al., 2016).

Therefore, the goals of this original study were to 1) collect and compile LCI data, and conduct a regionalized LCA, on regional water supply for agricultural irrigation in the Okanagan Valley in Cana-da; and 2) collect and compile LCI data on irrigation technology used on orchards in the Okanagan, in order to conduct an LCA of cherry production using these regionally representative water delivery and irrigation processes.

Material and methods

The LCA methods for this study follow the ISO 14044 standard for LCA best practices (ISO, 2006a), as well as the ISO 14046 standard for water footprint assessment, which are based on and compatible with the methods prescribed in ISO 14044 (ISO, 2014).

Water delivery LCA methods and LCI data

A cradle-to-gate attributional LCA was performed - from the withdrawal of water from a ground or surface-water source, to the treatment, pumping, and delivery of water to agricultural users (Figure 1). The functional unit of this system was 1 m^3 of irrigation water delivered to farms in the Okanagan. Some water delivery systems provide water to both domestic and agricultural users – in these cases, inputs were allocated on a volume/mass basis using the ratio between annual domestic and agricultural water consumption, consistent with the second tier of the multifunctionality hierarchy prescribed by ISO 14040 (ISO, 2006b).

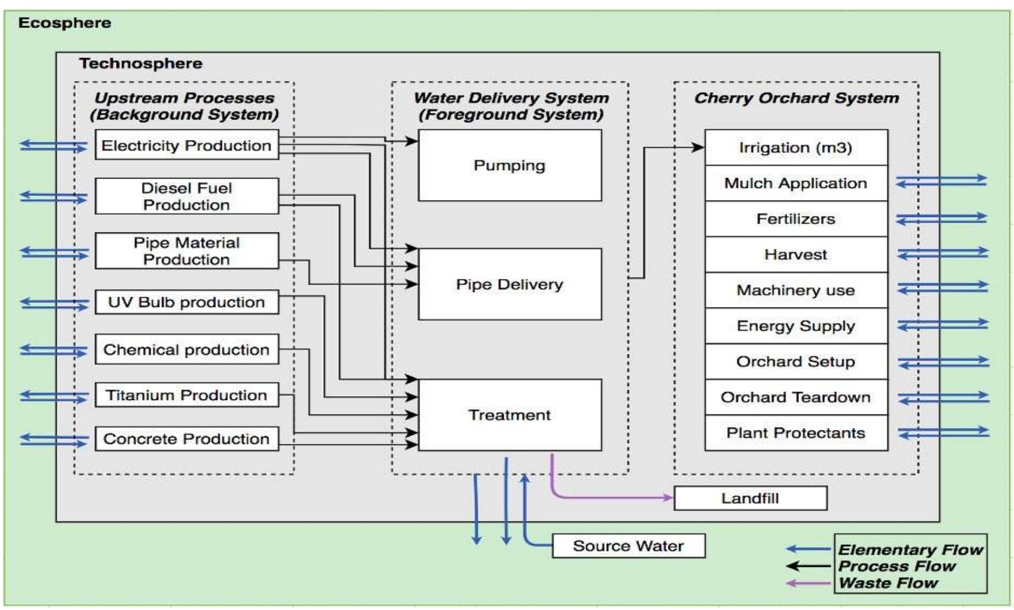

Figure 1. System flow diagram of the Okanagan water delivery and cherry product systems. Areas in green and grey represent the ecosphere and technospere, respectively. Within the technosphere, background and foreground processes are joined along the supply chain with the use of colour-coded arrows representing elementary, process, and waste flows (see legend).

Baseline LCIs were developed that characterized the regionally specific supply chains of different water delivery systems in the Okanagan, based on surveys sent to water purveyors. Specifically, da-ta were collected on delivery pipes (type, diameter and length), water treatment processes, and water pumping (amount, capacity, and horsepower of pumps). Data from ecoinvent v3 were used to model all background data, modified when relevant to reflect Canadian production conditions.

LCI data were collected from 14 water delivery systems in the Okanagan. Five distinct treatment methods were employed: no treatment, treatment at a plant, and treatment at the source intake with trucked in chlorine, trucked in hypochlorite, or hypochlorite generated on-site (Table 1). Of the 14 systems, two were gravity fed, five were pumped, and seven were mixed (Table 1). A total of 9 pipe types of various diameters were included in the inventory (Table 2). The length of each pipe type required to deliver a cubic meter of water to an agricultural user was found by dividing the production weighted average length of each pipe by the average volume of water delivered over a 50-year lifespan.

Table 1. Each reported system from three water purveyors and the attributes associated with each system: total volume of water consumed during the irrigation months April – October (2018), the production proportion, delivery method, water source, and treatment type

System	Irrigation Season Volume (m^3)	Proportion of Production	Delivery Method	Water Source	Treatment Type
Kelowna[1]	7,664,450	23%	Gravity	Surface	Delivered Chlorine
Oliver 1 – Mud Lake[2]	1,627,680	5%	Mix	Surface	None
Oliver 1 – Buchanan[2]	180,520	1%	Mix	Ground	None
Oliver 2 – Black Sage Wells[2]	721,980	2%	Pumped	Ground	Delivered Hypochlorite
Oliver 2 - Miller RD[2]	60,010	0%	Pumped	Ground	Generated Hypochlorite
Oliver 2B[2]	404,630	1%	Pumped	Surface	None
Oliver 4[2]	3,542,830	11%	Mix	Surface	None
Oliver 5[2]	1,515,160	5%	Mix	Surface	None
Oliver 6[2]	1,771,430	5%	Mix	Surface	None
Oliver 7[2]	1,434,500	4%	Mix	Surface	None
Goose Lake Non-potable[3]	662,300	2%	Pumped	Surface	None
King Edward non-potable[3]	813,080	2%	Gravity	Surface	None
Duteau Non-potable[3]	805,350	2%	Pumped	Surface	None
Duteau Combined[3]	11,710,450	36%	Mix	Surface	None

[1]From City of Kelowna (pers. comm. Brad Stuart; (Hoppe, 2019)

[2]From Town of Oliver (Goodsell, 2018)

[3]From Regional District of North Okanagan (Clark, 2018); pers. comm. Skyler Ganz)

Table 2. Lengths of each pipe type per functional unit. Pipe types include asbestos concrete (AC), concrete, ductile iron (DI), high-density polyethylene (HDPE), fiberglass reinforced plastic (FRP), polyvinyl chloride (PVC), steel, galvanized steel (galv), and reinforced concrete cylinder pipe (RCCP).

Pipe Type	Weighted Average Length (km)	Length per Functional Unit (km m^{-3})
AC 500	18.08	1.4×10^{-7}
Concrete 500	16.75	1.3×10^{-7}
DI 500	4.30	3.3×10^{-8}
HDPE 500	0.02	1.5×10^{-10}
FRP 500	0.11	8.6×10^{-10}
PVC 500	9.12	7.0×10^{-8}
Steel 500	5.81	4.5×10^{-8}
Galv 500	0.09	6.5×10^{-10}
RCCP 500	2.01	1.5×10^{-8}

OpenLCA (GreenDelta, 2020) – an open-source life cycle assessment software – was used to model the study system. This software enables the practitioner to model impacts for both midpoint and endpoint impact categories using suites of LCIA methodologies imported into the software. For this study, the IMPACT World+ methodological suite (Bulle et al., 2019) was used for classification and characterization at the midpoint level, including site-dependent characterization factors for Canadian ecozones. Uncertainty was assessed using the ecoinvent pedigree matrix, and propagated using Monte Carlo simulation (1000 runs).

Cherry orchard LCA methods and LCI data

The Okanagan cherry orchard system was modelled using an attributional LCA with a cradle-to-market system boundary. The LCI of the cherry orchard system therefore included the setup, maintenance (irrigation, mulch, fertilizers, harvest, machinery use, energy supply, plant protectants, field emissions), and teardown of a cherry orchard with a lifespan of 20 years and a functional unit of 1 kg of edible cherries delivered to market gate (Figure 1).

To compare irrigation infrastructure and technologies at the orchard level, a previously published LCI model representative of the Okanagan cherry product system (Sanderson et al., 2019) was adapted. The Okanagan water delivery system described above was included in the model. The type of irrigation technology used on Okanagan cherry orchards was collected from the Agricultural Land Use Inventory (BC Ministry of Agriculture, 2016; B.C. Ministry of Agriculture, 2014) through the Okanagan Basin Water Board. Efficiencies of each technology (i.e., the proportion of irrigation that remains available for crop uptake) were derived from the Okanagan Water Demand Model technical description (Fretwell, 2009). A total of 12 different irrigation technologies were employed on Okanagan cherry orchards (Table 3). The two most common technologies were micro-sprinkler and solid-set undertree, which were utilized in 50% and 24% of the irrigated cherry orchards in the survey, respectively.

Hannam et al. (2016) found that bicarbonate (HCO_3) originating in the Okanagan Lake was delivered to orchard soils through irrigation, where a chemical reaction can produce inorganic carbonates and CO_2, in the presence of sufficient cations. The quantity of CO_2 released from irrigated soil per m^3 of irrigation water due to the bicarbonate contained in the source water was therefore derived from Hannam et al., (2016), scaled by the efficiency coefficient (Table 3).

Direct and indirect nitrous oxide (N_2O) emissions from fertilizer application were calculated using IPCC Tier 2 country-specific emission factors, for the drip irrigation scenario (Table 4). Based on the results of a study of apple orchards in the Okanagan, micro-sprinkler irrigation was found to have 29% lower N_2O emissions than drip irrigation (Fentabil et al., 2016). Therefore, the N_2O emissions associated with the micro-sprinkler scenario were modelled as 29% less than the drip scenario (7.53×10^{-5} kg of N_2O kg^{-1} of usable cherry yield).

Table 3. The type, efficiency, and percent frequency of each irrigation technology employed on Okanagan cherry orchards that used irrigation (n=1422). The input volume describes the volume of water required to deliver a cubic meter of water to the soil for crop uptake and is calculated using the efficiency coefficient. The last column represents the $CO_{2(g)}$ released from the soil due to bicarbonates delivered by a cubic meter of irrigation water, with irrigation technology efficiency accounted for. ss. = solid-set

Irrigation Used	Percent	Efficiency	Input volume (m^3 m^{-3})	$CO_{2(g)}$ (kg m^{-3})
Drip	3%	0.92	1.09	0.0095
Handline	2%	0.70	1.43	0.0124
Microspray	10%	0.88	1.14	0.0099
Micro-sprinkler	50%	0.78	1.28	0.0112
Overtreedrip	0.4%	0.92	1.09	0.0095
SDI	0.1%	0.95	1.05	0.0092
Ss. Overtree*	2%	0.70	1.43	0.0124
Ss. Sprinkler*	1%	0.72	1.39	0.0121
Wheelline	0.1%	0.72	1.39	0.0121
Blank	0.1%	0.72	1.39	0.0121
Sprinkler	8%	0.72	1.39	0.0121
Ss. Undertree*	24%	0.74	1.35	0.0118
Production Weighted Average	-	0.78	1.29	0.0112

Table 4. Mass of direct and indirect N_2O, NO_3-, NH_3, and NO_x emitted at the orchard level due to synthetic fertiliser application per functional unit of 1 kg of usable cherries

GHG Species	Amount	Unit	Elementary flow compartment
N_2O - Dinitrogen monoxide	1.06×10^{-4}	kg	Emission to air/unspecified
Direct N_2O (– air)	9.02×10^{-5}	kg	
Indirect N_2O (NO_x + NH_3 – air)	4.87×10^{-6}	kg	
Indirect N_2O (NO_3- – water)	1.10×10^{-5}	kg	
NH_3 - non combustion	6.08×10^{-4}	kg	Emission to air/unspecified
NO_3- - Nitrate	4.13×10^{-3}	kg	Emission to water/unspecified
NO_x - non combustion	1.19×10^{-4}	kg	Emission to air/unspecified

Impact assessment was performed using IMPACTWorld+ in openLCA, and uncertainty propagated using Monte Carlo simulation (1000 runs).

Results

Of the 9 impacts categories shown in Figure 2, delivery piping had the largest contribution across process stages for 6 of them. Particularly, piping was responsible for 85% of the impacts of mineral resource use. This was largely due to various forms of steel production for steel, ductile iron, and concrete piping, accounting for a total of 63% of the water delivery system's impacts for this category. Delivery piping was responsible for 53% of fossil and nuclear energy use, where 21% of the total impacts of the system were from steel casting used in ductile iron pipe manufacturing, and 12% from polyvinylchloride used in PVC pipe manufacturing. Delivery piping accounted for 53% of freshwater eutrophication impacts, 52% of human toxicity impacts, and 50% of short-term climate change impacts – the highest contributions to which were from steel manufacturing processes. Treatment was responsible for 80% of the impacts on freshwater ecotoxicity associated with the system, as well as 49% of terrestrial acidification (Figure 2). Treatment also contributed 37-45% of impacts for climate change, fossil and nuclear energy use, freshwater eutrophication, and human toxicity, with minimal contributions to mineral resource use and water scarcity. These impacts were due to the treatment plant infrastructure, treatment chemicals (mostly chlorine and hypo-chlorite), electricity use and transportation of inputs. Source water (majority surface water) was the highest contributor to the water scarcity impacts (96%), with no contribution to any other impacts (Figure 2). Pumping had a relatively small role across impact categories compared to other processes in the system, due to the large proportion of gravity-fed systems, and the relatively low impacts of the electricity grid in British Columbia.

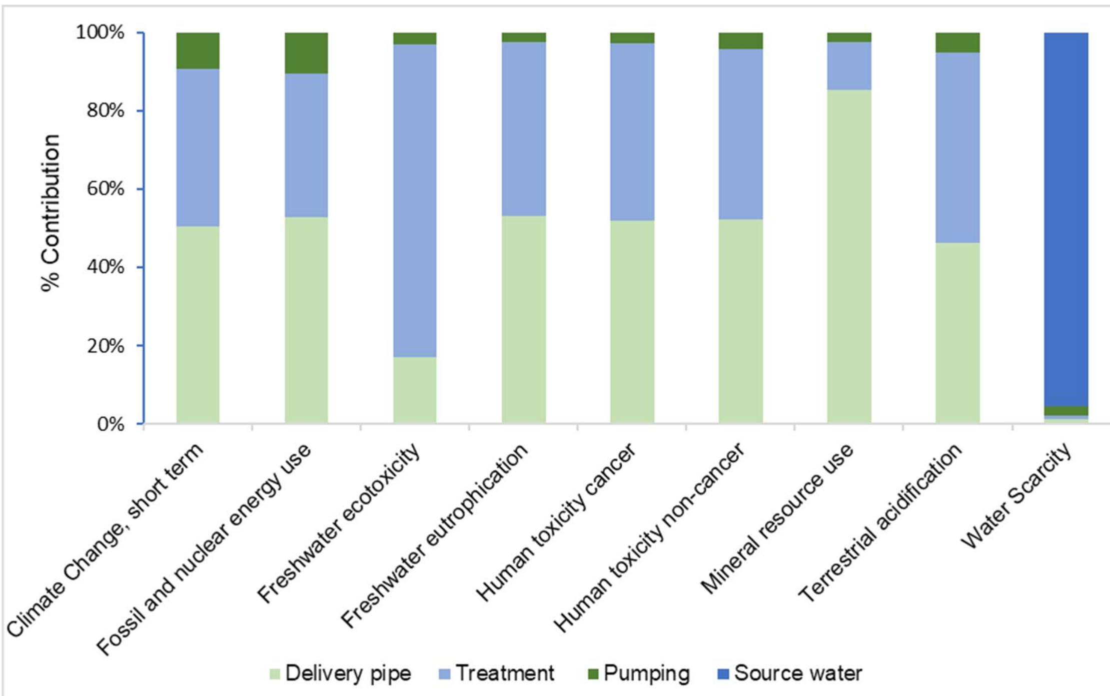

Figure 2. IMPACT World+ life cycle impact assessment results of the production weighted Okanagan water delivery system for each of nine impact categories. Results are broken down by process (delivery, treatment, pumping, and source water) and shown as the percent contribution, where 100% is the total impact score of the water supply network model for each impact category.

Cherry orchard LCIA

Across most impact categories, irrigation water had the largest contribution per unit of cherries produced, followed either by fertilizer application or energy supply (Table 5). The regionalized Okanagan water delivery cherry orchard system was compared to the cherry orchard system using the default irrigation provider used by Sanderson et al. (2019) derived from a Quebec dataset for tap water production from ecoinvent 3.4 (Figure 3). Irrigation had higher impacts in the present study compared to the original model from Sanderson et al. (2019). The impact categories that showed the largest differences between the two systems were water scarcity, human toxicity (cancer), and freshwater ecotoxicity (Figure 3).

Table 5. Life cycle impact assessment results per functional unit of one kg of usable cherries for the Okanagan cherry production system, using the production weighted Okanagan water delivery system as the irrigation provider. Irrigation, fertilizer application, and energy supply processes results, total system results and associated standard deviation (SD) were included for all 14 impact categories assessed.

Impact Category	Unit	Irrigation	Fertilizer application	Energy supply	Total	SD
Climate change, long term	kg CO_2 eq (long)	6.0 x 10^{-2}	5.8 x 10^{-2}	2.3 x 10^{-2}	2.1 x 10^{-1}	2.1 x 10^{-2}
Climate change, short term	kg CO_2 eq (short)	6.6 x10^{-2}	5.9 x10^{-2}	2.4 x 10^{-2}	2.2 x 10^{-1}	2.2 x 10^{-2}
Fossil and nuclear energy use	MJ deprived	8.3 x 10^{-1}	5.1 x 10^{-1}	3.4 x 10^{-1}	2.9 x 10^{0}	8.2 x 10^{-2}
Freshwater acidification	kg SO_2 eq	1.7 x 10^{-15}	1.3 x 10^{-15}	4.5 x 10^{-16}	6.0 x 10^{-15}	2.1 x 10^{-16}
Freshwater ecotoxicity	CTUe	1.5 x 10^{3}	1.1 x 10^{2}	5.1 x 10^{2}	2.3 x 10^{3}	3.8 x 10^{3}
Freshwater eutrophication	kg PO_4 P-lim eq	1.8 x 10^{-7}	2.2 x 10^{-7}	2.1 x 10^{-8}	8.8 x 10^{-7}	4.0 x 10^{-8}
Human toxicity cancer	CTUh	1.6 x 10^{-8}	9.8 x 10^{-10}	2.7 x 10^{-9}	2.3 x 10^{-8}	6.9 x 10^{-9}
Human toxicity non cancer	CTUh	2.1 x 10^{-8}	5.1 x 10^{-9}	7.1 x 10^{-9}	4.1 x 10^{-8}	6.3 x 10^{-8}
Marine eutrophication	kg N N-lim eq	6.7 x 10^{-6}	4.6 x 10^{-4}	7.6 x 10^{-7}	4.8 x 10^{-4}	3.5 x 10^{-4}
Mineral resources use	kg deprived	3.6 x10^{-3}	5.8 x 10^{-4}	4.1 x 10^{-4}	6.2 x 10^{-3}	3.1 x 10^{-4}
Ozone layer depletion	kg CFC-11 eq	7.0 x 10^{-9}	4.1 x 10^{-9}	2.0 x 10^{-9}	2.2 x 10^{-8}	1.7 x 10^{-9}
Photochemical oxidant formation	kg NMVOC eq	2.0 x 10^{-4}	9.6 x 10^{-5}	4.6 x 10^{-5}	8.2 x 10^{-4}	2.0 x 10^{-5}
Terrestrial acidification	kg SO_2 eq	1.1 x 10^{-9}	9.2 x 10^{-10}	2.9 x 10^{-10}	4.0 x 10^{-9}	1.4 x 10^{-10}
Water scarcity	m^3 world-eq	2.6 x 10^{0}	6.2 x 10^{-2}	2.3 x 10^{-1}	3.0 x 10^{0}	2.2 x 10^{-1}

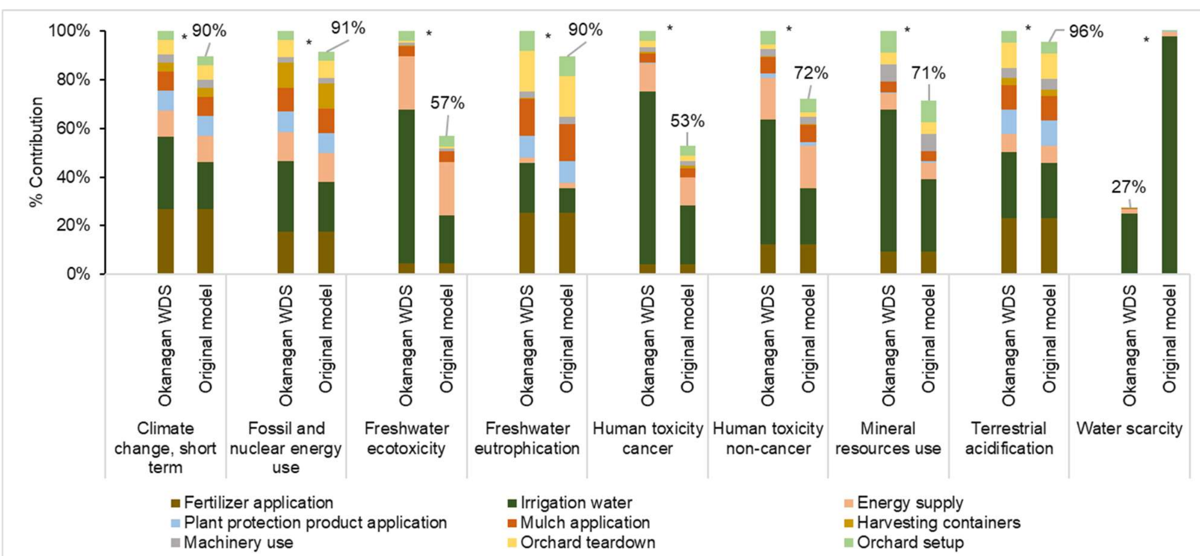

Figure 3. LCIA results shown as relative percent contributions of each process stage during cherry production across nine impact categories and comparing two orchard systems. 100% is the impact score of the scenario which had the highest impacts between the two scenarios for a given impact category. The Okanagan water delivery system (WDS) model used the production weighted Okanagan WDS as the provider for orchard irrigation. The original model was from Sanderson et al., (2019), and used Quebec conventional tap water production as the provider for orchard irrigation. All other inputs and processes were held constant within the two scenarios, except for the irrigation provider. * Indicates statistical significance.

Deposited bicarbonate from irrigation accounted for only 4% of the impacts of water delivered to orchards (Figure 4), or 1% (2.63×10^{-3} kg CO_2 eq kg^{-1} usable cherries) of the orchard's overall short-term impacts to climate change. Across all impact categories, the percentage difference in total impacts between each irrigation technology was the same (Figure 4). Sub-surface drip irrigation (SDI) performed the best and had 18% and 19% reductions in impacts compared to the micro-sprinkler irrigation and production weighted (PW) average, respectively.

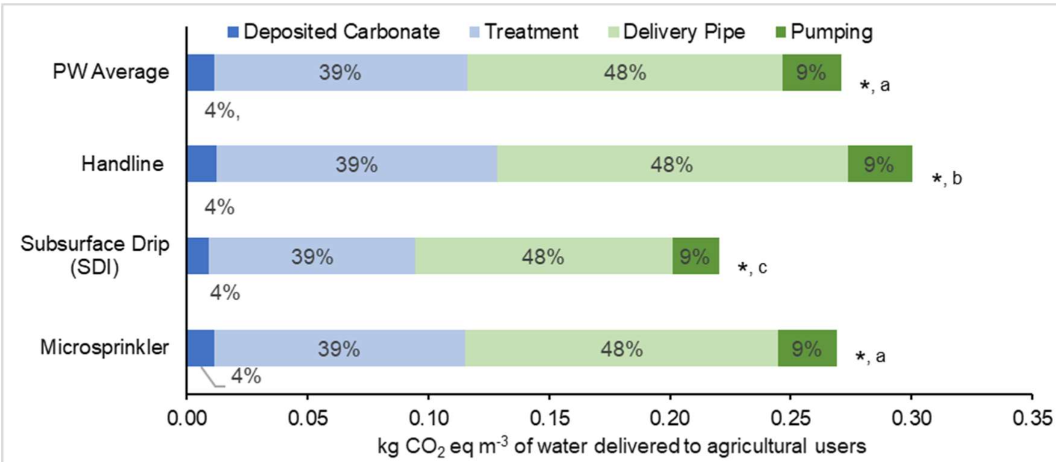

Figure 4. Impacts to climate change (short term) from the PW average Okanagan water supply network for three irrigation technology scenarios: handline, SDI, micro-sprinkler and the PW average. All other processes and in-puts to the water supply network model were held constant. * Indicates statistical significance and bars that share the same letter were not significantly different according to a Bonferroni post hoc test (p<0.013). Percent-ages indicate the percent each process (treatment, pipe delivery, and pumping) contributed to the systems' total impacts to climate change (short term).

Drip outperformed microsprinkler in every impact category except climate change even when the decrease in N_2O emissions from agricultural soil due to employing microsprinkler was accounted for (Figure 5). For most impact categories, these reductions were minor. For climate change, the 29% decrease in N_2O emissions resulting from using microsprinkler over drip irrigation was cancelled out by the 18% higher usage of water due to the lower efficiency of microsprinkler technology (thus requiring more water usage which consequently resulted in higher emission impacts to climate change originating from the water delivery system).

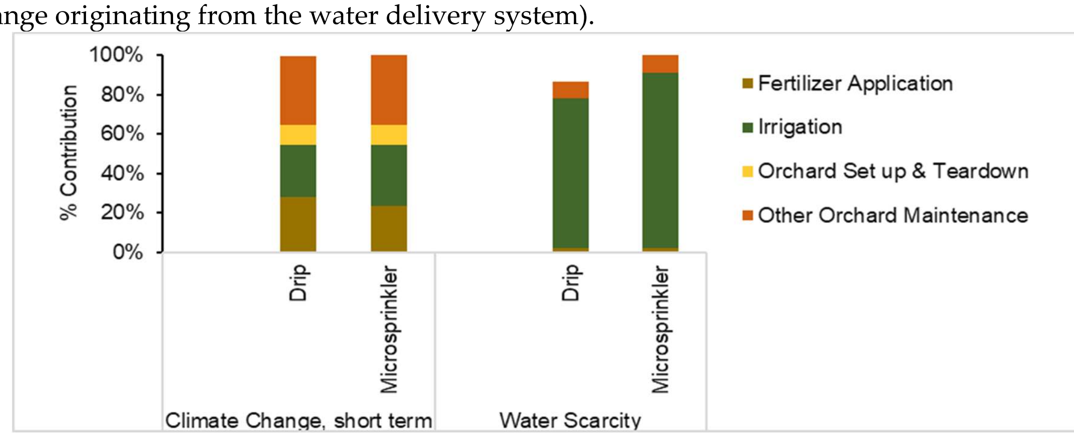

Figure 5. Relative percent contribution of drip versus micro-sprinkler systems at the orchard level. The difference between drip and microsprinkler was not statistically significant for the impact categories climate change, short term (two sample T-test; df = 1996; t Stat = -0.93; p=0.35) and water scarcity (two sample T-test; df = 1777; t Stat = 0.89; p=0.37)

Discussion
The large contribution of delivery piping to the impacts of water delivery in the Okanagan was congruent with the meta-analysis of potable water supply network LCAs performed by (Meron et al., 2016), which described impacts associated with materials and construction of the distribution network as making a significant contribution to the impacts of water supply networks. However, the contributions seen in this system were somewhat higher than in other literature - for example 50% to climate change, compared to 10-40% seen in the literature (Frischknecht et al., 2005; Godskesen et al., 2013; Lane et al., 2011; Meron et al., 2016; Slagstad and Brattebø, 2014; Uche et al., 2014). This could be explained, in part, by the varying lifespans reported for different piping materials, some of which may outlive their assumed 50-year lifespan (pers. comm. Shawn Goodsell). Water treatment was one of the highest contributors to the impacts of water delivery, which has similarly been shown in previous LCAs due to energy and treatment chemical inputs (Bonton et al., 2012; Buckley et al., 2011; Jeong et al., 2015). As new technologies improve the efficiencies of water supply networks and reduce environmental burdens in other stages, the significance of including piping infrastructure in LCAs of water supply networks will become proportionally larger (Jeong et al., 2015).

In the present study, irrigation from the production weighted Okanagan water supply network contributed 28.6% and 29.7% to the orchard's total impact to climate change long term and short term, respectively (Figure). It is clear that irrigation makes a significant contribution to the overall energy consumption and GWP of Okanagan cherry production systems. In contrast, several cherry production LCAs indicate irrigation makes only a small contribution to total energy consumption (Gaspar et al., 2021; Kizilaslan, 2009), or do not indicate irrigation as a significant predictor for environmental impacts of cherry orchard systems (Bravo et al., 2017; Tassielli et al., 2018). In all of these studies, irrigation as an input was only considered as the water consumed and the electricity consumed to pump either from a private groundwater source or to pump along the on-farm irrigation network. In this way, the background processes of water supply were not considered. This is a justifiable methodological choice where water is being derived from a private pump. However, this was not the case in the Okanagan, as many agricultural users were supplied by water purveyors with large distribution networks and often with some water treatment involved prior to arriving at the farm gate. This is a major reason the impacts of irrigation in the present study accounted for a larger proportion of the environmental impacts of the orchard system than is observed in other studies.

Additionally, the difference in environmental burdens of the orchard using different background datasets for irrigation (regional data compared to generic ecoinvent data) reflect the importance of selecting regionalized life cycle inventory data where available. No direct comparison of environmental impacts between irrigation technologies has been studied in other cherry production LCAs. However, Shen et al. (2021) reported the use of sprinkler irrigation in open-field cherry production, where electricity consumption from irrigation accounted for 29.1% of the orchard's energy use. In contrast, irrigation water using a more efficient drip technology on a cherry orchard studied by Gaspar et al. (2021) was responsible for only 4.3% of the total energy consumption of the orchard. Though these two study systems are not directly comparable due to varying energy consumptions of other inputs during the cherry production phase, it is likely that irrigation efficiency contributed to some degree to the difference between relative contributions of irrigation. The conclusion of this analysis was that the benefit of using the more efficient drip irrigation technology was offset by the consequently increased soil emissions of N_2O for the climate change impact category. However, the efficiency of drip irrigation resulted in observable environmental benefits in other impact categories.

The results of this research demonstrated the importance of using site-specific LCI data to characterize water delivery and irrigation technologies for agricultural production systems (specifically for cherry production in the Okanagan). Therefore, the regional specificity of this study is both a strength and a limitation. The results of this study are highly representative of the water delivery systems and irrigation technologies present on Okanagan cherry orchards. However, this specificity means that these results are not generalizable to other production systems. This further highlights the importance of collecting regionalized LCI data when possible.

Conclusion

This research underscores the importance of collecting regionalized LCI data for agricultural water delivery and irrigation systems, the corollary of which being that these results should only be used to provide recommendations in the intended context of the Okanagan Valley, Canada. In particular, this research demonstrated the importance of delivery pipe infrastructure and we recommend the inclusion of these data in future LCAs of water supply networks. After pipes, water treatment had the next highest contribution to the impacts of water delivery. The Okanagan does not have a fully separated agricultural irrigation water system, meaning water is unnecessarily treated at a plant prior to delivery to some agricultural users. Having separated agriculture and potable drinking water networks is therefore a meaningful way to substantially reduce the environmental burdens associated with both the irrigation water and agricultural systems in the Okanagan.

The impacts of irrigation in agricultural systems are often attributed to energy consumption, and influenced by factors such as climate conditions, water source, irrigation type, etc. The research presented herein contests water source as being a deterministic factor for environmental outcomes, as the difference in environmental impacts associated with ground or surface water are dependent on multiple factors including water quality and the energy consumed along the distribution network.

We found that irrigation does make substantial contributions to most life cycle impacts of cherry production. The research outcomes indicate that a meaningful reduction to water scarcity and other environmental impact categories could be achieved by switching to more efficient irrigation technologies, such as drip and SDI, despite higher N_2O emissions. Existing Okanagan tree fruit production systems, as well as new developments, can switch to or select the most efficient irrigation technologies as a relevant adaptive management strategy that mitigates the water demand and environmental impacts associated with irrigation.

Acknowledgements

The paper is an outcome from the Agricultural Greenhouse Gas Project which was funded by Agriculture and Agri-Food Canada.

References

- Abeliotis, K., Detsis, V., Pappia, C., 2013. Life cycle assessment of bean production in the Prespa
- BC Ministry of Agriculture, 2016, Agricultural Land Use Inventory: Regional District of North Okanagan, Summer 2013 – 2014. 58.
- B.C. Ministry of Agriculture, 2014. Agricultural Land Use Inventory: City of Kelowna, Regional District of Central Okanagan, Summer 2014.
- Bonton, A., Bouchard, C., Barbeau, B., Jedrzejak, S., 2012. Comparative life cycle assessment of water treatment plants. Desalination 284, 42–54.
- Bravo, G., Lopez, D., Vasquez, M., Iriarte, A., 2017. Carbon Footprint Assessment of Sweet Cherry Production: Hotspots and Improvement Options. Polish Journal of Environmental Studies 26, 559–566. https://doi.org/10.15244/pjoes/65361
- Buckley, C., Friedrich, E., Von Blottnitz, H., 2011. Life-cycle assessments in the South African water sector: a review and future challenges. Water SA 37.

- Bulle, C., Margni, M., Patouillard, L., Boulay, A.M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R.K., Roy, P.O., Shaked, S., Fantke, P., Jolliet, O., 2019. IMPACT World+: a globally regionalized life cycle impact assessment method. International Journal of Life Cycle Assessment 24, 1653–1674. https://doi.org/10.1007/s11367-019-01583-0
- Clark, R., 2018. Greater Vernon Water 2018 Annual Report.
- Deng, J., Guo, L., Salas, W., Ingraham, P., Charrier-Klobas, J.G., Frolking, S., Li, C., 2018. Changes in Irrigation Practices Likely Mitigate Nitrous Oxide Emissions From California Cropland. Global Biogeochemical Cycles 32, 1514–1527. https://doi.org/10.1029/2018GB005961
- Fentabil, M.M., Nichol, C.F., Neilsen, G.H., Hannam, K.D., Neilsen, D., Forge, T.A., Jones, M.D., 2016. Effect of micro-irrigation type, N-source and mulching on nitrous oxide emissions in a semi-arid climate: An assessment across two years in a Merlot grape vineyard. Agricultural Water Management 171, 49–62. https://doi.org/10.1016/j.agwat.2016.02.021
- Foley, J., Gretchen C. Daily, Robert Howart, David A. Vaccari, Adele C. Morris, Eric F. Lambin, Scott C. Doney, Peter H. Gleick, David W. Fahey, 2010. Boundaries for a Healthy Planet. Scientific American 302, 54–57. https://doi.org/10.1038/scientificamerican0410-54
- Fretwell, R., 2009. Irrigation Water Demand Model Technical Description.
- Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent Database: Overview and Methodological Framework (7 pp). The International Journal of Life Cycle Assessment 10, 3–9. https://doi.org/10.1065/lca2004.10.181.1
- Gaspar, P.D., Godina, R., Barrau, R., 2021. Influence of Orchard Cultural Practices during the Productive Process of Cherries through Life Cycle Assessment. Processes 9. https://doi.org/10.3390/pr9061065
- Godskesen, B., Hauschild, M., Rygaard, M., Zambrano, K., Albrechtsen, H.-J., 2013. Life-cycle and freshwater withdrawal impact assessment of water supply technologies. https://doi.org/10.1016/j.watres.2013.02.005
- Goodsell, S., 2018. 2018 Annual Water Report. https://doi.org/10.1016/S0378-777X(85)80094-9 GreenDelta, 2020. OpenLCA.
- Hannam, K.D., Kehila, D., Millard, P., Midwood, A.J., Neilsen, D., Neilsen, G.H., Forge, T.A., Nichol, C., Jones, M.D., 2016. Bicarbonates in irrigation water contribute to carbonate formation and CO2 production in orchard soils under drip irrigation. Geoderma 266, 120–126. https://doi.org/10.1016/j.geoderma.2015.12.015
- Hoppe, E., 2019. 2018 City of Kelowna Annual Water and Filtration Deferral Report.
- ISO, 2014. 14046: INTERNATIONAL STANDARD Environmental management — Water footprint Principles , requirements 2014.
- ISO, 2006a. ISO 14044: Environmental management - Life cycle assessment - Requirements and guilelines. Geneva, Switzerland.
- ISO, 2006b. 14040: International Standard Environmental management — Life cycle assessment —
- Principles and framework.
- Jeong, H., Minne, E., Crittenden, J.C., 2015. Life cycle assessment of the City of Atlanta, Georgia's centralized water system. The International Journal of Life Cycle Assessment 20, 880–891. https://doi.org/10.1007/s11367-015-0874-y
- Kizilaslan, H., 2009. Input–output energy analysis of cherries production in Tokat Province of Turkey.
- Applied Energy 86, 1354–1358. https://doi.org/10.1016/j.apenergy.2008.07.009

- Lane, J., Haas, D. De, Lant, P., 2011. Life Cycle Assessment of the Gold Coast Urban Water System. Urban Water Security Research Alliance Technical Report No . 52.
- Meron, N., Blass, V., Garb, Y., Kahane, Y., Thoma, G., 2016. Why going beyond standard LCI databases is important: lessons from a meta-analysis of potable water supply system LCAs. International Journal of
- Life Cycle Assessment 21, 1134–1147. https://doi.org/10.1007/s11367-016-1096-7 Sanderson, V.,
- Bamber, N., Pelletier, N., 2019. Cradle-to-market life cycle assessment of Okanagan (Canada) cherries: Helicopters, seasonal migrant labour and flying fruit. Journal of Cleaner Production 229, 1283–1293. https://doi.org/10.1016/j.jclepro.2019.04.398
- Shen, J., Zhang, P., Chang, Y., Zhang, L., Hao, Y., Tang, S., Xiong, X., 2021. The environmental performance of greenhouse versus open-field cherry production systems in China. Sustainable Production and Consumption 28, 736–748. https://doi.org/10.1016/j.spc.2021.07.002
- Slagstad, H., Brattebø, H., 2014. Life cycle assessment of the water and wastewater system in Trondheim, Norway - A case study: Case Study. Urban Water Journal. https://doi.org/10.1080/1573062X.2013.795232
- Tassielli, G., Notarnicola, B., Renzulli, P.A., Arcese, G., 2018. Environmental life cycle assessment of fresh and processed sweet cherries in southern Italy. Journal of Cleaner Production 171, 184–
- 197. https://doi.org/10.1016/j.jclepro.2017.09.227
- Uche, J., Martínez-Gracia, A., Carmona, U., 2014. Life cycle assessment of the supply and use of water in the Segura Basin. International Journal of Life Cycle Assessment 19, 688–704.
- Van Der Gulik, T., Neilsen, D., Fretwell, R., 2010. Agricultural Water Demand Model: Report for the Okanagan basin.

A dual-functional unit LCA framework towards absolute impact reductions: the case of residential buildings

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Abstract

Current sustainability assessment frameworks for buildings typically rely on gross floor area (GFA)-based functional units, while the core function of accommodating occupants is ignored outside urban-scale studies. This disconnect can potentially lead to suboptimal design strategies and higher absolute environmental impacts. To address this, we propose a dual functional unit framework for building LCA that introduces functional multidimensionality and better aligns relative performance metrics with ab-solute sustainability goals. A life cycle assessment (LCA) is conducted on eight detached houses, focusing on embodied global warming potential (GWP), with results normalized by both GFA and occupancy. The comparison reveals substantial performance shifts—with some buildings' relative performance shifting from +13.9% per GFA to –36.5% per occupant. A multi-criteria decision-making (MCDM) method is employed to integrate both functions, generating composite scores that prioritize buildings performing well across both. The framework supports evaluation of products with multiple functions and offers a practical route toward absolute sustainability by relating impacts to broader societal roles, such as accommodation.

Keywords: Residential Buildings, Absolute Sustainability, Multi Criteria Decision Making, Functional Unit

Introduction

The construction sector is one of the most environmentally impactful industries, contributing significantly to global greenhouse gas emissions and resource depletion (United Nations Environment Pro-gramme, 2023). As the operational energy of buildings becomes increasingly decarbonized through renewable energy transitions, the focus of environmental impact mitigation has shifted toward embodied impacts (Goldstein and Rasmussen, 2018). Recently, the concept of absolute sustainability has gained traction, examining whether a product fits within its allocated share of the planet's environmental budget. Recent studies have applied this approach to residential buildings in New Zealand and found that current practices exceed the safe operating space by more than 10 times, in some cases (McLaren et al., 2020). Similar conclusions have emerged globally for various sectors, suggesting that even environmentally improved products often remain far from truly sustainable.

The selection of the functional unit (FU) in Life Cycle Assessment (LCA) of buildings, as well as in other fields, remains a pivotal methodological choice (de Simone Souza et al., 2021). At the building scale, gross floor area (GFA)—often normalized over time (e.g., per m²/year)—is the dominant FU (Saade et al., 2020), while urban-scale studies for buildings adopt occupant-based metrics (González-García et al., 2021; Lavagna et al., 2018). This divergence reflects the multifaceted role of buildings--providing space and shelter. These roles align with the environmental drivers—technology and affluence (Holdren and Ehrlich, 1974). Improving performance per GFA mirrors technological advancement (less impact per product=space), while assessing buildings per occupant relates to affluence (im-pacts/resources per unit of population). However, some FUs may unintentionally promote resource consumption (Kim et al., 2017). For instance, larger buildings often show less impacts per GFA (Tozan et al., 2024), creating a paradox: increasing building size may improve performance per area, while in-creasing absolute impacts.

Considering those, there is a growing need for LCA approaches that not only evaluate environmental efficiency relative to functional performance but also integrate product performance in relation to their deeper societal function—a dimension directly related to affluence and absolute environmental im-pacts. This study proposes a dual-functional unit framework for the LCA of residential buildings, based on a clear distinction between their core functions. The proposed framework enables a more comprehensive understanding of building sustainability, while being a conceptual and practical tool for LCA practitioners that seek absolute impact reductions, alongside relative ones.

Material and methods

Conceptual Framework

The conceptual framework proposed in this study is illustrated in Figure 1. It introduces a distinction between the product's direct function (what is consumed) and its broader societal role (why is it consumed). Practitioners are encouraged to select the most widely adopted functional unit (FU) as the primary FU, while identifying the societal role of the product by isolating the underlying human need (drivers of consumption) that drives its consumption, independent of current market preferences (as established in (Creutzig et al., 2018)).For instance, in the case of food products, this core function could be nutritional provision, while for buildings, it is the provision of shelter (Creutzig et al., 2018) .

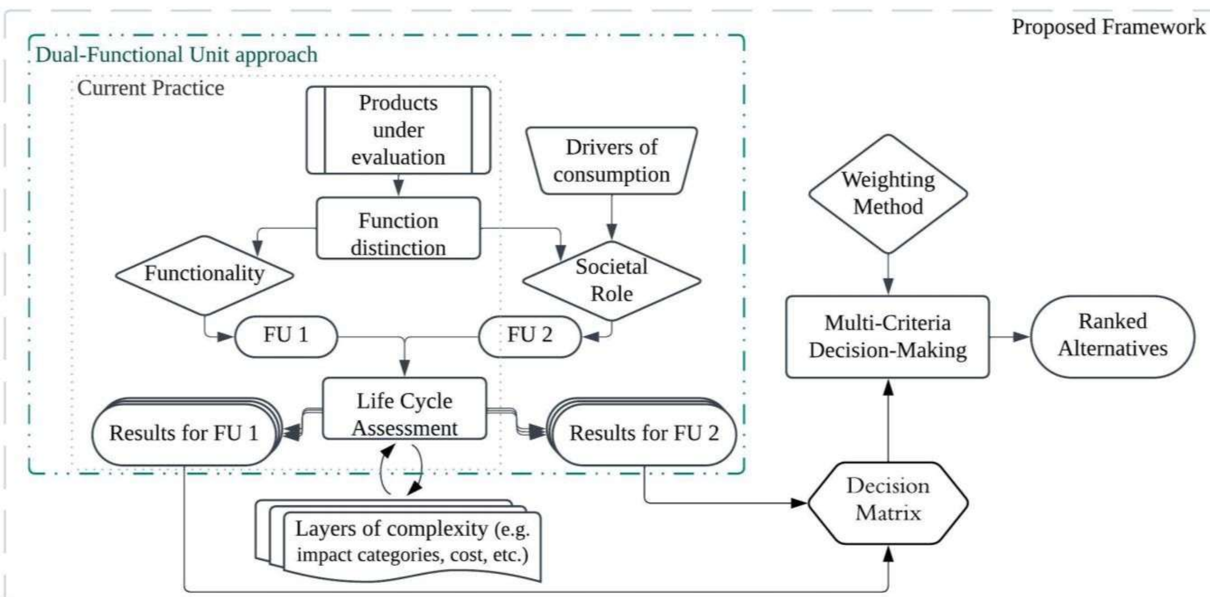

Figure 1. The proposed dual-functional unit framework, where FU: functional unit

Once both functions are identified, the life cycle assessment (LCA) is conducted, and the results are normalized for each functional unit. Several layers of complexity can be added at this point. These could include results for more than one impact categories, cost, and more, which are often included in multi-criteria decision-making (MCDM) problems. Once normalized for the distinct FUs, the results create a decision matrix for the MCDM model, and the practitioner chooses the appropriate weighting method. The output consists of the rankings for the several product alternatives.

Case- study

Data Collection and preprocessing

Building Information Modelling (BIM) models for eight detached residential buildings were obtained from the Building Research Association of New Zealand (BRANZ), as shown in Figure 2 and Table 1. The Occupational Load Factor (OLF) is used here to express the occupancy density for each building as *'occupants per gross floor area'* (De Sanctis et al., 2014). Buildings within each typology are ranked in descending order of OLF.

Table 1. Case-study buildings and their characteristics

Building ID	Type	GFA* (m^2)	Occupants	OLF*
D1	2-storey Detached	106	4	3.77E-02
D2	2-storey Detached	186	5	2.69E-02
D3	2-storey Detached	194	5	2.58E-02
D4	2-storey Detached	190	4	2.11E-02
S1	1-storey Detached	113	4	3.54E-02
S2	1-storey Detached	146	4	2.74E-02
S3	1-storey Detached	194	5	2.58E-02
S4	1-storey Detached	166	4	2.41E-02

* GFA: gross floor area ; OLF: occupational load factor

Figure 2. Screenshots of the BIM models examined in this study

Next, the bills of quantities were extracted from the BIM models using Autodesk Revit's (Autodesk, 2023) *'material takeoff'* function, and were then linked with corresponding environmental product declarations (EPDs) from BRANZ's '*CO2nstruct*' database (Building research Association of New Zealand, n.d.)—representing New Zealand-specific construction materials. A data assurance step was also under-taken to ensure comparability across buildings: materials unique to specific buildings (primarily land-scaping materials such as sand and granular fill) were excluded.

Life Cycle Assessment

The LCA followed the four standard ISO 14040:14044 steps (International Standards Organization, 2006a, 2006b). The goal and scope of the study was to compare the environmental performance of the buildings using two distinct FUs. The selected impact category was Global Warming Potential (GWP), chosen due to its prominence in the LCA literature (Anand and Amor, 2017). The impact assessment was performed using *LCAQuick v3.6* (Building Research Association of New Zealand, 2016), a tool devel-oped by BRANZ for building assessments in the New Zealand context. The life cycle stages included in the study covered the embodied impacts of the buildings, namely: the production stage (A1–A3), transportation (A4), construction waste (A5), maintenance/replacement (B2 and B4), and end-of-life (C1–C4). Calculations for each module were performed according to BRANZ's standards (Building Research Association of New Zealand, n.d.). The two FUs used to normalize the GWP results were *gross floor area (m^2)*, and *number of occupants*, estimated using the formula '*number of bedrooms + 1*' (Enz and Hastings, 2006; Harley and Gifford, 2008). A building lifespan of 50 years was assumed for all cases, as defined by the New Zealand Building Code (New Zealand Government, 1992). Consequently, no temporal normalization was applied to the FUs.

Multi Criteria Decision Making model; TOPSIS

The *Technique for Order of Preference by Similarity to Ideal Solution* (TOPSIS) method was used in this study due to its frequent application in sustainability assessments of buildings (Mecca, 2023; Ziemba, 2022). A full methodological explanation is not included here, but the steps followed are presented below, while the equations used can be found in Appendix Table A1. First, the decision matrix was constructed (Equation 1), with buildings as rows and the two criteria (GWP per GFA and GWP per occupant) as columns. Vector normalization followed (Equation 2), where each table value was divided by the Euclidean norm of its column. Next, the weighted normalized matrix was formed using Equation 3 (assuming equal weighting). Following this, the ideal and anti-ideal solutions were determined (Equations 4 and 5), and each building's Euclidean distances were calculated using Equation 6 & 7. Finally, the relative proximity (TOPSIS score) was computed using Equation 8. Buildings with higher TOPSIS scores were ranked higher (e.g. 1st), indicating better overall performance across both criteria. A sensitivity analysis was also performed by shifting the initial equal weighting among the two criteria (50%–50%) in both directions by ±15%, in 5% increments. Furthermore, to assess ranking stability with regards to LCA inputs, a Monte Carlo simulation (1000 iterations) was performed by perturbing both criteria with Gaussian noise (σ = 10% of the original value), recalculating TOPSIS scores, and calculating Monte Carlo mean rankings to test uncertainty.

Results

Figure 3 shows the GWP results normalized and presented for both functional units (FUs). Results vary significantly for each building depending on the FU used. For some buildings, extreme variation is observed when altering FUs. For example, when comparing D1 with D4, D1 has 13.9% more impacts per gross floor area, but 36.5% less impacts per occupant. Similarly, large variations in relative performance across the two FUs' results are observed for other case-studies (such as S1), alongside shifted relative performance across buildings (such as comparing S1 with S3 or S4).

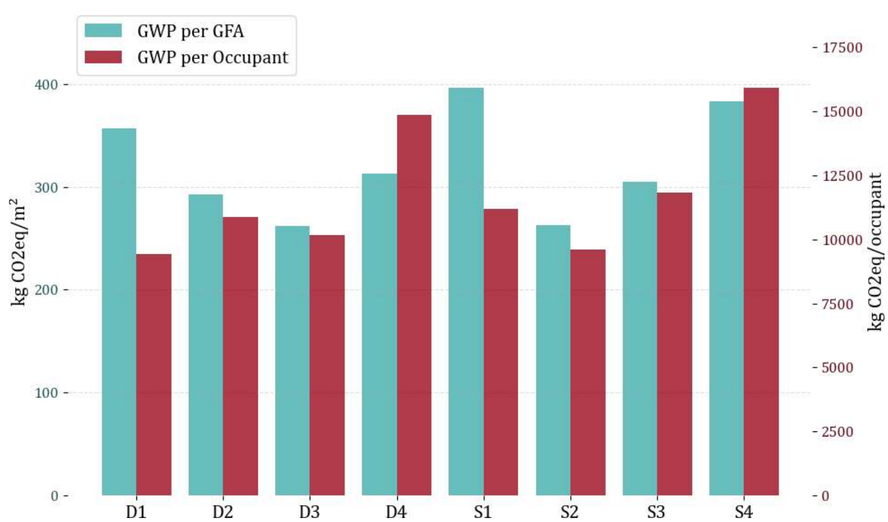

Figure 3. Global Warming Potential for the 8 buildings; results are presented for both functional units

Figure 4 presents the TOPSIS results, showing each building's score (relative proximity to the ideal solution) along with sensitivity ranges represented as error bars. Among all cases, D3 and S2 stand out as the most efficient buildings, exhibiting both high TOPSIS scores and low sensitivity to changes in weighting—indicating stable performance across FUs. In contrast, D1, S1, and D4 showed the greatest variation in TOPSIS scores across sensitivity scenarios, a result of their inconsistent performance de-pending on the FU used (as seen in Figure 3). This sensitivity can be attributed to their extreme Occupational Load Factors (OLF), with D1 and S1 having the highest OLFs and D4 the lowest (Table 1).

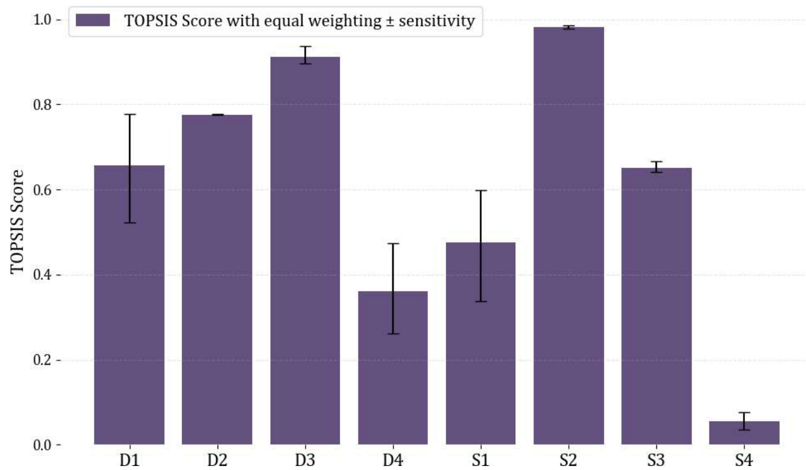

Figure 4. TOPSIS Score (relative proximity to ideal solution) for the eight buildings

Figure 5 shows the buildings ranked by their LCA results for each FU, alongside the TOPSIS rankings, which also include the results of the sensitivity analysis on the weighting method. Most buildings received a TOPSIS ranking that fell between the rankings assigned by the GFA-centric and occupant-centric assessments. The two most performative buildings were D3 and S2. D3 was ranked 1st and 3rd in the GFA-centric and occupant-centric assessments respectively, while S2 was ranked 2nd in both. The TOPSIS model ranked S2 1st and D3 2nd, and these rankings remained unaffected by the sensitivity analysis, which tested a ±15% variation from equal weighting. For one more building, S4, the TOPSIS ranking also remained unchanged throughout the sensitivity analysis—S4 was consistently ranked last. Among the remaining buildings, the sensitivity analysis caused a maximum shift of one position in the rankings (i.e., a building moving from rank *x* to *x+1* or *x–1*), except for D1, whose ranking oscillated across three positions. This is likely due to D1 exhibiting one of the largest impact variations between FUs alongside S1 (Figure 3), and notably showing the greatest difference in FU-based rankings—ranked 7th in the GFA-centric assessment and 1st in the occupant-centric one (Figure 5). As a result, D1 fluctuated between ranks 3, 4, and 5 in the TOPSIS model under the sensitivity scenarios. Overall, the TOPSIS results prioritized buildings that performed well across both functional units, which explains why S2 was ranked first. If single-functional assessments had been used, S2's balanced, multi-dimensional performance would not have been fully identified or promoted. Furthermore, the model appears to be quite stable with respect to the weighting method. While equal weighting was used here for demonstration purposes, both subjective and objective weighting approaches could be applied depending on the specific context and goals of the assessment.

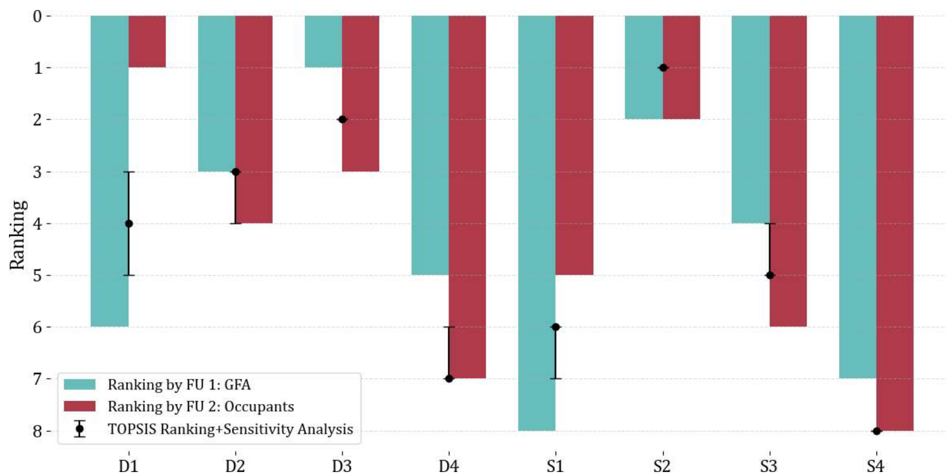

Figure 5. Buildings ranked for both functional units' results, alongside the TOPSIS rankings

Figure 6 shows the results of the Monte Carlo simulation based on the parameters described in Section 2.2.3. Most of the baseline TOPSIS rankings were close to the mean ranks obtained from the simulation. Only D4, S2, and S3 showed mean rankings that were relatively distant from their actual TOPSIS results but remained within the range defined by the simulation's standard deviation. Therefore, it can be concluded that the TOPSIS rankings are robust under uncertainty—even in borderline cases, such as the close competition between D3 and S2 for the first position.

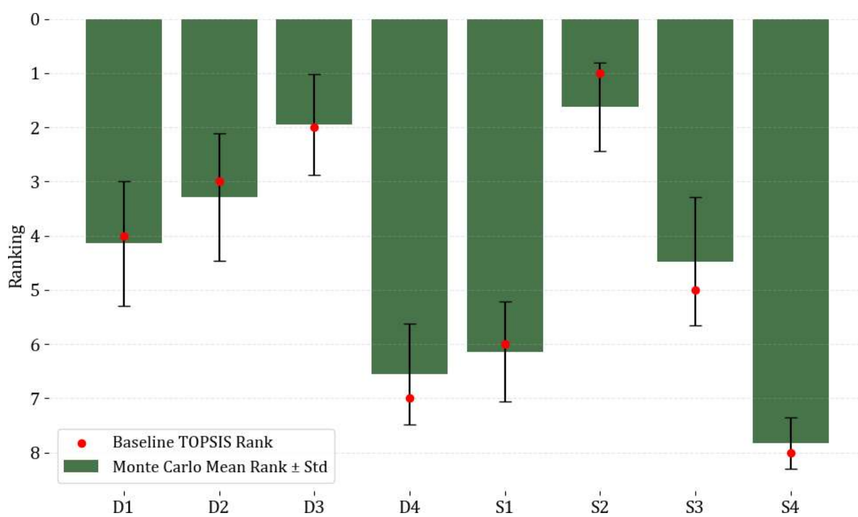

Figure 6. Monte Carlo simulation results alongside the baseline TOPSIS rankings

Discussion

The results obtained in this study regarding the Global Warming Potential (GWP) per gross floor area for the eight buildings are consistent with findings reported in the literature. For example, (Dani et al., 2022) assessed two residential building designs in the context of New Zealand and reported values (ap-proximately 235-335kgCO_2eq/m^2 for a 50-year period) comparable to those obtained in this analysis (262-396 kgCO_2eq/m^2), for the under-study life cycle modules. Furthermore, the embodied environ-mental cost of accommodating one occupant over a 50-year period was found to be between 9,440 and 15,907 kgCO_2eq in this study, while literature findings usually present aggregated results, and therefore direct comparison is challenging. (González-García et al., 2021) for example reported aggregated im-pacts per capita across sectors, while (Lavagna et al., 2018) did not make a distinction among life cycle modules, reporting approximately 125,500 kgCO_2eq for 50 years of housing per capita in Europe, inclusive of modules B6-B7 which are absent in our scope—their study also reflected European materials, typologies, and energy systems, which differ significantly from the New Zealand context.

As for the multi-criteria approach, the proposed framework is not novel in its logic; MCDM models are widely applied across disciplines when conflicting performances must be evaluated to inform a single decision. What is particularly noteworthy, however, is that while the selection of functional units is widely acknowledged in the literature as both challenging and critical for meaningful LCAs, an integrated multi-functional unit framework has not been introduced but only at a speculative basis where several FUs are applied to compare results (e.g. (Ross et al., 2017)). This may be attributed to the historic focus on process-based LCA, which traditionally assesses environmental impacts at the level of individual processes, where functionality and functional unit selection have a different meaning and are mainly significant for proper impact allocation, rather than framing environmental performance according to budgets from an *impact/carbon accounting* perspective. The results of this study showed significant variation across FUs and therefore support the need for frameworks capable of delivering assessments of products across functions—especially the product's core societal function which arguably drives consumption (via affluence (Holdren and Ehrlich, 1974)) more fundamentally than volatile market conditions. This aligns with emerging sustainability research and European guidelines advocating for simplified strategies focused on impact avoidance rather than reactive impact mitigation or management in the building sector (European Environment Agency, 2022; Hvid Horup et al., 2024), and research that proposes the integration of affluence-related and demand-oriented factors in impact mitigation strategies (Creutzig et al., 2018; Wiedmann et al., 2020).

The framework's value expands beyond the building sector; recently, LCAs of food products and systems have introduced nutritional FUs in an attempt to express impacts at a commodity basis (nutrition provision) and beyond its currently established market function (food mass provision) (Cortesi et al., 2024; McAuliffe et al., 2020). This aligns with the proposed framework's rationale. Products serve both as essential commodities that meet fundamental human needs as well as discretionary items linked to personal preference and consumption. Distinguishing between these functions is critical for managing environmental impacts within defined boundaries. In the building sector which this study examined, impact reductions could be facilitated by introducing limitations on Occupancy Load Factors (OLFs), particularly in high socioeconomic areas, typically associated with lower occupancy density buildings and therefore higher environmental impacts per capita. Such measures would help constrain absolute resource use and environmental impacts at regional or national levels. In the food sector, comparable strategies would involve promoting the production and consumption of food products that demonstrate high efficiency in terms of nutritional value relative to environmental impact as well as per conventional FUs (mass of product), therefore aiding societal transition into a more sustainable future without significantly limiting affluence. Other sectors may benefit from such function distinction accordingly.

This study is limited to the New Zealand context and the specific case studies used for the LCA results and TOPSIS rankings. It focuses solely on embodied impacts, excluding operational impacts (modules B6, B7) as well as modules B1, B3, and B5 due to data limitations. In addition, only the Global Warming Potential (GWP) impact category is considered. Nonetheless, the main contribution lies in the conceptual emphasis on the dual functional unit framework, rather than the technical outputs alone.

Conclusion

This study proposed and applied a novel framework capable of assessing buildings across multiple functions using distinct functional units (FUs) and ranking them accordingly. The differentiation between FUs was grounded in the recognition that buildings, like many products, fulfil not only a primary function—provision of physical space—but also a core societal function—provision of shelter. This dis-tinction is particularly relevant in the context of current research on absolute sustainability, which increasingly emphasizes the need for absolute impact reductions but often lacks actionable pathways to achieve them. Addressing this gap, the proposed framework was applied to eight buildings in the New Zealand context, assessed against both functional perspectives, and ranked using a multi-criteria approach. The findings showed notable result variation across FUs, while the proposed framework effectively highlighted buildings with consistent performance, offering a more comprehensive assessment approach. The framework is methodologically simple, and accessible to practitioners across the sector, including designers, architects, and LCA practitioners—empowering them to contribute meaningfully to impact reduction from the bottom up. Equally important is the role of top-down actors such as policymakers, local authorities, and environmental agencies. For the building sector to align with absolute sustainability goals, future regulatory approaches must integrate building design parameters such as the Occupational Load Factor (OLF) to include affluence-related impacts in mitigation strategies. Managing or limiting OLF in new developments could reduce impacts by curbing resource use at the source—shifting the focus from impact management to impact avoidance. Future research should build upon this framework, apply it across sectors, and explore scenario-based applications to assess its broader potential for systemic impact reduction.

Appendix

Table A1: Equations used for TOPSIS model

Equation	Name
$X = \begin{bmatrix} x_{11} & \cdots & x_{i1} \\ \vdots & \ddots & \vdots \\ x_{1j} & \cdots & x_{ij} \end{bmatrix}$	*Equation 1*
$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}}$	*Equation 2*
$v_{ij} = w_i \times z_{ij}$, $\sum_{i=1}^{n} w_i = 1$	*Equation 3*
$v^+ = \{v_1^+, v_2^+, \ldots, v_n^+\}$, $v^- = \{v_1^-, v_2^-, \ldots, v_n^-\}$ where $v_i^+ = min\,v_{ij}$, $v_i^- = max\,v_{ij}$, for all j	*Equations 4 & 5*
$S_j^+ = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^+)^2}$, $S_j^- = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^-)^2}$	*Equation 6 & 7*
$C_j = \frac{S_j^-}{S_j^+ + S_j^-}$ Where $0 \leq C_j \leq 1$	*Equation 8*

Acknowledgements
The authors acknowledge funding from two sources: the New Zealand Ministry of Business, Innovation and Employment, under the Āmiomio Aotearoa project – Circular Economy for the Wellbeing of New Zealand hosted by The University of Waikato (UOWX2004), and the Building Research Levy.

References

- Anand, C.K., Amor, B., 2017. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renewable and Sustainable Energy Reviews 67, 408–
- 416. https://doi.org/10.1016/j.rser.2016.09.058Autodesk, 2023. Autodesk Revit.Building Research Association of New Zealand, 2016. LCAQuick v3.6 [WWW Document]. URL https://www.branz.co.nz/environment-zero-carbon-research/framework/lcaquick/version-his-tory/ (accessed 4.8.25).
- Building research Association of New Zealand, n.d. CO_2NSTRUCT [WWW Document]. URL https://www.branz.co.nz/environment-zero-carbon-research/framework/branz-co2nstruct/ Building Research Association of New Zealand, n.d. Data [WWW Document]. BRANZ. URL
- https://www.branz.co.nz/environment-zero-carbon-research/framework/data/. (accessed 3.4.25).
- Cortesi, A., Yannou-Le Bris, G., Pénicaud, C., 2024. Using nutritional functional units provides a nuanced view of the environmental performance of food products within the same category. International Journal of Life Cycle Assessment 29, 838–856. https://doi.org/10.1007/s11367-024-02285-y
- Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine De Bruin, W., Dalkmann, H., Edelen-bosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nat Clim Chang. https://doi.org/10.1038/s41558-018-0121-1
- Dani, A.A., Roy, K., Masood, R., Fang, Z., Lim, J.B.P., 2022. A Comparative Study on the Life Cycle Assessment of New Zealand Residential Buildings. Buildings 12. https://doi.org/10.3390/buildings12010050
- De Sanctis, G., Kohler, J., Fontana, M., 2014. Probabilistic assessment of the occupant load density in retail buildings. Fire Saf J 69, 1–11. https://doi.org/10.1016/j.firesaf.2014.07.002
- de Simone Souza, H.H., de Abreu Evangelista, P.P., Medeiros, D.L., Albertí, J., Fullana-i-Palmer, P., Boncz, M.Á., Kiperstok, A., Gonçalves, J.P., 2021. Functional unit influence on building life cycle assessment. International Journal of Life Cycle Assessment 26, 435–454. https://doi.org/10.1007/s11367-020-01854-1
- Enz, D., Hastings, R., 2006. Proven Designs for very Low Energy Housing – Swiss Experience, in: EUROPEAN CONFERENCE AND COOPERATION EXCHANGE - Sustainable Energy
- Systems for Buildings: Challenges and Changes. Vienna, Austria.
- European Environment Agency, 2022. Building renovation: where circular economy and climate meet. https://doi.org/10.2800/416573
- Goldstein, B., Rasmussen, F.N., 2018. LCA of Buildings and the Built Environment, in: Life Cycle Assessment. Springer International Publishing, Cham, pp. 695–722. https://doi.org/10.1007/978-3-319-56475-3_28
- González-García, S., Caamaño, M.R., Moreira, M.T., Feijoo, G., 2021. Environmental profile of the municipality of Madrid through the methodologies of Urban Metabolism and Life Cycle Anal-ysis. Sustain Cities Soc 64. https://doi.org/10.1016/j.scs.2020.102546

- Harley, B., Gifford, A., 2008. Field Guide Residential New Construction. NJ, USA.
- Holdren, J.P., Ehrlich, P.R., 1974. Human Population and the Global Environment: Population growth, rising per capita material consumption, and disruptive technologies have made civili-zation a global ecological force 62, 282–292.
- Hvid Horup, L., Ohms, P.K., Hauschild, M., Gummidi, S.R.B., Secher, A.Q., Thuesen, C., Ryberg, M., 2024. Evaluating mitigation strategies for building stocks against absolute climate targets. Buildings and Cities 5, 117–132. https://doi.org/10.5334/bc.413
- International Standards Organization, 2006a. International Standard ISO 14040 (2006) Environ-mental Management—Life Cycle Assessment—Principle and Framework.
- International Standards Organization, 2006b. International Standard ISO 14044 (2006) Environ-mental management — Life cycle assessment — Requirements and guidelines.
- Kim, S.J., Kara, S., Hauschild, M., 2017. Functional unit and product functionality—addressing in-crease in consumption and demand for functionality in sustainability assessment with LCA. International Journal of Life Cycle Assessment 22, 1257–1265. https://doi.org/10.1007/s11367-016-1233-3 2018. Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock. Build Environ 145, 260–275. https://doi.org/10.1016/j.buildenv.2018.09.008
- McAuliffe, G.A., Takahashi, T., Lee, M.R.F., 2020. Applications of nutritional functional units in commodity-level life cycle assessment (LCA) of agri-food systems. Int J Life Cycle Assess 25, 208–221. https://doi.org/10.1007/s11367-019-01679-7
- McLaren, S.J., Chandrakumar, C., Dowdell, D., Bullen, L., Jaques, R., 2020. Application of abso-lute sustainability assessment to new zealand residential dwellings, in: IOP Conference Series: Earth and Environmental Science. IOP Publishing Ltd. https://doi.org/10.1088/1755-1315/588/2/022064
- Mecca, B., 2023. Assessing the sustainable development: A review of multi-criteria decision analy-sis for urban and architectural sustainability. Journal of Multi-Criteria Decision Analysis 30, 203–218. https://doi.org/10.1002/mcda.1818
- New Zealand Government, 1992. Clause B2 Durability – Building Code 1992 [WWW Document]. URL https://www.legislation.govt.nz/regulation/public/1992/0150/latest/whole.html (accessed 5.19.25).
- Ross, S.A., Topp, C.F.E., Ennos, R.A., Chagunda, M.G.G., 2017. Relative emissions intensity of dairy production systems: Employing different functional units in life-cycle assessment. Ani-mal 11, 1381–1388. https://doi.org/10.1017/S1751731117000052
- Saade, M.R.M., Guest, G., Amor, B., 2020. Comparative whole building LCAs: How far are our expectations from the documented evidence? Build Environ 167. https://doi.org/10.1016/j.buildenv.2019.106449
- Tozan, B., Hoxha, E., Ole Olsen, C., Grau Sørensen, C., Birgisdóttir, H., 2024. Exploring the rela-tionship of building area and GHGe: a mitigation strategy? IOP Conf Ser Earth Environ Sci 1402, 012048. https://doi.org/10.1088/1755-1315/1402/1/012048
- United Nations Environment Programme, 2023. Building Materials and the Climate: Constructing a New Future. Nairobi.
- Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists’ warning on affluence.
- Nat Commun 11. https://doi.org/10.1038/s41467-020-16941-y
- Ziemba, P., 2022. Application Framework of Multi-Criteria Methods in Sustainability Assessment.
- Energies (Basel) 15. https://doi.org/10.3390/en15239201

Assessment of the Baseline Carbon Footprint of the University of the Philippines Los Baños

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Abstract

In response to the Race to Zero (R2Z) global campaign led by the UNFCCC Champions for Climate Action in 2021, the University of the Philippines Los Baños (UPLB) recognized the need to promote sustainability and reduce its environmental impact. UPLB committed to establishing a roadmap to become a net zero or low-carbon universi-ty. However, carbon footprint (CF) measurement was not yet integrated into UPLB's operation, presenting a challenge for initiating sustainability efforts. To address this, a series of training workshops were conducted across UPLB units and offices to equip them in measuring and reporting their CF. Additionally, a university CF calculator was developed and utilized, enabling units to assess their emissions. Through collaborative participation, UPLB successfully calculated its baseline CF for 2021.

The study followed the Life Cycle (LCA) methodology framework as prescribed in ISO 14040, and the GHG Proto-col Corporate Standard was used to determine the emissions scope to be included in the University's emissions. The CF accounting aimed to identify the key sources of greenhouse gas emissions and to provide recommendations for minimizing the University's environmental impacts. UPLB's baseline CF for 2021 was calculated at 10,833.25 MT CO2e, with Scope 2 emissions (from electricity consumption) being the largest contributor at 76.8%. Scope 1 emissions (direct emissions) and Scope 3 emissions (indirect emissions such as material consumption, indirect fuel emission, waste generation, and employee and student commuting) contributed 10.5% and 12.7%, respectively. Based on these findings, the University was advised to prioritize energy efficiency in its operations by reducing electricity and fuel consumption, exploring cleaner energy sources, and implementing carbon offsetting strategies. The results of this study can serve as a model for other universities in the country to conduct carbon footprint assessments in pursuit of a shared goal of achieving net-zero emissions in higher education institutions.

Keywords: Carbon Footprint Calculator; LCA Capacity Building; LCA-based Carbon Accounting; Net Zero Emissions; Carbon Footprint

Introduction

To pursue efforts to establish climate change mitigation strategies aligned with keeping the global temperature rise below 2°C above pre-industrial level, an increasing number of governments are pledging to achieve net zero emissions [1]. However, current GHG reduction projections remain insufficient to meet the net zero target by 2050. Emission reduction initiatives of non-state actors (i.e., universities and colleges) are estimated to con-tribute up to 15 to 23 GtCO2e per year, potentially helping to close the gap toward achieving this goal [2].

A successful climate mitigation strategy requires a multi-sectoral approach. Universities, as GHG emitters, play a vital role. In 2021, over 1,000 universities across 68 countries made commitments to achieving net-zero emissions by 2050, as reported by Times Higher Education Climate Impact Forum [3].

In the Philippines, only a few universities have taken steps toward emission reduction. The University of the Philippines Los Baños (UPLB), through the UPLB Interdisciplinary Life Cycle Assessment Laboratory (ILCAL), has begun developing a roadmap to become a net zero or low carbon institution. Establishing a baseline carbon footprint is a critical first step. This study calculated the UPLB's 2021 baseline carbon footprint to identify major emission sources and recommend strategies for reducing environmental impacts.

Material and Methods

In order to assess the environmental impact of UPLB, a life cycle assessment (LCA) was conducted for the establishment of the baseline carbon footprint of the university. The study followed ISO 14040 [4] in conducting LCA as illustrated in Figure 1. These steps were systematically followed to provide a comprehensive and accurate baseline carbon footprint accounting of UPLB.

Goal and Scope Definition

The study followed the GHG Protocol Corporate Standard [5] to define the scope emissions UPLB must account for. Figure 2 shows the simplified emission scopes: Scope 1 covers the institution's direct emissions; Scope 2 includes emission from purchased electricity; and Scope 3 captures emissions from inputs, products, co-products, and waste. Table 1 shows the detailed inclusion of emissions accounted under each scope. The assessment includes CO2, CH4, and N2O, which are the three (3) major GHG driving climate change. UPLB's baseline carbon footprint was calculated for calendar year 2021, during which online learning was still in place due to the COVID-19 pandemic. Emissions were reported in terms of metric tons of CO2 equivalent per year.

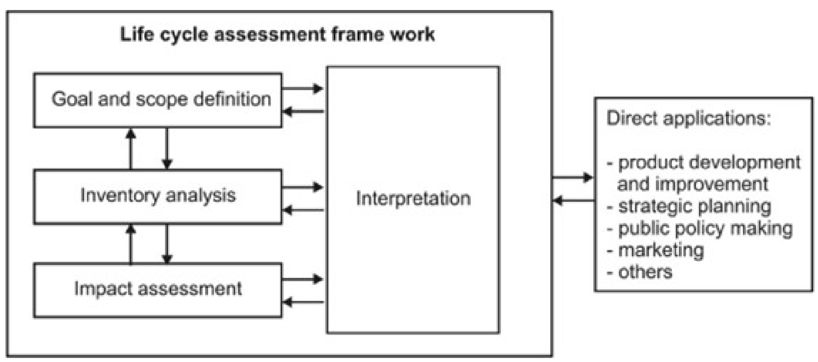

Figure 1. Stages of LCA according to ISO 14040 [4]

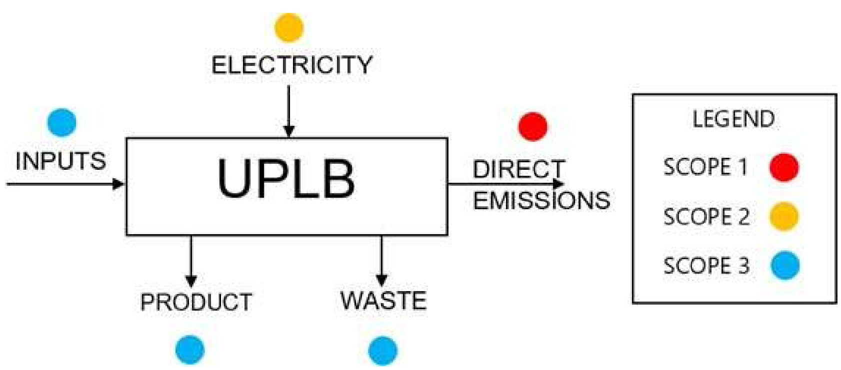

Figure 2. GHG Emissions Covered in the Baseline Carbon Footprint of UPLB.

Scope	Category	Definition
1	Stationary combustion	Emission from fuel consumption in fixed installation
	Leakage of refrigerants	Emission associated with the leakage of fluorinated
	Mobile combustion	Emission from operation of owned or leased mobile sources (vehicles, etc.) by the university
	Other direct emission	Emission from other direct emission such as fertilizer application, animal emissions, etc.
2	Electricity consumption	Emission from the generation of purchased or acquired electricity
3	Water consumption	Emission from water consumption
	Paper consumption	Emission from paper consumption (i.e bondpaper, tissues)
	Cleaning material consumption	Emission from the use of cleaning materials (i.e alcohol, soaps)
	Other material consumption	Emission from the consumption of materials that do not fall under the previous categories
	Electrical and electronic equipment procurement	Emission from the procurement of equipment for the defined calendar year.
	Waste generation	Emission from the waste generation by the organization
	Official travel	Emission generated during official travels of students and employees
	Employee commuting	Emission due to commuting of employees from their homes to the institution and back.
	Student commuting	Emission due to commuting of students from their homes to the institution and back

Life Cycle Inventory Analysis

The inventory analysis accounted for all the inputs and outputs between January to December 2021 within the system boundary established for UPLB. Since the institution comprises many academic units and offices, a systematic way of collecting data was established as shown in Figure 3.

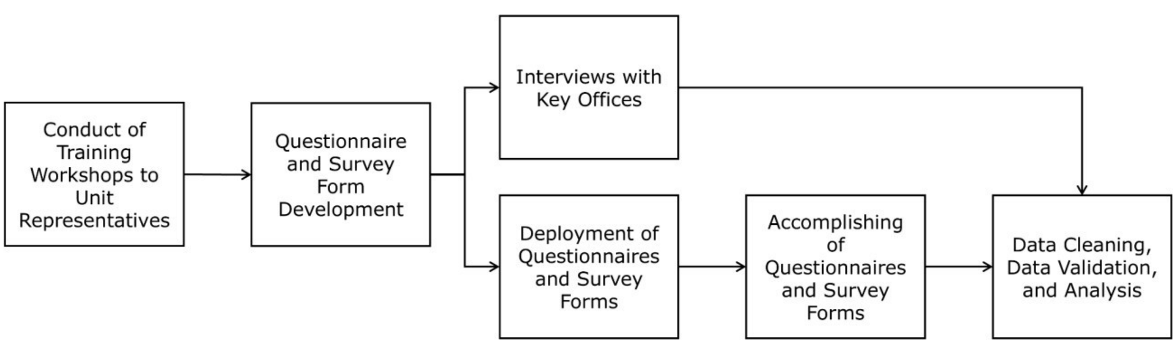

Figure 3. Data Collection Process for UPLB Carbon Footprint Accounting

For efficient data gathering, each unit of UPLB was assigned to have a representative to collect data related to carbon footprint accounting in their respective units. Training workshops were held for unit representatives to guide them on their roles in the data collection, and to help them identify the sources of Scope 1, 2 and 3 emissions in their unit. Questionnaires were developed, which served as tools to account for each scope. Additionally, an online survey was created to estimate the emissions from employee and student commuting under Scope 3. The data gathered through the survey form included frequency of commuting, mode of transportation, and distance travelled going to and from the university.

The unit representatives submitted the accomplished questionnaires to a centralized Google Drive for data consolidation, cleaning, and analysis. Data validation was done through a series of training workshops. The duration of data collection and validation lasted for three months, from August 2022 to October 2022.

Aside from data collected from each UPLB unit, key informant interviews were conducted in respective offices to determine the entire electricity consumption, water consumption, and waste generation of the institution.

Life Cycle Impact Assessment

Data collected was converted to its equivalent carbon footprint. The fundamental equation for calculating carbon footprint can be found below:

$$CF = AD \times EF \qquad \text{Equation 1}$$

where CF stands for carbon footprint, AD is the quantification of an activity data in units that can be combined with the emission factor, and EF is the value of scaling emissions to activity data in terms of standard rate of emission per unit activity.

The activity data were the data collected from the accomplished questionnaire form such as fuel consumption (L per year), paper consumption (reams per year) and waste generation (kg plastics per year). Emission factors, on the other hand, were pooled from credible sources such as Ecoinvent v. 3.8, US EPA (2020), UNFCCC (2021) and journal articles.

Life Cycle Interpretation

During the interpretation phase, environmental (GHG) hotspots within the defined system of the institution were identified. From this, recommendations were crafted for suitable GHG reduction strategies once baseline carbon footprint and will serve as a guide in creating a roadmap towards net zero or low carbon campus over the next years.

Results

From the 81.2% academic units and offices that participated in the carbon footprint assessment, the baseline carbon footprint of the UPLB for the year 2021 is projected to be at 10,833.25 MT CO2e, representing 100% of the units and offices' participation. Moreover, the university has a carbon footprint emission avoidance of 495.95 MT CO2e. Avoided GHG comes from waste management, where a portion of the waste generated is recycled. The details of the carbon footprint results per category and scope can be found in Table 2.

Table 2. Baseline Carbon Footprint of UPLB for 2021

Scope	Category	Total Emissions Per Category MT CO_2e yr^{-1}	Total Emissions Per Scope MT CO_2e yr^{-1}
Scope 1	Stationary Fuel Combustion	218.17	1,135.62
	Leakage of Refrigerants	297.36	
	Mobile Fuel Combustion	469.97	
	Other Direct Emissions	150.13	
Scope 2	Electricity Purchased	8,324.34	8,324.34
Scope 3	Water Consumption	164.23	1,374.46
	Paper Consumption	45.75	
	Laboratory Chemicals Consumption	120.89	
	Cleaning Material Consumption	16.39	
	Other Material Consumption	9.97	
	Electrical and Electronic Equipment Consumption	36.42	
	Waste Generation	24.71	
	Indirect Fuel Emission	304.30	
	Other Indirect Emission	0.21	
	Official Travel	71.34	
	Employee Commuting	579.08	
	Student Commuting	0.00	
Total GHG Emission			**10,833.25**
Total GHG Avoidance (Recycling of Waste)			**495.95**

With 11,584 undergraduate and 2,277 graduate students enrolled, the emission per student is calculated to be 0.78 MT CO2e/student-year. With 1,114 faculties, 455 reps, 5 reps faculty, and 1597 admin staff, the emission per person is estimated at 0.64 MT CO2e/capita-year. In terms of emission per area, the campus has a land area of 5,445 ha, resulting in 1.99 MT CO2e/ha-year.

The percent GHG contribution per scope can be found in Figure 4. Scope 1 emissions contributed approximately 10.5% of the overall GHG emissions, while Scope 2 emissions contributed the largest share at about 76.8%. Scope 3 emission constituted 12.7%.

The percent GHG contribution per category can be found in Figure 5. For Scope 1 emission, the greatest comes from mobile fuel combustion, contributing to about 4.3% of the overall GHG emission. For Scope 3 emissions, the highest contributor comes from employee commuting which is 5.3% of the overall GHG emission of the university.

The percent share of carbon footprint per university's type of operation, categorized into five types: teaching, research, administrative, production, and auxiliary operations is shown in Figure 6. Administrative operations such as office operations, coordinating, planning, directing services, and bookkeeping contribute to 69.1% of the overall GHG. Research contributes 15.5%, while teaching has a contribution of 8.9%. Production, which involves producing and developing a specific product, contributes to 2.9%. Lastly, the auxiliary operations contribute to 3.0%.

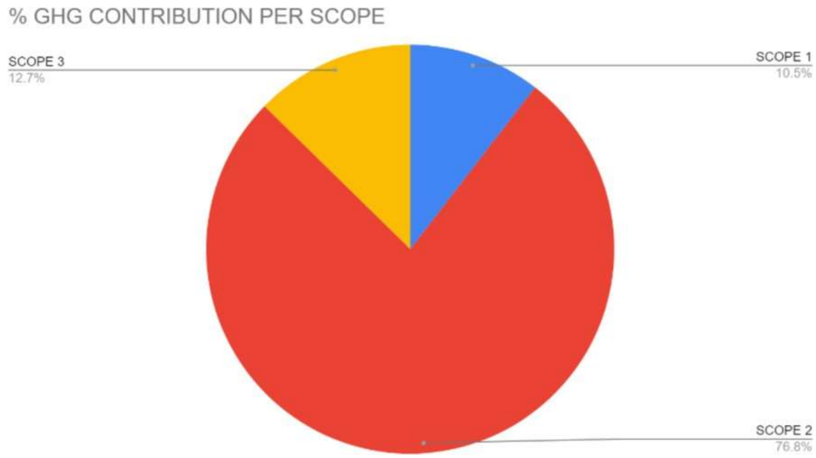

Figure 4. Percent GHG contribution per Scope

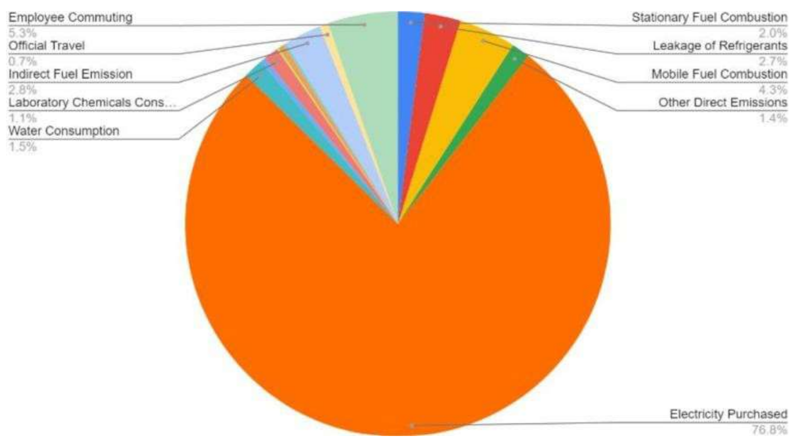

Figure 5. Percent GHG contribution per Category

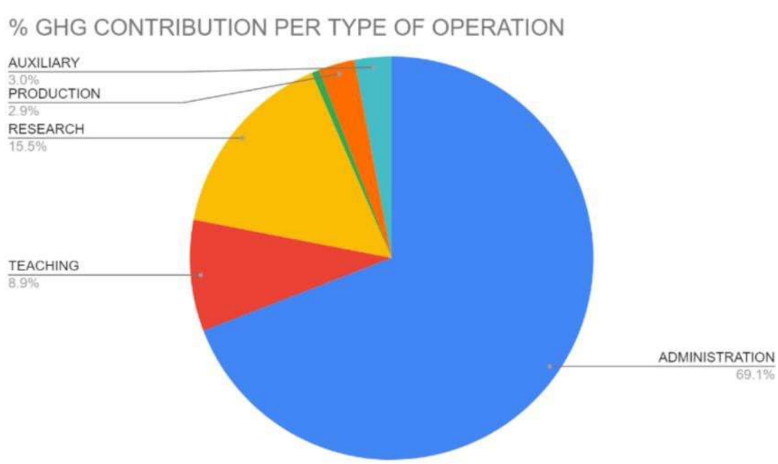

Figure 6. Percent GHG Contribution per Type of Operation

Discussion

Scope 1 Emission: Direct Emission

Scope 1 emissions accounted for approximately 10.5% of the university's total carbon footprint. The largest portion, at 4.3%, was due to fuel combustion in mobile sources, including university-owned or leased vehicles and grasscutters. Stationary fuel combustion, mainly from generators used during power outages, contributed 2.0%. Refrigerant leakage from air conditioning and refrigerators, despite quantified in smaller volumes, represents 2.7% due to their higher global warming potential of the substances involved. Other direct emissions from the university's animal farm, including cows and buffaloes., contributed 1.4% of the total Scope 1 emissions.

The fuel combustion in mobile sources as the largest contributor to Scope 1 emissions reflects that a significant portion of the university's activities involves official travel. This is further supported by the percentage share of carbon footprint by type of operation. Official travel is primarily associated with the Administration and Research operations, which are the two highest contributors among the five types of operation.

Scope 2 Emission: Indirect Emission from Electricity Consumption

The most significant contributor to GHG emission of UPLB comes from Scope 2 emission, which is the emission from purchased or used electricity of the university. It contributes to about 76.8% of the overall GHG emission. The university's annual electricity consumption amounts to 8,964.06 MWh, which was calculated to have an emission of 8,324.34 MT CO2e/year. Electricity consumption is one of the major carbon footprint hotspots in an academic institution. Based on the study of Helmers et al. [6], which compares the carbon footprint of universities worldwide, the largest impact of the university's carbon footprint is its energy consumption.

Scope 3 Emission: Other Indirect Emission

The second contributor of GHG emission of UPLB comes from Scope 3 emission. The greatest share comes from employee commuting which accounts for 5.3% of the overall GHG emission. Official travel of UPLB employees contributes to 0.7% of the overall GHG emission. There is no emission related to student commuting as online learning is still being implemented during the Calendar Year 2021.

The inclusion of emissions due to student and employee commuting in a university is highly important. Mobility impacts from universities account for between 22.9% and 90.8%, and the majority of its contribution comes from student commuting [6]. Moreover, in a German case study, the result of inclusion of employee mobility results to have a carbon footprint impact share between 32-69% [7].

The calculated emission from employee and student commuting in UPLB is relatively low compared to the previous studies as most of the university's operations shifted online, and no students were present on the campus as online learning mode is still being practiced. Emission related to commuting is expected to rise in the following years as the university prepares to transition from online learning to face-to-face learning as guidelines and protocols for COVID-19 in the country loosens due to reduced cases.

Material consumption which includes water, paper, laboratory chemicals, cleaning materials, other materials, and electronic and electrical devices, contributes to a total of 3.63% of the overall GHG emission of the university. The GHG emissions that are accounted for in this category mostly come from the production of these materials up to the transport of these materials to the university as it is the end-user of these materials, thus it is needed to be accounted for and included in the overall carbon footprint.

For waste generated by the university, solid waste, as well as hospital and COVID lab wastes, contribute to about 0.23% of the overall GHG emission. Regarding the university's waste management practice, solid waste generated by the university is sent to a sanitary landfill from January to August 2021. Before wastes are sent to landfill, a portion of plastic and paper waste and glass and metal waste are recycled. Waste recycling inside the university results in an annual emission avoidance of 495.95 MT CO2e.

In September 2021, a new Waste-to-Energy (WTE) facility was established in the university. Once operational, waste will be combusted rather than disposed in landfills. Diverting waste from landfilling to be used as feedstock for WTE facilities results in lesser waste being sent to landfill and reducing the release of GHG into the atmosphere [8].

GHG Mitigation Strategies

Based on the carbon footprint assessment, it is noteworthy that the university's electricity consumption has the largest share of the overall GHG emission. Thus, it is recommended to prioritize lowering this emission through energy conservation, transitioning to more energy-efficient systems, and considering the use of renewable sources of energy.

Another significant hotspot identified is related to mobility impacts such as employee commuting, official travel, and mobile fuel combustion. The recommendation to lower carbon footprint is through transitioning to cleaner ways of commuting, such as biking and carpooling, instead of driving alone.

Conclusion

With the collaborative participation across different units, the baseline CF of UPLB was successfully calculated, covering Scope 1, Scope 2 and Scope 3 emissions. The baseline CF provides a foundation for establishing a roadmap towards a net zero or low-carbon university in the coming years. To achieve this, the university should prioritize improving energy efficiency by reducing electricity and fuel consumption, and exploring cleaner energy sources. Additionally, the result of this study can serve as a model for other universities in the country to con-duct carbon footprint assessments and support the common goal of achieving net-zero emissions.

Acknowledgements

The researchers would like to thank the UPLB Office of Vice Chancellor for Research and Extension and the representatives from various UPLB units and offices that participated in the data collection and gathering. Establishing the institution's carbon footprint would not be possible without the collective action of each of the units that participated.

References

- International Energy Agency 2021, Net zero by 2050: a roadmap for the global energy sector. IEA, Paris. https://www.iea.org/reports/net-zero-by-2050, Licence: CC BY 4.0
- Hsu, A., Widerberg, O., Weinfurter, A., Chan, S., Roelfsema, M., Lütkehermöller, K., Bakhtiari, F., 2018. Bridging the emissions gap - the role of non state and subnational actors. The Emissions Gap Report 2018. A UN Environment Synthesis Report. United Nations Environment Programme. Nairobi
- UN Environment Programme (UNEP)., 2021. Over 1,000 universities and colleges make net-zero pledges as new nature initiative is unveiled. https://www.unep.org/news-and-stories/press-release/over-1000-universities-and-colleges-make-net-zero-pledges-new-nature
- International Organization for Standardization [ISO]., 2006. Environmental management: life cycle assessment; Principles and Framework. ISO.

- World Resources Institute and World Business Council for Sustainable Development. 2004. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. Revised edition. Washington, DC: World Resources Institute. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf
- Helmers, E., Chang, C. C., & Dauwels, J., 2021. Carbon footprinting of universities worldwide: Part I—objective comparison by standardized metrics. Environmental Sciences Europe, 33(1), 30. https://doi.org/10.1186/s12302-021-00454-6
- Pelzeter, A.., 2022). Employee mobility and service-related management in the carbon footprint of services—German case studies. The International Journal of Life Cycle assessment, 27(7), 902-915. https://doi.org/10.1007/s11367-022-02065-6
- Serre, B. M., & McCarthy, L. H., 2023. Municipal solid waste management: production, management, and environmental effects. Encyclopedia of Soils in the Environment (Second Edition), Academic Press. 321-332. ISBN 9780323951333. https://doi.org/10.1016/B978-0-12-822974-3.00192-0.

Environmental Performance of Australian Universities – The Case Study of the Queensland University of Technology

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Abstract

Higher education institutions such as universities play a central role in improving environmental sustainability by educating students and staff about sustainability and circular economy. In addition, university leaders and facilities management need to be aware of the environmental impact of their university's operation and how to improve their sustainability performance. Life cycle assessment guidelines for higher education institutions are applied to the operation of the Queensland University of Technology in the year 2022 considering 16 environmental impact categories. Overall, energy supply is identified as the most impactful input category, i.e. accounting for over 48% in each of eight impact categories. The guideline is further developed and data gaps are identified.

Keywords: LCA, University, Higher Education Institutions, Environmental Performance

Introduction

Addressing global challenges such as climate change, biodiversity loss, and the overconsumption of both renewable and non-renewable resources is becoming increasingly critical**.** Life Cycle Assessment (LCA) is widely used across sectors like agriculture, energy, and chemicals to evaluate the environmental dimension of sustainability. Higher Education Institutions (HEI) play a vital role in the effort to preserve a sustainable future by educating current generations and conducting research that supports sustainable development and technological innovation. However, given their substantial size, large populations of students and staff, and significant resource use, it is equally important to assess and understand the environmental impact of HEIs themselves.

Material and methods

The guideline for LCA of HEI published by (Jürgens et al., 2023) is applied to model the LCA of the Queensland University of Technology (QUT). The goal of the study is the evaluation of the environmental impact of QUT over one year (i.e. 2022) targeting decision makers of QUT as well as other HEI with an interest in reducing their environmental impacts caused by the operation of their institutions.

QUT is based in Brisbane (Queensland, Australia) and belongs to the tertiary education sector. The university has five faculties with a total of 30 schools which are located on two campuses (Gardens Point and Kelvin Grove). The reference period for this study is 2022. In 2022, 50,216 students were enrolled at QUT. During this year QUT employed 4,488 staff. Brisbane has a humid subtropical climate (Köppen-Geiger climate classification: Cfa) with hot and humid summers, and cool to mild winters.

Operational control is chosen, and a cradle-to-gate approach is used for QUT's LCA as the down-stream environmental impacts of QUT's academic activities is difficult to implement, i.e. no data is available to quantify the effect of applying QUT's academic outputs. The system boundaries for QUT include the Gardens Point and Kelvin Grove campuses as well as off-campus facilities such as the Mate-rials and Energy Research Facility, Samford, Australian Research Centre for Aerospace Automation, Banyo, and Mackay Sugar Pilot Plant (see Figure 2.1). The total building volume is estimated to be 15.572 m^3. Input categories considered for the life cycle inventory (LCI) are: Energy supply, Operating materials, Transport (external and internal), Equipment, Infrastructure, Waste, and Other. LCI data is collected from QUT's 2022 and 2023 Annual Reports, Facilities Management, financial department, QUT's GHG protocol, surveys, and chemical and business travel databases. For some LCI categories, primary data is not available and is modelled using literature data and assumptions.

The collected LCI data is subsequently used for modelling environmental impacts using the LCA for Experts software (formerly known as GaBi) by Sphera using aggregated datasets from two databases, namely the Managed LCA Content (MLC) database from Sphera (Sphera 2024) and ecoinvent v3.10 (ecoinvent 2024). The life cycle impact assessment (LCIA) is performed with the LCA for Experts soft-ware by Sphera using the EF 3.1 methodology as the LCIA method (European Commission: Joint Re-search Centre, 2023). The following environmental impact assessment categories are assessed: Acidification, Climate change, Ecotoxicity (freshwater), Eutrophication (freshwater, marine and terrestrial), Human toxicity (cancer and non-cancer), Ionising radiation, Land use, Ozone depletion, Particulate matter, Photochemical ozone formation and Resource use (fossils and mineral and metals).

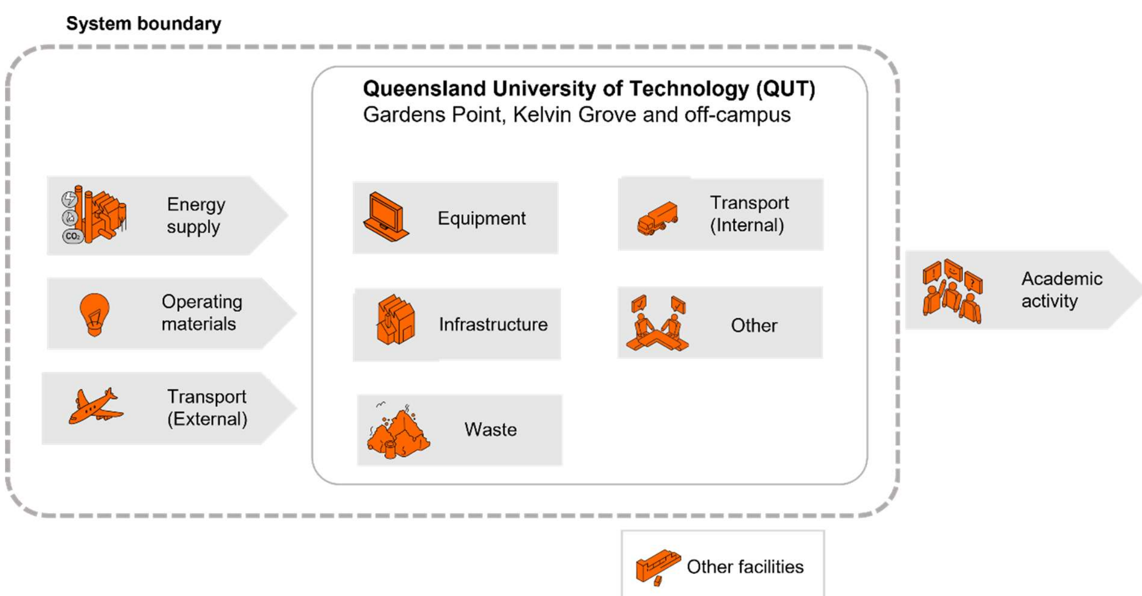

Figure 1. System boundaries of QUT; Other facilities such as shared research facilities are not included.

Results and discussion

Figure 2 illustrates the relative contributions of various QUT input areas to each environmental impact category. This breakdown highlights which input areas have the greatest influence across 16 environmental impact categories, thereby identifying key areas where targeted actions can most effectively reduce QUT's overall environmental footprint.

Energy supply accounts for the largest share in half of the environmental impact categories, while infrastructure dominates in six categories. Internet access contributes most significantly to the *Ionising Radiation* category, and operating materials have the highest impact on *Water Use*. Notably, the waste input for *Water Use* shows a negative percentage, indicating that more clean water is generated through wastewater treatment than is consumed across other waste-related data points.

Energy supply emerges as the most impactful contributor overall, representing more than 48% of the total impact in eight environmental categories. Within this area, electricity generation from hard coal is the predominant source, accounting for over 90% of the impact in categories such as acidification, climate change, terrestrial and marine eutrophication, particulate matter, fossil resource depletion, and photochemical ozone formation affecting human health.

In the ozone depletion category, refrigerant production—particularly R134a—has the most pronounced impact, with refrigerants used in air conditioning systems contributing 99% of the total effect. R134a is notable for its high global warming potential (GWP100 = 1,300), according to the Greenhouse Gas Protocol. Although the quantity of refrigerants used is relatively small compared to the extensive use of coal for energy, their usage is more controllable, suggesting a clear opportunity for targeted improvements.

Infrastructure has the most significant impact in six categories: resource use (minerals and metals), land use, human toxicity (cancer and non-cancer), eutrophication (freshwater), and ecotoxicity (freshwater). Transport ranks as the second most significant contributor in eight of the 16 environmental impact categories. Air travel, particularly within the external transportation category, holds a substantial share due to travel associated with international students and domestic students from outside Southeast Queensland returning home. Given Australia's geographic isolation, international students have limited alternatives to air travel, making it a largely unavoidable source of impact.

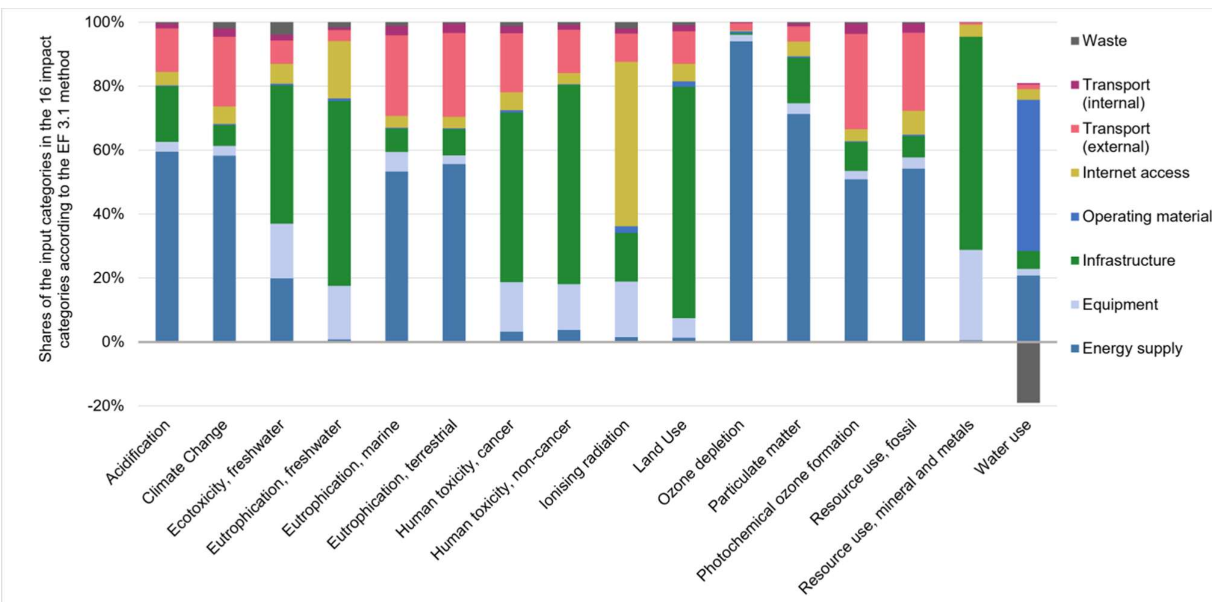

Figure 2: Shares of QUT input areas on the impact categories.

Equipment ranks as the third most significant contributor in four environmental impact categories: *ecotoxicity*, *freshwater eutrophication*, *human toxicity*, and *land use*. It also holds the second-highest impact in *ionising radiation*, *non-cancer human toxicity*, and *mineral and metal resource use*. Within this category, the production of displays and computers is particularly influential, accounting for over 70% of the total impact across these areas. Table 1 summarises the absolute results of QUT's overall environmental impacts as well as the per person impact based on 54.704 persons.

Table 1: Environmental impact results of the reporting flow (QUT's academic activities in 2022).

Impact category	Unit	Results	Per person (staff + students = 54.704)
Acidification	mol H^+ eq	549,301.49	10.04
Climate Change	kg CO2 eq	80,309,423.64	1,468.07
Ecotoxicity, freshwater	CTUe	248,057,364.90	4,534.54
Eutrophication, freshwater	kg P eq	11,702.67	0.21
Eutrophication, marine	kg N eq	119,231.89	2.18
Eutrophication, terrestrial	mol N eq	1,246,993.44	22.80
Human toxicity, cancer	CTUh	0.11	$2.01 \cdot 10^{-6}$
Human toxicity, non-cancer	CTUh	1.30	0.002
Ionising radiation	kBq U235 eq	1,180,208.42	21.57
Land Use	Pt	193,414,487.91	3,535.66
Ozone depletion	kg CFC-11 eq	11.96	$2.19 \cdot 10^{-4}$
Particulate matter	Disease incidences	4.07	$7.44 \cdot 10^{-5}$
Photochemical ozone formation	kg NMVOC eq	351,763.65	6.43
Resource use, fossils	MJ	935,187,455.39	17,094,48
Resource use, mineral and metals	kg Sb eq	1,454.22	0.03
Water use	m^3 world equiv.	23,377,638.85	427.35

A scenario analysis is carried out to explore potential pathways for enhancing environmental sustainability at QUT. This involves identifying key improvement measures commonly linked to reducing environmental impacts. These measures include transitioning from conventional (i.e. hard coal) to renewable energy sources (photovoltaics), lowering overall energy consumption, reducing business travel, and minimizing car use for commuting. In the scenario analysis for electricity, hard coal is re-placed by 50, 75, and 100% electricity from photovoltaics (Case 1, 2, 3 respectively). Replacing hard coal with photovoltaic energy leads to substantial reductions in environmental impact across seven of the 16 categories, with improvements of at least 20%. Specifically, climate change impacts are reduced by 23.96% in Case 1, 39.58% in Case 2, and 54.79% in Case 3, compared to the 2022 baseline scenario.

Regarding the lowering of overall energy consumption, a scenario is developed targeting a 25% reduction in energy supply, encompassing both a 25% decrease in total energy consumption and a 25% reduction in refrigerant usage. In seven impact categories – acidification, climate change, terrestrial and marine eutrophication, particulate matter, photochemical ozone creation and fossil resource use – overall reductions between 9% and 14% compared to the selected baseline scenario can be achieved. Especially important is the 23.5% reduction observed in the ozone depletion category, representing the most significant improvement among all impact areas. Since refrigerants account for 99% of ozone depletion within the energy supply category, the reduction in impact closely mirrors the decrease in refrigerant consumption. Reduction of business trips by 50 and 25% results in impact reductions between 0 and a maximum of 3%. Increase in the use of public transport by 5% results in only a marginal reduction in QUT's overall environmental impact. Therefore, the largest reduction in environmental impact caused by the operation of QUT can be achieved by switching from electricity generated from hard coal to photovoltaics and by a reduction of the total energy consumption.

In addition to the scenario analysis, it is important to analyse data gaps. A significant data gap exists regarding the environmental impact of QUT's buildings. As no primary data for these buildings is available, the dataset 'building, multi-storey' from the ecoinvent v3.10 dataset is used. This dataset de-scribes a non-residential building and models a combination of two concrete buildings with a lifespan of 80 years and includes materials use, end-of-life, and electricity consumption for construction, maintenance, and demolition. However, the actual environmental impact of QUT's buildings may vary considerably due to differences in architectural styles—ranging from heritage structures to modern buildings with glass facades—and functional uses, such as offices, libraries, and laboratory-intensive facilities.
In addition, large laboratory equipment, such as analytical instruments, is not included in the current LCA. These instruments are expected to significantly influence the environmental performance of a higher education institution. Therefore, future LCAs should incorporate large laboratory equipment to provide a more comprehensive assessment.

Conclusion
To the best of our knowledge, the current study is the first LCA of an Australian university assessing 16 environmental impact categories, i.e. not just climate change, and therefore providing a detailed analysis of the environmental impact of operating a higher education institution. LCAs for universities are a valuable tool to assess the impact of sustainability action plans and the success of measures to improve sustainability. In addition, they contribute to enhanced transparency of environmental impact and associated actions.

For subsequent LCAs, it is important to gather more detailed infrastructure data as part of the LCI. including collecting specific information on the various building types—such as heritage buildings, laboratories, libraries, offices, and lecture theatres. To obtain accurate data, it is recommended to use building plans, expert assessments, or estimates from architects and engineers. Establishing a comprehensive infrastructure dataset is a crucial first step before meaningful recommendations can be further developed.

Attribution and Licence

References

- European Commission: Joint Research Centre, 2023, Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Serenella, S., Fulvio, A. 2023 Updated characterisation and normalisation factors for the environmental footprint 3.1 method, Publications Office of the European Union, https://data.europa.eu/doi/10.2760/798894 .
- Jürgens, M., Hartmann, K., Endres, H.-J., Spierling, S., 2023. Life cycle assessment of higher education institutions – method and case study. J. Cleaner Prod. 430, 139649. https://doi.org/10.1016/j.jclepro.2023.139649.

A review of recycling allocation methods in life cycle assessments of food waste reduction strategies within a circular economy framework

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Abstract

Halving food waste (FW) by 2030 requires a shift from the current linear model to a circular model in food production systems. FW reduction strategies, such as prevention, redistribution, reuse for animals, and valorisation, aim to retain or recover the value of wasted food in alignment with circular economy principles. Life cycle assessment (LCA) is used to assess the environmental sustainability of these strategies, where recycling allocation plays a critical role. Currently, there is a lack of studies that systematically review recycling allocation methods across FW reduction strategies. To address this gap, this study critically examines the application of recycling allocation methods in LCAs of FW reduction strategies within a circular economy framework. This aim is achieved through a comprehensive review of 73 scholarly and grey literature articles published between 2012 and 2023. A total of 76 FW reduction strategies were recorded, with 100:0 and 0:100 as the main methods reported. FW prevention is typically treated as a closed-loop system (54%), with 0:100 method assigning impacts to the product generating FW. However, 43% of prevention strategies excluded recycling impacts. FW redistribution mainly follows 100:0 (67%), while 33% strategies exclude recycling impacts. In FW reuse for animals, all studies use 100:0 method. Seventy percent of valorisation strategies used 100:0, while 30% deviated by incorporating upstream burdens. A significant variation is observed in the adoption of recycling allocation methods within and across FW reduction strategies, limiting the comparability of LCA results. The 100:0 and 0:100 recycling methods do not provide flexibility in allocating upstream environmental burdens to FW. Therefore, it is recommended to explore the suitability of other recycling methods for assessing FW reduction strategies. Further, a common recycling allocation method is needed to improve consistency and comparability in FW reduction LCAs.

Keywords: Life cycle assessment, allocation, recycling, food waste, circular economy

Introduction

The United Nations introduced SDG target 12.3 to halve food waste (FW) by 2030, acknowledging its significant environmental, social, and economic consequences (FAO, 2011; UN, 2015; FAO, 2019). Aligned with circular economy principles—eliminating waste, keeping materials in use, and regenerating natural systems—food supply chains can transition from linear to circular models by preventing, redistributing, reusing for animals, and valorising FW, thereby contributing to this global target (EC, 2008; Ellen MacArthur Foundation, 2019; Ojha et al., 2020; Omolayo et al., 2021; Lugo et al., 2022).

In recent years, researchers have increasingly applied life cycle assessment (LCA) to FW reduction strategies, highlighting the urgency of mitigating FW's environmental impacts. Incorporating suitable recycling allocation methods in these LCAs ensures accurate and transparent attribution of environ-mental burdens (ISO, 2006; EC, 2010). Recycling procedures are categorised as closed-loop, where materials retain inherent properties, and open-loop, where properties change (ISO, 2006). Allocation methods addressing these include 0:100 (BSI, 2011; ISO, 2012), 100:0 (BSI, 2011), 50:50 (Lindfors et al., 1995), quality adjusted 50:50 (Allacker et al., 2017), linearly degressive (Allacker et al., 2017), allocation at the point of substitution (APOS) (Wernet et al., 2016), and circular footprint formula (EU, 2018). These methods guide the allocation of environmental burdens and credits between primary and secondary systems, considering system boundaries, material quality, and substitution effects in LCA (ISO, 2006).

Few studies explicitly focus on recycling allocation in FW contexts. Aldama et al. (2023) reviewed 113 LCAs on FW reuse for animals and valorisation, identifying allocation practices in agricultural and food-related systems. Ekvall et al. (2020) examined modelling approaches for open-loop recycling across all recyclable materials. Siddique et al. (2024) focused on upstream allocation in LCAs of FW re-use for animals. Schrijvers et al. (2016) reviewed recycling allocation approaches and proposed a universal framework applicable to all materials. Despite these contributions, research on recycling allocation in FW LCAs remains fragmented, with limited cross-strategy comparisons. This review addresses that gap by critically examining recycling allocation methods used in LCAs of FW prevention, redistribution, reuse, and valorisation, thereby advancing understanding of current modelling practices and provides a consolidated basis for future methodological refinement and harmonisation in FW-focused LCAs. Furthermore, it establishes a conceptual foundation for developing more consistent and trans-parent recycling allocation approaches in future FW assessments.

Material and methods

Literature survey

We conducted a comprehensive literature survey that integrated both scientific and grey literature to address the research objectives. To capture relevant publications, we formulated a search string consisting of two main keyword blocks: (i) "life cycle assessment" and (ii) "food waste reduction" along with their respective synonyms. We executed the primary search in Scopus and Web of Science databases, which are known for their extensive coverage of peer-reviewed scientific literature. To broaden the scope, we carried out a secondary search using the general Internet, targeting domains such as .edu, .gov, and .org. The searches yielded 158 records from Scopus, 73 from Web of Science, and 472 from the general Internet (Figure 1). We then applied predefined inclusion and exclusion criteria to screen the retrieved documents. We included publications that (1) were published between 2012 and 2023, (2) incorporated an LCA methodological framework, and (3) assessed one or more environmental impacts. We excluded publications that (4) were duplicates, (5) were written in languages other than English, (6) were review articles, or (7) focused on FW end-of-life treatments such as composting and landfilling. After applying these filters, we identified 47 eligible publications. We also employed a snowballing technique during data extraction to capture additional relevant publications, resulting in the inclusion of 26 more articles, resulting in a total of 73 articles selected for full review.

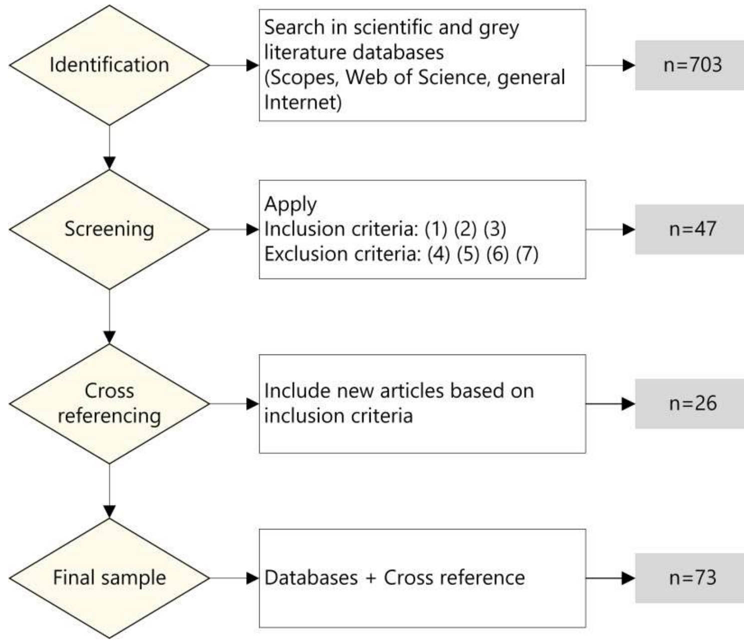

Figure 1. Methodology adopted in the selection of the final sample for the literature review.

Data extraction

We systematically reviewed each of the 73 selected articles to identify the recycling allocation method applied. From each article, we extracted key information, including the title, publication year, FW reduction strategy, research objective, functional unit(s), type(s) of FW considered, LCA modelling approach, upstream allocation method, and recycling allocation method. This process enabled the identification of 76 distinct FW reduction strategies. Of these, 30 strategies focused on FW prevention, 6 on FW redistribution, 17 on FW reuse for animal feed, and 23 on FW valorisation into other valuable products.

Results and discussion

Recycling allocation methods in FW reduction strategies

The reviewed LCA studies employed two primary recycling allocation methods: 100:0 and 0:100, as illustrated in Figure 2. Among these, 45% of the FW reduction strategies applied the 100:0 method, al-so known as the recycled content approach or cutoff approach, which assigns the recyclable material as burden-free, while fully attributing recycling impacts to the product using the recycled material (Buhe et al., 1997; BSI, 2011; WRI and WBCSD, 2011; Allacker et al., 2017; Ekvall et al., 2020). In contrast, 21% of the studies adopted the 0:100 method, also known as the end-of-life recycling approach or closed-loop approach, allocating all the recycling impacts to the product producing a recycled mate-rial, while no burdens are allocated to downstream products using input recycled material (BSI, 2011; ISO, 2012; Allacker et al., 2017; Ekvall et al., 2020). Further, 15% of the strategies have incorporated the 100:0 method in LCA studies allocating upstream environmental burdens; this method is referred to as the 100:0 method with upstream burdens in this study (Figure 2). Notably, 19% of the reviewed strategies did not include recycling impacts in their LCAs, either due to methodological omissions or the specific scope and objectives of the studies.

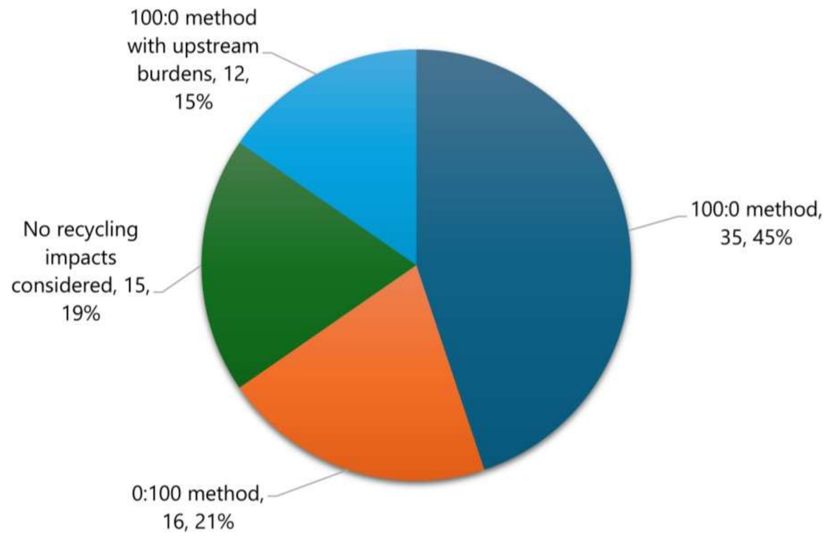

Figure 2. Recycling allocation methods employed in reviewed articles

Figure 3 and Table 1 illustrate the recycling allocation methods applied across the four FW reduction strategies: prevention, redistribution, reuse for animals, and valorisation. Notably, FW prevention is the only strategy in which the 0:100 allocation method was adopted. This reflects the treatment of FW prevention as a closed-loop process, where avoided waste is conceptually reintroduced into the same food system, displacing equivalent primary production (ISO, 2006; EC, 2010). Closed-loop recycling, as defined in ISO (2006), refers to the reintegration of recovered materials into the same product system without significant loss of quality or function. Sixteen of the 30 FW prevention studies employed the 0:100 allocation method (Figure 3). These studies typically used main product-based functional units—such as 1 kg of consumed strawberries or 1 kg of packaged food—linking the environ-mental burdens to the product responsible for FW generation (Table 1). In these cases, upstream environmental burdens are allocated to the main product, while the environmental credits associated with avoided waste are retained within the same system, consistent with the 0:100 approach (EC, 2010; WRI and WBCSD, 2011; Allacker et al., 2017). Only one study applied the 100:0 method to FW prevention. This study was associated with the selection of a unitary functional unit, based on the mass of FW prevented (Laurent et al., 2014; Lehn et al., 2023). However, in this study, upstream burdens of the FW were allocated to the functional unit, representing a deviation from standard 100:0 practice. This inconsistency underscores the importance of aligning allocation methods with clearly defined functional units and system boundaries. Thirteen FW prevention studies did not incorporate recycling impacts in their LCAs (Figure 3 and Table 1). Several factors may explain this omission. First, some studies were national-level assessments focused on quantifying avoidable FW or evaluating progress toward national FW reduction targets, without modelling specific interventions or technologies. Second, several studies assessed behavioural change strategies (e.g., improved consumer awareness), which are often modelled without detailed material flow accounting. While such approaches facilitate macro-scale policy evaluation, they may underrepresent the environmental benefits of FW prevention. In some cases, the absence of recycling impact modelling may also reflect the ISO (2006) allowance to avoid allocation in open-loop systems where the recycled material retains its inherent properties and substitutes virgin material with-out additional processing. The diversity of modelling choices observed across FW prevention LCAs—particularly in the selection of functional units, allocation methods, and treatment of system boundaries—has led to inconsistent application of recycling allocation.

The 100:0 recycling allocation method is used in LCA studies of FW redistribution (Figure 3). Two studies followed the standard 100:0 application. However, two others deviated from this convention by incorporating upstream burdens, introducing inconsistencies in system boundaries. Additionally, two redistribution studies did not account for recycling impacts at all. All reviewed FW redistribution studies used unitary functional units—typically defined by the mass of redistributed food—which structurally align with the 100:0 method (Table 1). Nonetheless, methodological variation in upstream allocation decisions and omission of recycling impacts can lead to divergent environmental outcomes, thereby complicating cross-study comparison and limiting the transparency of impact attribution.

In the case of FW reuse for animals, all reviewed LCA studies adopted the standard 100:0 allocation method (Figure 3). This method reflects the open-loop nature of animal feed production from FW, whereby the recycled material enters a different product system. Moreover, two studies have incorporated upstream environmental burdens in addition to the standard method (Bava et al., 2019; Bosch et al., 2019). Functional unit selection varied in the reviewed studies: six studies adopted output-based functional units (e.g., per tonne of animal feed), while the remainder employed unitary units based on input FW mass (Table 1). The consistent application of the 100:0 method in this context is largely attributable to the use of mixed FW streams from multiple stages of the supply chain, which are typically treated as burden-free inputs. Moreover, converting FW into animal feed is methodologically straight-forward compared to FW prevention, as it clearly involves open-loop recycling without ambiguity in system boundaries.

Among the 23 LCA studies on FW valorisation, 16 applied the standard 100:0 allocation method, while seven incorporated upstream burdens of the FW into the modelling framework (Figure 3). In these latter cases, the studies considered the origin of the FW and attributed a share of its environmental load to the valorisation system—particularly where the waste retained economic value or resulted from avoidable losses. All valorisation studies employed output-based functional units (Table 1). The consistent use of the 100:0 approach in FW valorisation reflects its broad acceptance as a conventional open-loop recycling process within LCA practice like FW reuse for animals. This consistency enhances the comparability of studies within the valorisation domain, although upstream allocation decisions—when applied—should be clearly justified and harmonized to ensure methodological consistency.

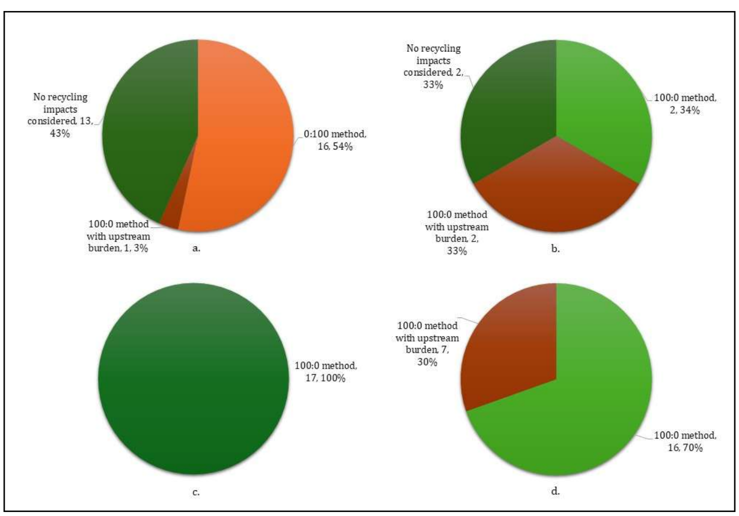

Figure 3. Recycling allocation methods used across FW reduction strategies: a. Prevention, b. Redistribution, c. Reuse for animals, d. Valorisation

Table 1. Methodological choices in LCAs of FW reduction strategies

No.	Reference	Functional unit/s	FW type/s	LCA model	Modelling approach	Allocation procedure	Method of recycling allocation
1	Lehn et al. (2023)	Quantity of FW prevented	Salmon	–	Co-product	Mass	100:0
2	Yano et al. (2023)	Annual rate of provision of services and products consumed by households within Kyoto City	All[a]	–	Waste	Avoided/zero burden	–
3	Villanova-Estors et al. (2023)	1 kg of packaging film to contain fresh-cut salad	Carrot; iceberg lettuce; red cabbage	Attributional	Waste	Avoided/zero burden	0:100
4	Lévesque et al. (2023)	The food used during one day of restaurant operations and the food discarded during one day of restaurant operations	All[a]	–	Waste	Avoided/zero burden	–
5	Eaton et al. (2022)	1 tonne of household FW	All[a]	Consequential	Waste	Avoided/zero burden	–
6	TP da Costa et al. (2022)	Sum of all products included in the distribution stage	All[a]	–	Waste	Avoided/zero burden	0:100
7	Casson et al. (2022)	1 packaging unit which contains 500 g of sliced beef in relation to the expected shelf-life for each packaging system	Beef	–	Waste	Avoided/zero burden	0:100
8	Goossens et al. (2022)	1 kg of food available at the buffet	All[a]	–	Waste	Avoided/zero burden	0:100
9	Sasaki et al. (2022a)	Transporting 1 kg of undamaged peaches to the retail stage	Peach	–	Waste	Avoided/zero burden	0:100
10	Sasaki et al. (2022b)	1 kg of consumed strawberries	Strawberry	–	Waste	Avoided/zero burden	0:100
11	Settier-Ramirez et al. (2022)	218 g of packed pastry cream	Pastry cream	–	Waste	Avoided/zero burden	0:100
12	Shrivastava et al. (2022)	1 metric tonne of cucumbers sold at retail	Cucumber	–	Waste	Avoided/zero burden	0:100
13	Meier et al. (2021)	1 kg of FW	All[a]	Attributional	Co-product	Mass	–
14	Wohner et al. (2020)	Consumption of 3.8 kg of ketchup	Tomato ketchup	Attributional	Waste	Avoided/zero burden	0:100
15	Winans et al. (2020)	1 kg of cultivated product	Processing peach	Attributional	Waste	Avoided/zero burden	–
16	Slorach et al. (2020)	1 t of avoidable or possibly avoidable FW	All[a]	–	Co-product	Mass	–
17	Vigil et al. (2020)	A packaging unit intended to contain a 130 g serving of fresh-cut lettuce	Lettuce	Attributional and consequential	Waste	Avoided/zero burden	0:100
18	Goossens et al. (2020)	A food portion of 80 g and the number of portions served for one year	Atlantic Salmon	–	Waste	Avoided/zero burden	0:100
19	De Menna et al. (2019)	The amount of peaches/nectarines through-put per year at one wholesaler in UK	Peach; nectarine	Consequential	Waste	Avoided/zero burden	–
20	Albizzati et al. (2019)	Management of 1 tonne of surplus food (wet weight basis) including associated packaging, as generated by the retail sector in France	All[a]	Consequential	Co-product	Mass	–
21	Zhang et al. (2019)	1 kg of food product and the required amount of nano-packaging materials	Fruits; meat	–	Waste	Avoided/zero burden	0:100
22	Tonini et al. (2018)	1 tonne of avoidable FW generated by pro-cessing, wholesale & retail, food service, and	All[a]	Consequential	Co-product	Mass	–

Table 1. Methodological choices in LCAs of FW reduction strategies (Continued)

No.	Reference	Functional unit/s	FW type/s	LCA model	Modelling approach	Allocation procedure	Method of recycling allocation
23	Yokokawa et al. (2018)	Consumption of 105 g of ham	Ham	–	Waste	Avoided/zero burden	0:100
24	Salemdeeb et al. (2017a)	1 tonne of UK household FW	All[a]	Consequential	Waste	Avoided/zero burden	–
25	Oldfield et al. (2016)	Annual amount of WFFR[b] managed in Ireland	All[a]	–	Waste	Avoided/zero burden	–
26	Schott and Andersson (2015)	Service of managing 1 tonne of FW from Swedish households	All[a]	Consequential	Co-product	Mass	–
27	Gruber et al. (2015)	1 kg of food disposed after the customer stage	Potatoes; milk; rice	–	Co-product	Mass	–
28	Conte et al. (2015)	100 g of packaged portioned sheep's milk cheese	Cheese	Attributional and consequential	Waste	Avoided/zero burden	0:100
29	Zhang et al. (2015)	Delivering 1 kg fresh beef to the retail gate and displaying it until the end of shelf life	Beef	–	Waste	Avoided/zero burden	0:100
30	Wikström et al. (2014)	1 kg of eaten food	Rice; yoghurt	–	Waste	Avoided/zero burden	0:100
Redistribution							
31	Sundin et al. (2023)	1 kg surplus food ready for dispatch at the retail gate	All[a]	Attributional	Waste	Avoided/zero burden	100:0
32	Cakar (2022)	1 kg of each food commodity	Fruits; vegetables	–	Co-product	Mass	–
33	Sundin et al. (2022)	1 kg surplus food prepared for transportation at the retail gate.	All[a]	Attributional	Waste	Avoided/zero burden	100:0
34	Damiani et al. (2021)	1 kg of surplus food redistributed by each emporium up to the gate	All[a]	Attributional and consequential	Co-product	Mass	100:0
35	Eriksson and Spångberg (2017)	1 kg of wasted food in a waste management scenario; removal of 1 kg of FW from a supermarket.	Fruits; vegetables	–	Co-product	Mass	–
36	Eriksson et al. (2015)	Removal of 1 kg of FW (including packaging) from the supermarket	Bananas; iceberg lettuce; grilled chicken; stewing beef; bread	–	Co-product	Mass	100:0
Reuse for animals							
37	Alsaleh and Aleisa (2023)	1 ton of FW received from retail, food service and household	All[a]/mixed	Consequential	Waste	Avoided/zero burden	100:0
38	Goyal et al. (2021)	1 kg LH[c] pellets	Organic and peeling waste	–	Waste	Avoided/zero burden	100:0
39	Loyola et al. (2021)	1 kg of nutritionally equivalent diet for laying hens in the US	Bakery; mixed waste from grocer-ies	Attributional	Waste	Avoided/zero burden	100:0
40	Albizzati et al. (2021)	Providing 1 Scandinavian feed unit of animal feed; providing 1 kg of protein	All[a]/mixed	Consequential	Waste	Avoided/zero burden	100:0
41	Mosna et al. (2021)	1 kg of finished pet food	Meat	Attributional	Waste	Avoided/zero burden	100:0
42	Bosch et al. (2019)	1 kg of fresh larvae; 1 kg of larval protein	Bakery; vegetable and fruit refuse	–	Co-product (Avoidable)	Mass	100:0
43	Smetana et al. (2019)	1 kg of dried and pelletized organic fertilizer; 1 kg of fresh BSF[d] biomass (puree) used as a component for pet food production; 1 kg of protein concentrated meal used as feed ingredient	Wheat	Attributional and censequential	Waste (Unavoidable) Waste	Avoided/zero burden Avoided/zero burden	100:0
44	Tedesco et al. (2019)	1 kg of dried meal of earthworm	Fruits	Attributional	Waste	Avoided/zero burden	100:0
45	Bava et al. (2019)	1 kg of larvae (dry wet weight); 1 kg of protein from larvae 1 kg of fat content	Legumes and pulses; beverages	–	Co-product	Economic	100:0
46	De Menna et al. (2019)	Yearly amount of food surplus generated from the manufacturing (not primary produc-tion), retail, and catering sectors in UK or France, which can be converted into pig feed	All[a]/mixed	Consequential	Waste	Avoided/zero burden	100:0
47	Laso et al. (2018)	1 kg of fresh anchovy captured in the fishing stage	Anchovy	–	Waste	Avoided/zero burden	100:0
48	Mondello et al. (2017)	1 tonne of FW to be treated	All[a]/mixed	–	Waste	Avoided/zero burden	100:0
49	Salemdeeb et al. (2017b)	Processing 1 tonne of municipal FW	All[a]/mixed	Consequential	Waste	Avoided/zero burden	100:0
50	Salomone et al. (2017)	1 tonne of FW biodigested; 1 kg of proteins; 1 kg of lipids	All[a]/mixed	–	Waste	Avoided/zero burden	100:0
51	Smetana et al. (2016)	1 kg of dried defatted insect powder; 1 kg of ready for consumption fresh product at the processing gate	All[a]/mixed	Attributional	Waste	Avoided/zero burden	100:0
52	van Zanten et al. (2015)	1 ton larvae meal on dry matter basis	All[a]/mixed	–	Waste	Avoided/zero burden	100:0

Table 1. Methodological choices in LCAs of FW reduction strategies (Continued)

No.	Reference	Functional unit/s	FW type/s	LCA model	Modelling approach	Allocation procedure	Method of recycling allocation
53	Eriksson et al. (2015)	Removal of 1 kg of FW from the supermarket	Bananas; grilled chicken; lettuce; beef; bread	_	Waste	Avoided/zero burden	100:0
54	Rebolledo-Leiva et al. (2023)	1 kg of dietary fibre product	Chickpea	_	Co-product	Economic	100:0
55	Vanapalli et al. (2023)	1 kg of Lactic acid production	Bread	_	Waste	Avoided/zero burden	100:0
56	Tsouko et al. (2023)	Production of 1 kg of dry bacterial cellulose after 10 days of fermentation	Barley	_	Waste	Avoided/zero burden	100:0
57	Khanpit et al. (2023)	40 kg of soluble dietary fiber concentrate	Orange	_	Waste	Avoided/zero burden	100:0
58	Coelho et al. (2023)	Provision of 1 kg of protein ingredient	Herring; lingonberry	_	Co-product	Mass	100:0
59	García-Velásquez and van der Meer (2023)	Production of 1 kg of biobased purified ter-ephthalic acid at the factory gate	Sugar beet	_	Co-product	Mass	100:0
60	Abu-Bakar et al. (2023)	1 tonne of glucose produced at the milling gate	Rice	_	Waste	Avoided/zero burden	100:0
61	Gallo et al. (2022)	Production of 1 kg of biocomposite in the form of alveoli trays (food containers)	Vegetables	Attributional	Waste	Avoided/zero burden	100:0
62	JS da Costa et al. (2022)	1 kg of pectin	Orange	Attributional	Waste	Avoided/zero burden	100:0
63	Ríos-Fuentes et al. (2022)	1 ton of frozen broccoli	Broccoli	_	Co-product	Mass	100:0
64	Ramos and Ferreira (2022)	1 kg of 2POP[e] with 60% moisture	Olive	_	Waste	Avoided/zero burden	100:0
65	Ioannidou et al. (2022)	1 kg of dry waste stream after the production of 2.15 kg wine	Grape	_	Waste	Avoided/zero burden	100:0
66	Bartek et al. (2022)	1 ton potato starch	Potato	Consequential	Co-product	Mass	100:0
67	Nikkhah et al. (2021)	1 kg of oil produced from olive kernel;100 MJ energy in oil	Olive	Attributional	Waste	Avoided/zero burden	100:0
68	Albizzati et al. (2021)	Providing 1 kg of lactic acid; providing 1 kg of polylactic acid; providing 1 kg of succinic acid	All[a]	Consequential	Waste	Avoided/zero burden	100:0
69	Mariana et al. (2021)	1 L of orange juice	Orange	Attributional	Waste	Avoided/zero burden	100:0
70	Munagala et al. (2021)	1 kg of lactic acid	Sugarcane	_	Co-product	Economic	100:0
71	da Silva et al. (2021)	1 kg of mango kernel starch	Mango	_	Co-product	Mass and economic	100:0
72	Santiago et al. (2021)	1 kg of rutin	Asparagus	Attributional	Waste	Avoided/zero burden	100:0
73	Eriksson et al. (2021)	1 kg of collected broccoli parts	Broccoli	Attributional and consequential	Waste	Avoided/zero burden	100:0
74	Ulmer et al. (2020)	1 kg of fresh insects; 1 kg of proteins (content of extracted fresh insects); 1 kg of extruded intermediate product containing between 20 and 30% of protein (mass-based comparison) at the processing gate	Honey	Attributional	Waste	Avoided/zero burden	100:0
75	Cortés et al. (2020)	1 tonne of grape marc	Grape	_	Waste	Avoided/zero burden	100:0
76	Tedesco et al. (2019)	1 kg of dried meal of earthworm	Fruits	Attributional	Waste	Avoided/zero burden	100:0

This includes food under following sub-categories: fruits and vegetables, fish and meat, bread and bakery, dairy and eggs, processed food.

[b] Wasted food and food residue.

[c] Pallets produced from *Lemna minor* and *Hermetia illucens*.

[d] Black Soldier Fly larvae.

[e] Two-or-three phase olive pomaces.

Conclusion

This review revealed significant inconsistencies in the application of recycling allocation methods across FW reduction strategies, including prevention, redistribution, reuse for animals, and valorisation. The most frequently applied method was the 100:0 approach, particularly in redistribution, re-use, and valorisation strategies, reflecting the dominance of open-loop recycling in these contexts. In contrast, the 0:100 method was uniquely applied in some FW prevention studies, which considered the system as closed-loop. However, even within FW prevention, deviations were evident, such as the allocation of upstream burdens despite using unitary functional units, highlighting conceptual and methodological ambiguities.

These inconsistencies hinder the comparability of LCA results both within and across FW reduction strategies. More critically, the strict application of either 100:0 or 0:100 methods lack flexibility in accurately reflecting the environmental burdens of recycled FW, particularly when avoidable fractions or materials with economic value are reintroduced into secondary systems. In such cases, allocating a portion of upstream impacts to the recycling process is justifiable and necessary for an accurate representation of system-level trade-offs.

Alternative allocation approaches, such as the 50:50 method, quality-adjusted 50:50 or APOS, offer more-balanced frameworks by splitting or scaling burdens based on quality, function, or substitution potential. These methods may better accommodate the complexities inherent in FW systems, especially where the boundary between waste and by-product is unclear or context dependent.

To enhance transparency, methodological rigour, and policy relevance, future FW reduction LCAs should consider the broader suite of available recycling allocation methods. A harmonised approach would improve the consistency of results and facilitate more robust comparisons across studies. Establishing such methodological guidance is critical for supporting evidence-based decision-making in FW reduction policy and practice.

Overall, this review provides a consolidated synthesis of recycling allocation modelling practices in FW LCAs, highlighting critical methodological gaps and inconsistencies. It contributes to bridging the methodological disconnect between FW and broader recycling LCA literature, thereby advancing the foundation for more coherent, transparent, and harmonised allocation approaches in future FW assessments.

Acknowledgements

The authors are very grateful to the financial support provided by the End Food Waste Cooperative Research Centre whose activities are funded by the Australian Government's Cooperative Research Centre Program.

References

- Abu-Bakar, N.A., Roslan, A.M., Hassan, M.A., Rahman, M.H.A., Ibrahim, K.N., Abd Rahman, M.D. Mohamad, R., 2023. Environmental impact assessment of rice mill waste valorisation to glucose through biorefinery platform. Nature, 13. https://doi.org/10.1038/s41598-023-28487-2.
- Albizzati, P.F., Tonini, D. Astrup, T.F., 2021. High-value products from food waste: An environmental and socio-economic assessment. Science of the Total Environment, 755, 142466. https://doi.org/10.1016/j.scitotenv.2020.142466.
- Albizzati, P.F., Tonini, D., Chammard, C.B. Astrup, T.F., 2019. Valorisation of surplus food in the French retail sector: Environmental and economic impacts. Waste Management, 90, 141-151. https://doi.org/10.1016/j.wasman.2019.04.034.

- Aldama, D.D., Grassauer, F., Zhu, Y., Ardestani-Jaafari, A. Pelletier, N., 2023. Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. Journal of Cleaner Production, 421. https://doi.org/10.1016/j.jclepro.2023.138488.
- Allacker, K., Mathieux, F., Pennington, D. Pant, R., 2017. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. The 8-20 November 2025
- International Journal of Life Cycle Assessment, 22, 1441-1458. https://doi.org/10.1007/s11367-016-1244-0.
- Alsaleh, A. Aleisa, E., 2023. Triple Bottom-Line Evaluation of the Production of Animal Feed from Food Waste: A Life Cycle Assessment. Waste Biomass Valorization, 14, 1169-1195. https://doi.org/10.1007/s12649-022-01914-7.
- Bartek, L., Sundin, N., Strid, I., Andersson, M., Hansson, P.A. Eriksson, M., 2022. Environmental benefits of circular food systems: The case of upcycled protein recovered using genome edited potato.
- Journal of Cleaner Production, 380. https://doi.org/10.1016/j.jclepro.2022.134887.
- Bava, L., Jucker, C., Gislon, G., Lupi, D., Savoldelli, S., Zucali, M. Colombini, S., 2019. Rearing of Hermetia Illucens on Different Organic By-Products: Influence on Growth, Waste Reduction, and Environmental Impact. Animals (Basel), 9. https://doi.org/10.3390/ani9060289.
- Bosch, G., van Zanten, H.H.E., Zamprogna, A., Veenenbos, M., Meijer, N.P., van der Fels-Klerx, H.J. van Loon, J.J.A., 2019. Conversion of organic resources by black soldier fly larvae: Legislation, efficiency and environmental impact. Journal of Cleaner Production, 222, 355-363. https://doi.org/10.1016/j.jclepro.2019.02.270.
- BSI, 2011. PAS 2050:2011 - Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution, London, UK. Available online at: https://shop.bsigroup.com/forms/PASs/PAS-2050/. (Accessed 20 April 2025).
- Buhe, C., Achard, G., Teno, J.F.L. Chevalier, J.L., 1997. Integration of the recycling processes to the life cycle analysis of construction products. Resources, Conservation and Recycling, 20, 227-243. https://doi.org/10.1016/S0921-3449(97)00015-3.
- Cakar, B., 2022. Bounce back of almost wasted food: Redistribution of fresh fruit and vegetables surpluses from Istanbul's supermarkets. Journal of Cleaner Production, 362. https://doi.org/10.1016/j.jclepro.2022.132325.
- Casson, A., Giovenzana, V., Frigerio, V., Zambelli, M., Beghi, R., Pampuri, A., Tugnolo, A., Merlini, A., Colombo, L., Limbo, S. Guidetti, R., 2022. Beyond the eco-design of case-ready beef packaging: The relationship between food waste and shelf-life as a key element in life cycle assessment. Food Packaging and Shelf Life, 34. https://doi.org/10.1016/j.fpsl.2022.100943.
- Coelho, C.R.V., Peters, G., Zhang, J., Abdollahi, M. Undeland, I., 2023. Fish beyond fillets: Life cycle assessment of cross-processing herring and lingonberry co-products into a food product.
- Resources, Conservation and Recycling, 188. https://doi.org/10.1016/j.resconrec.2022.106703.
- Conte, A., Cappelletti, G.M., Nicoletti, G.M., Russo, C. Del Nobile, M.A., 2015. Environmental implications of food loss probability in packaging design. Food Research International, 78, 11-17. https://doi.org/10.1016/j.foodres.2015.11.015.
- Cortés, A., Moreira, M.T., Domínguez, J., Lores, M. Feijoo, G., 2020. Unraveling the environmental impacts of bioactive compounds and organic amendment from grape marc. Journal of Environmental Management, 272. https://doi.org/10.1016/j.jenvman.2020.111066.

- da Costa, J.S., Maranduba, H.L., de Sousa Castro, S., de Almeida Neto, J.A. Rodrigues, L.B., 2022.
- Environmental performance of orange citrus waste as raw material for pectin and essential oil production. Food and Bioproducts Processing, 135, 165-177. https://doi.org/10.1016/j.fbp.2022.07.008.
- da Costa, T.P., Gillespie, J., Pelc, K., Adefisan, A., Adefisan, M., Ramanathan, R.a. Murphy, F., 2022. Life cycle assessment tool for food supply chain environmental evaluation. Sustainability, 15. https://doi.org/10.3390/su15010718.
- da Silva, A.K.P., Cardoso, A., de Sá Filho, E.B., de Azeredo, H.M.C., Freire, F., Filho, F.C. de Figueirêdo, M.C.B., 2021. Integrating life cycle assessment in early process development stage: The case of extracting starch from mango kernel. Journal of Cleaner Production, 321. https://doi.org/10.1016/j.jclepro.2021.128981.
- Damiani, M., Pastorello, T., Carlesso, A., Tesser, S. Semenzin, E., 2021. Quantifying environmental implications of surplus food redistribution to reduce food waste. Journal of Cleaner Production,
- 289. https://doi.org/10.1016/j.jclepro.2021.125813.
- De Menna, F., Davis, J., Bowman, M., Peralta, L.B., Bygrave, K., Herrero, L.G., Karen, L., McManus, W.,
- Vittuar, M., van Zanten, H. Ostergren, K., 2019. LCA & LCC of food waste case studies: Assessment of food side flow prevention and valorisation routes in selected supply chains. WP5.5. Available online at: https://eu-refresh.org/lca-lcc-food-waste-case-studies.html. (Accessed 12 November 2023).
- Eaton, E., Hunt, A., Di Leo, A., Black, D., Frost, G. Hargreaves, S., 2022. What Are the Environmental Benefits and Costs of Reducing Food Waste? Bristol as a Case Study in the WASTE FEW Urban Living Lab Project. Sustainability (Switzerland), 14. https://doi.org/10.3390/su14095573.
- EC (European Commission), 2008. Directive 2008/98/EC of the European parliament and of the council of 19 November 2008 on waste and repealing certain Directives. Available online at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098. (Accessed 02
- September 2024).
- EC (European Commission), 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Available online at: https://publications.jrc.ec.europa.eu/repository/handle/JRC48157. (Accessed 23 July 2023).
- Ekvall, T., Björklund, A., Sandin, G., Jelse, K., Lagergren, J.a. Rydberg, M., 2020. Modeling recyling in life cycle assessment. Swedish Life Cycle Center. 47270-1. Available online at: https://www.lifecyclecenter.se/wp-content/uploads/2020_05_Modeling-recyling-in-life-cycle-assessment-1.pdf. (Accessed 20 March 2025).
- Ellen MacArthur Foundation, 2019. Cities and circular economy for food. Available online at: https://content.ellenmacarthurfoundation.org/m/6136f12537e70e5b/original/Cities-and-circular-economy-for-food.pdf. (Accessed 12 April 2025).
- Eriksson, M., Bartek, L., Löfkvist, K., Malefors, C. Olsson, M.E., 2021. Environmental assessment of upgrading horticultural side streams—The case of unharvested broccoli leaves. Sustainability (Switzerland), 13. https://doi.org/10.3390/su13105327.
- Eriksson, M. Spångberg, J., 2017. Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarkets. Waste Management, 60, 786-799. https://doi.org/10.1016/j.wasman.2017.01.008.

- Eriksson, M., Strid, I. Hansson, P.A., 2015. Carbon footprint of food waste management options in the waste hierarchy - A Swedish case study. Journal of Cleaner Production, 93, 115-125. https://doi.org/10.1016/j.jclepro.2015.01.026.
- EU, 2018. Product Environmental Footprint Category Rules Guidance.
- FAO, 2011. Global food losses and food waste- Extent, causes and prevention. Rome. Available online at: https://openknowledge.fao.org/server/api/core/bitstreams/10388b16-5f1a-45d0-b690-e89bb78d33bb/content. (Accessed 20 July 2024).
- FAO, 2019. The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction.
- Rome. Licence: CC BY-NC-SA 3.0 IGO. Available online at: http://www.fao.org/3/ca6030en/ca6030en.pdf. (Accessed 14 March 2024).
- Gallo, M., Arrighi, G., Moreschi, L., Del Borghi, A., Athanassiou, A. Perotto, G., 2022. Life Cycle Assessment of a Circular Economy Process for Tray Production via Water-Based Upcycling of Vegetable Waste. ACS Sustainable Chemistry and Engineering, 10, 13936-13944. https://doi.org/10.1021/acssuschemeng.2c02942.
- García-Velásquez, C. van der Meer, Y., 2023. Mind the Pulp: Environmental and economic assessment of a sugar beet pulp biorefinery for biobased chemical production. Waste Management, 155, 199-
- 210. https://doi.org/10.1016/j.wasman.2022.10.038.
- Goossens, Y., Leverenz, D. Kuntscher, M., 2022. Waste-tracking tools: A business case for more sustainable and resource efficient food services. Resources, Conservation and Recycling Advances,
- 15. https://doi.org/10.1016/j.rcradv.2022.200112.
- Goossens, Y., Schmidt, T.G. Kuntscher, M., 2020. Evaluation of food waste prevention measures-the use
- of fish products in the food service sector. Sustainability (Switzerland), 12. https://doi.org/10.3390/su12166613.
- Goyal, S., Ott, D., Liebscher, J., Höfling, D., Müller, A., Dautz, J., Gutzeit, H.O., Schmidt, D. Reuss, R., 2021.
- Sustainability Analysis of Fish Feed Derived from Aquatic Plant and Insect. Sustainability, 13. https://doi.org/10.3390/su13137371.
- Gruber, L.M., Brandstetter, C.P., Bos, U., Lindner, J.P. Albrecht, S., 2015. LCA study of unconsumed food and the influence of consumer behavior. The International Journal of Life Cycle Assessment, 21, 773-784. https://doi.org/10.1007/s11367-015-0933-4.
- Ioannidou, S.M., Filippi, K., Kookos, I.K., Koutinas, A. Ladakis, D., 2022. Techno-economic evaluation and life cycle assessment of a biorefinery using winery waste streams for the production of succinic acid and value-added co-products. Bioresour Technol, 348, 126295. https://doi.org/10.1016/j.biortech.2021.126295.
- ISO, 2006. ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines. https://www.iso.org/standard/38498.html.
- ISO, 2012. ISO TR 14049:2012: Environmental management – Life cycle assessment – Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis.
- Khanpit, V.V., Tajane, S.P. Mandavgane, S.A., 2023. Technoeconomic and life cycle analysis of soluble dietary fiber concentrate production from waste orange peels. Waste Management, 155, 29-39. https://doi.org/10.1016/j.wasman.2022.10.036.
- Laso, J., García-Herrero, I., Margallo, M., Vázquez-Rowe, I., Fullana, P., Bala, A., Gazulla, C., Irabien, Á. Aldaco, R., 2018. Finding an economic and environmental balance in value chains based on circular economy thinking: An eco-efficiency methodology applied to the fish canning industry. Resources, Conservation and Recycling, 133, 428-437. https://doi.org/10.1016/j.resconrec.2018.02.004.

- Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T.H. Hauschild, M.Z., 2014. Review of LCA studies of solid waste management systems--part II: methodological guidance for a better practice. Waste Management, 34, 589-606. https://doi.org/10.1016/j.wasman.2013.12.004.
- Lehn, F., Goossens, Y. Schmidt, T., 2023. Economic and environmental assessment of food waste reduction measures – Trialing a time-temperature indicator on salmon in HelloFresh meal boxes. Journal of Cleaner Production, 392. https://doi.org/10.1016/j.jclepro.2023.136183.
- Lévesque, J., Perreault, V. Mikhaylin, S., 2023. Food waste environmental impact assessment as leverage to better guide restaurants toward improving their sustainability. International Journal of Gastronomy and Food Science, 33. https://doi.org/10.1016/j.ijgfs.2023.100742.
- Lindfors, L.G., Christiansen, K., Hoffman, L., Virtanen, Y., Juntilla, N., Hanssen, O.J., Rønning, A., Ekvall,
- T.a. Finnveden, G., 1995. Nordic Guidelines on Life Cycle Assessment.
- Loyola, C., Papadimitriou, C. Dettling, J., 2021. LCA of waste-to-feed diets for laying hens. Available online at: https://www.worldwildlife.org/publications/lca-of-waste-to-feed-diets-for-laying-hens. (Accessed 13 June 2024).
- Lugo, S.D.R., Kimita, K. Nishino, N., 2022. Circular Food Economy framework: Challenges and initiatives. Procedia CIRP, 112, 28-33. https://doi.org/10.1016/j.procir.2022.09.019.
- Mariana, O.S., Alzate, C. Ariel, C., 2021. Comparative environmental life cycle assessment of orange peel waste in present productive chains. Journal of Cleaner Production, 322. https://doi.org/10.1016/j.jclepro.2021.128814.
- Meier, T., von Borstel, T., Welte, B., Hogan, B., Finn, S.M., Bonaventura, M., Friedrich, S., Weber, K. de Teran, T.D., 2021. Food waste in healthcare, business and hospitality catering: Composition, environmental impacts and reduction potential on company and national levels. Sustainability (Switzerland), 13. https://doi.org/10.3390/su13063288.
- Mondello, G., Salomone, R., Ioppolo, G., Saija, G., Sparacia, S. Lucchetti, M., 2017. Comparative LCA of Alternative Scenarios for Waste Treatment: The Case of Food Waste Production by the Mass-Retail Sector. Sustainability, 9. https://doi.org/10.3390/su9050827.
- Mosna, D., Bottani, E., Vignali, G. Montanari, R., 2021. Environmental benefits of pet food obtained as a result of the valorisation of meat fraction derived from packaged food waste. Waste Management, 125, 132-144. https://doi.org/10.1016/j.wasman.2021.02.035.
- Munagala, M., Shastri, Y., Nalawade, K., Konde, K. Patil, S., 2021. Life cycle and economic assessment of sugarcane bagasse valorization to lactic acid. Waste Management, 126, 52-64. https://doi.org/10.1016/j.wasman.2021.02.052.
- Nikkhah, A., Firouzi, S., Dadaei, K. Van Haute, S., 2021. Measuring Circularity in Food Supply Chain Using Life Cycle Assessment; Refining Oil from Olive Kernel. Foods, 10. https://doi.org/10.3390/foods10030590.
- Ojha, S., Bussler, S. Schluter, O.K., 2020. Food waste valorisation and circular economy concepts in insect production and processing. Waste Manag, 118, 600-609. https://doi.org/10.1016/j.wasman.2020.09.010.
- Oldfield, T.L., White, E. Holden, N.M., 2016. An environmental analysis of options for utilising wasted food and food residue. Journal of Environmental Management, 183, 826-835. https://doi.org/10.1016/j.jenvman.2016.09.035.
- Omolayo, Y., Feingold, B.J., Neff, R.A. Romeiko, X.X., 2021. Life cycle assessment of food loss and waste in the food supply chain. Resources, Conservation and Recycling, 164. https://doi.org/10.1016/j.resconrec.2020.105119.

- Ramos, J.S. Ferreira, A.F., 2022. Techno-economic analysis and life cycle assessment of olive and wine industry co-products valorisation. Renewable and Sustainable Energy Reviews, 155. https://doi.org/10.1016/j.rser.2021.111929.
- Rebolledo-Leiva, R., Sillero, L., Moreira, M.T. González-García, S., 2023. Identifying the environmental hotspots of dietary fibres extraction from chickpea hull. Food and Bioproducts Processing, 142, 59-
- 69. https://doi.org/10.1016/j.fbp.2023.09.004.
- Ríos-Fuentes, B., Rivas-García, P., Estrada-Baltazar, A., Rico-Martínez, R., Miranda-López, R. Botello-Álvarez, J.E., 2022. Life cycle assessment of frozen broccoli processing: Environmental mitigation scenarios. Sustainable Production and Consumption, 32, 27-34. https://doi.org/10.1016/j.spc.2022.04.001.
- Salemdeeb, R., Font Vivanco, D., Al-Tabbaa, A. zu Ermgassen, E.K.H.J., 2017a. A holistic approach to the environmental evaluation of food waste prevention. Waste Management, 59, 442-450. https://doi.org/10.1016/j.wasman.2016.09.042.
- Salemdeeb, R., Zu Ermgassen, E.K., Kim, M.H., Balmford, A. Al-Tabbaa, A., 2017b. Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. Journal of Cleaner Production, 140, 871-880. https://doi.org/10.1016/j.jclepro.2016.05.049.
- Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S. Savastano, D., 2017. Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens. Journal of Cleaner Production, 140, 890-905. https://doi.org/10.1016/j.jclepro.2016.06.154.
- Santiago, B., Feijoo, G., Moreira, M.T. González-García, S., 2021. Identifying the sustainability route of asparagus co-product extraction: From waste to bioactive compounds. Food and Bioproducts Processing, 129, 176-189. https://doi.org/10.1016/j.fbp.2021.08.005.
- Sasaki, Y., Orikasa, T., Nakamura, N., Hayashi, K., Yasaka, Y., Makino, N., Shobatake, K., Koide, S. Shiina, T., 2022a. Determination of the most environmentally friendly packaging for peach during transportation by modeling the relationship between food loss reduction and environmental impact. Journal of Food Engineering, 331. https://doi.org/10.1016/j.jfoodeng.2022.111120.
- Sasaki, Y., Orikasa, T., Nakamura, N., Hayashi, K., Yasaka, Y., Makino, N., Shobatake, K., Koide, S. Shiina, T., 2022b. Optimal packaging for strawberry transportation: Evaluation and modeling of the relationship between food loss reduction and environmental impact. Journal of Food Engineering,
- 314. https://doi.org/10.1016/j.jfoodeng.2021.110767.
- Schott, A.B.S. Andersson, T., 2015. Food waste minimization from a life-cycle perspective. Journal of Environmental Management, 147, 219-226. https://doi.org/10.1016/j.jenvman.2014.07.048.
- Schrijvers, D.L., Loubet, P. Sonnemann, G., 2016. Developing a systematic framework for consistent allocation in LCA. The International Journal of Life Cycle Assessment, 21, 976-993. https://doi.org/10.1007/s11367-016-1063-3.
- Settier-Ramirez, L., López-Carballo, G., Hernandez-Muñoz, P., Tinitana-Bayas, R., Gavara, R. Sanjuán, N., 2022. Assessing the environmental consequences of shelf life extension: Conventional versus active packaging for pastry cream. Journal of Cleaner Production, 333. https://doi.org/10.1016/j.jclepro.2021.130159.
- Shrivastava, C., Crenna, E., Schudel, S., Shoji, K., Onwude, D., Hischier, R. Defraeye, T., 2022. To Wrap Or to Not Wrap Cucumbers? Frontiers in Sustainable Food Systems, 6. https://doi.org/10.3389/fsufs.2022.750199.
- Siddique, S., Grassauer, F., Arulnathan, V., Sadiq, R. Pelletier, N., 2024. A review of life cycle impacts of different pathways for converting food waste into livestock feed.

Sustainable Production and Consumption, 46, 310-323. https://doi.org/10.1016/j.spc.2024.02.023.

- Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R. Azapagic, A., 2020. Assessing the economic and environmental sustainability of household food waste management in the UK: Current situation and future scenarios. Science of the Total Environment, 710. https://doi.org/10.1016/j.scitotenv.2019.135580.
- Smetana, S., Palanisamy, M., Mathys, A. Heinz, V., 2016. Sustainability of insect use for feed and food: Life Cycle Assessment perspective. Journal of Cleaner Production, 137, 741-751. https://doi.org/10.1016/j.jclepro.2016.07.148.
- Smetana, S., Schmitt, E. Mathys, A., 2019. Sustainable use of Hermetia illucens insect biomass for feed and food: Attributional and consequential life cycle assessment. Resources, Conservation and Recycling, 144, 285-296. https://doi.org/10.1016/j.resconrec.2019.01.042.
- Sundin, N., Bartek, L., Persson Osowski, C., Strid, I. Eriksson, M., 2023. Sustainability assessment of surplus food donation: A transfer system generating environmental, economic, and social values. Sustainable Production and Consumption, 38, 41-54. https://doi.org/10.1016/j.spc.2023.03.022.
- Sundin, N., Persson Osowski, C., Strid, I. Eriksson, M., 2022. Surplus food donation: Effectiveness, carbon footprint, and rebound effect. Resources, Conservation and Recycling, 181. https://doi.org/10.1016/j.resconrec.2022.106271.
- Tedesco, D.E.A., Conti, C., Lovarelli, D., Biazzi, E. Bacenetti, J., 2019. Bioconversion of fruit and vegetable waste into earthworms as a new protein source: The environmental impact of earthworm meal production. Science of the Total Environment, 683, 690-698. https://doi.org/10.1016/j.scitotenv.2019.05.226.
- Tonini, D., Albizzati, P.F. Astrup, T.F., 2018. Environmental impacts of food waste: Learnings and challenges from a case study on UK. Waste Management, 76, 744-766. https://doi.org/10.1016/j.wasman.2018.03.032.
- Tsouko, E., Pilafidis, S., Dimopoulou, M., Kourmentza, K. Sarris, D., 2023. Bioconversion of underutilized brewing by-products into bacterial cellulose by a newly isolated Komagataeibacter rhaeticus strain: A preliminary evaluation of the bioprocess environmental impact. Bioresource Technology, 387. https://doi.org/10.1016/j.biortech.2023.129667.
- Ulmer, M., Smetana, S. Heinz, V., 2020. Utilizing honeybee drone brood as a protein source for food products: Life cycle assessment of apiculture in Germany. Resources, Conservation and Recycling,
- 154. https://doi.org/10.1016/j.resconrec.2019.104576.
- UN, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. Available online at: https://sdgs.un.org/2030agenda. (Accessed 20 October 2023).
- van Zanten, H.H.E., Mollenhorst, H., Oonincx, D.G.A.B., Bikker, P., Meerburg, B.G. de Boer, I.J.M., 2015.
- From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed. Journal of Cleaner Production, 102, 362-369. https://doi.org/10.1016/j.jclepro.2015.04.106.
- Vanapalli, K.R., Bhar, R., Maity, S.K., Dubey, B.K., Kumar, S. Kumar, V., 2023. Life cycle assessment of fermentative production of lactic acid from bread waste based on process modelling using pinch technology. Science of the Total Environment, 905. https://doi.org/10.1016/j.scitotenv.2023.167051.
- Vigil, M., Pedrosa-Laza, M., Cabal, J.V.A. Ortega-Fernández, F., 2020. Sustainability analysis of active packaging for the fresh cut vegetable industry by means of attributional & consequential life cycle assessment. Sustainability (Switzerland), 12. https://doi.org/10.3390/su12177207.

- Villanova-Estors, R., Murcia-Velasco, D.A., Correa-Guimarães, A., López-Carballo, G., Hernández-Muñoz, P., Gavara, R. Navas-Gracia, L.M., 2023. Environmental consequences of shelf life extension: Conventional versus active packaging for fresh-cut salads. Agronomy, 13. https://doi.org/10.3390/agronomy13112749.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21, 1218-1230. https://doi.org/10.1007/s11367-016-1087-8.
- Wikström, F., Williams, H., Verghese, K. Clune, S., 2014. The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies - a neglected topic. Journal of Cleaner Production, 73, 100-108. https://doi.org/10.1016/j.jclepro.2013.10.042.
- Winans, K., Marvinney, E., Gillman, A. Spang, E., 2020. An Evaluation of On-Farm Food Loss Accounting in Life-Cycle Assessment (LCA) of Four California Specialty Crops. Frontiers in Sustainable Food Systems, 4. https://doi.org/10.3389/fsufs.2020.00010.
- Wohner, B., Gabriel, V.H., Krenn, B., Krauter, V. Tacker, M., 2020. Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup. Science of the Total Environment, 738. https://doi.org/10.1016/j.scitotenv.2020.139846.
- WRI WBCSD, 2011. Product Life Cycle Accounting and Reporting Standard. Available online at: https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf. (Accessed 20 April 2025).
- Yano, J., Yanagawa, R., Koshiba, J., Hirai, Y. Sakai, S., 2023. Greenhouse gas reduction potential by household waste prevention. Journal of Material Cycles and Waste Management, 25, 1792-1806. https://doi.org/https://doi.org/10.1007/s10163-023-01647-2.
- Yokokawa, N., Kikuchi-Uehara, E., Sugiyama, H. Hirao, M., 2018. Framework for analyzing the effects of packaging on food loss reduction by considering consumer behavior. Journal of Cleaner Production, 174, 26-34. https://doi.org/10.1016/j.jclepro.2017.10.242.
- Zhang, B.Y., Tong, Y., Singh, S., Cai, H. Huang, J.Y., 2019. Assessment of carbon footprint of nano-packaging considering potential food waste reduction due to shelf life extension. Resources, Conservation and Recycling, 149, 322-331. https://doi.org/10.1016/j.resconrec.2019.05.030.
- Zhang, H., Hortal, M., Dobon, A., Bermudez, J.M. Lara-Lledo, M., 2015. The effect of active packaging on minimizing food losses: Life cycle assessment (LCA) of essential oil component-enabled packaging for fresh beef. Packaging Technology and Science, 28, 761-774. https://doi.org/10.1002/pts.2135.

Enabling Circularity in 3D Printing: Life Cycle Sustainability Assessment of Recycled PLA Gear Components

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Abstract

This study evaluates the technical and life cycle sustainability of the use of post-consumer recycled polylactic acid (rPLA) in fused deposition modelling (FDM) for 3D-printed gear components. Five material compositions ranging from 0% to 100% rPLA were assessed for mechanical and functional performance, alongside a life cycle sustainability assessment (LCSA) integrating environmental (ELCA), economic (LCC), and social (SLCA) indicators for determining the sustainability score for each blend. Mechanical testing showed a slight reduction with higher rPLA ratios, but all blends retained functional gear performance. V50:R50 achieved the highest sustainability score (-1.29), offering a balanced trade-off. Findings support the viability of rPLA in non-critical applications and highlight the need for quality assurance in circular additive manufacturing.

Keywords: recycled PLA, circular economy, additive manufacturing, FDM, life cycle sustainability, performance gap, LCSA

Introduction

This paper assesses the life cycle sustainability implications of additive manufacturing as a replacement for subtractive manufacturing. Unlike subtractive manufacturing, which removes material from a solid block through cutting or machining, additive manufacturing builds components layer by layer from digital models, offering potential reductions in material waste and energy use (Hasan et al., 2024b). Whilst manufacturing processes offer socio-economic benefits mainly in terms of jobs and economic growth, it also causes significant environmental impacts and other associated socio-economic problems, which cannot be ignored (Jayawardane et al., 2023b). Traditional manufacturing contributes substantially to global greenhouse gas (GHG) emissions, energy consumption, and resource depletion (Panagiotopoulou et al., 2022, Hasan et al., 2024b, Javaid et al., 2021). According to the IPCC (2022), industrial activity accounts for approximately 24% of global emissions, second only to the energy sector. In response to climate change and resource scarcity, sustainable manufacturing practices are becoming a strategic imperative.

Additive manufacturing (AM), also known as 3D printing, provides an opportunity to rethink production in a more sustainable and decentralised manner (Panagiotopoulou et al., 2022, Hasan et al., 2024b, Javaid et al., 2021). Recently, polylactic acid (PLA) has gained attention as a filament for fused deposition modelling due to its biobased origin, biodegradability, and compatibility with household printing environments (Khosravani et al., 2022, Hasan et al., 2024b, Jayawardane et al., 2023a). While PLA is marketed as biodegradable, it requires industrial composting conditions to degrade effectively (Hsueh et al., 2021, Hasan et al., 2025, Hasan et al., 2024b). Although PLA is derived from renewable feedstocks, its limited biodegradability under typical landfill or domestic conditions means that improperly discarded items may persist in the environment, adding to plastic waste streams. As PLA use grows in household applications, the kerbside collection and recycling of the post-consumer PLA could lead to environmental concerns. The mechanical recycling of PLA into new filament for use in 3D printing can address the waste management challenge (Hsueh et al., 2021, Hasan et al., 2025, Hasan et al., 2024b).

The technical performance alone does not determine the sustainability of rPLA. As there are environmental impact, economic feasibility, and social contribution. Assessing these aspects in isolation risks overlooking key trade-offs and synergies. To address this, a life cycle sustainability assessment (LCSA) framework is employed, integrating environmental life cycle assessment (ELCA), life cycle costing (LCC), and social life cycle assessment (SLCA). This comprehensive approach enables the evaluation of rPLA across the full product life cycle, from resource extraction to end-of-life, capturing impacts on climate, cost, and community (Hasan et al., 2024b, Chang et al., 2017, Ahmad and Wong, 2019, Aybar et al., 2025, Janjua et al., 2021, Lim and Biswas, 2018). This paper thus applies LCSA to rPLA mechanical gear components, bridging a critical research gap between technical and sustainability performance. It supports evidence-based material selection in additive manufacturing and informs strategies for advancing circular, low-impact production systems.

Methodology

Study Design

Assessing the technical performance is crucial prior to determining the sustainability performance (Janjua, 2021). The study consisted of two integrated phases:

i. Technical Evaluation: Mechanical testing of 3D-printed gears and tensile specimens made from various rPLA-vPLA blends.
ii. Sustainability Evaluation: LCSA using environmental, economic, and social indicators, or triple bottom line indicators.

Technical Assessment

Material Preparation and Blending

Virgin PLA pellets were sourced from AURARUM (Australia). Post-consumer PLA waste was collected from local cafes and public bins in Perth. The waste included failed 3D prints, PLA packaging, and disposable PLA cups. After washing with mild detergent and sun drying for 12 hours, the waste was shredded using a local granulator into flakes of approximately 5 mm (Hasan et al., 2024a, Hasan et al., 2025). Five PLA compositions were prepared: V100:R0, V75:R25, V50:R50, V25:R75, and V0:R100. The flakes and virgin PLA pellets were mixed at the designated weight ratios and extruded using a Filabot EX6 extruder. The extrusion temperature zones were adjusted to accommodate viscosity differences between blends. Zone temperatures ranged from 170-180°C, with the feed zone at 40°C. Filament was extruded to a nominal diameter of 1.75 ± 0.05 mm and manually spooled using magnetic guides. All blends were extruded under controlled ambient laboratory conditions (24 ± 2°C, 34 ± 2% RH) (Hasan et al., 2024a, Hasan et al., 2025).

3D Printing and Mechanical Testing

The tensile specimens followed ASTM D638-22 Type IV geometry. CAD models were sliced using ideaMaker 4.3.3 and printed on a Raise3D E2 printer using a 0.4 mm nozzle, 0.3 mm layer height, 215°C nozzle temperature, and 100% rectilinear infill. Five specimens per blend were printed in horizontal orientation. Tensile tests were conducted using a Shimadzu AGS-X universal testing machine at 5 mm/min crosshead speed. Ultimate tensile strength, modulus of elasticity, and elongation at break were recorded.

In the second stage, spur gears were modelled and printed with the same parameters. Gear service life was evaluated on a custom-built test rig applying 1.5 Nm torque at 1000 rpm in a back-to-back setup. Operational life was determined by the time to first visual failure (e.g., tooth wear, fracture, slippage).

Life Cycle Sustainability Assessment

The life cycle sustainability assessment (LCSA) was employed to holistically evaluate the performance of recycled PLA (rPLA) gear components across environmental, economic, and social dimensions. Unlike traditional assessments focused solely on mechanical or environmental performance, LCSA is particularly relevant to circular additive manufacturing, where material reuse is evaluated for performance as well as for its broader impacts on cost, emissions, and community benefits (Janjua, 2021, Biswas and John, 2022).

A functional unit (FU) of one gear over its operational lifetime was used as the basis for all assessments. The system boundary was defined as "garbage-to-gear (g2g)", capturing the entire product chain from PLA waste collection, material recovery, filament extrusion, and 3D printing, through to functional use and end-of-life treatment.

Life Cycle Inventory (LCI) and Data Sources

Primary inventory data were gathered from lab-scale trials including shredding, drying, extrusion, filament blending, CAD design, and FDM printing. This included energy consumption, material quantities, operational durations, and equipment loads specific to a desktop-scale production environment. Secondary data on emission factors, material background flows, and water use were sourced from the Australian LCI databases to represent the local situation. LCI inputs for LCC included raw material prices, local electricity rates, labour wages, equipment depreciation, and transport distances, adjusted to 2024 price indices. Social data were derived through direct stakeholder interviews, field observations of community-based recycling activities, and local labour statistics. Environmental, economic and social indicators were calculated by using ELCA, LCC and SLCA, respectively.

Indicator Selection and Weighting

To determine the relevance and weight of each indicator, a structured survey was conducted among 25 stakeholders with demonstrated expertise in additive manufacturing, sustainable materials, and polymer recycling. The group included academics, sustainability researchers, industry professionals, and policy advisors familiar with recycled polymer applications. Participants were asked to rank each indicator based on two criteria: contextual importance in small-scale 3D printing using recycled PLA, and practical measurability. Ratings were given on a four-point Likert scale, from 1 (less important) to 4 (most important). Sixteen sustainability indicators (KPI) were systematically selected through the survey to determine the triple bottom line (TBL) objectives, as more than 50% of the respondents deemed them relevant for assessing the sustainability of rPLA-based gears (Lim and Biswas, 2018). The ratings given by the experts or stakeholders were converted to weights (Janjua et al., 2020, Biswas and John, 2022).

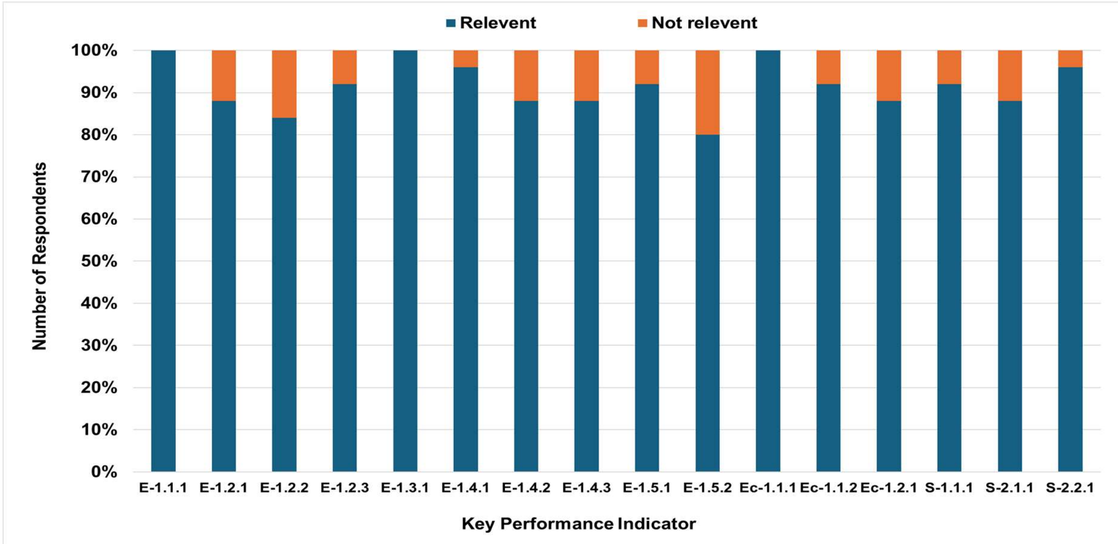


Figure 1. Relevance rankings for TBL KPIs (E-1.1 Global Warming Potential, E-1.2 Acidification Potential, E-2.1 Eutrophication Potential, E-2.2 Freshwater Aquatic Ecotoxicity, E-3.1 Cumulative Energy Demand, E-3.2 Abiotic Resource Depletion, E-3.3 Water Consumption, E-3.4 Land Use, E-4.1 Human Toxicity, E-4.2 Particulate Matter Formation Potential, Ec-1.1 Life Cycle Cost, Ec-1.2 Carbon Tax Saving, Ec-1.3 Net Benefit, S-1.1 Local Employment, S-2.1 Quality of Life, S-2.2 Workplace Training and Skill Development)

Performance Gap Calculation

To quantify the sustainability performance of rPLA-based gear production, this study applied a structured performance gap analysis approach adapted from Biswas and John (2022). For each of the 16 KPIs, a threshold value (representing optimal performance) and a minimum value (representing the lowest acceptable standard) were established through a review of relevant case studies, national sustainability standards, industry reports, and environmental benchmarks specific to additive manufacturing and polymer recycling in Australia. To visualize ELCA, LCC, and SLCA outcomes and identify hotspots, the calculated value of each KPI was then positioned on a 5-point Likert scale, with two extreme ends: a score of 5 indicated that the required level of performance was met or a threshold value, and a score of 1 representing performance at the minimum benchmark level. The position of the calculated value of a KPI on a 5-point Likert scale is determined by the equations below:

$$\text{Likert}_{KKKKKK} = 1 + \left(\frac{\text{Upper}_{KKKKKK} - \text{MV}_{KKKKKK}}{\text{Interval}_{KKKKKK}}\right), \text{ where Interval}_{KKKKKK} = \frac{\text{Min}_{KKKKKK} - \text{TV}_{KKKKKK}}{5}$$

(Equation 1)

The performance gap for each KPI, which is the gap between the threshold and calculated value of a KPI, was then determined as the deviation from the threshold score (Biswas and John, 2022):

$$\text{Gap}_{KKKKKK} = \text{Likert}_{KKKKKK} - 5 \qquad \text{(Equation 2)}$$

This gap was multiplied by the indicator’s weight (from stakeholder input) to obtain a weighted KPI gap (Biswas and John, 2022)**:**

$$\text{WGap}_{KKKKKK} = \text{Gap}_{KKKKKK} \times w_{KKKKKK} \qquad \text{(Equation 3)}$$

Next, each headline-performance indicator (HPI) was calculated by aggregating the weighted KPI gaps within the HPI group (Biswas and John, 2022):

$$\mathrm{HPI}_{\sim} = \frac{\sum_{kk=1}^{nn} \mathrm{WGap}_{kk-h}}{\sum_{kk=1}^{nn} WW_{kk-h}} \qquad \text{(Equation 4)}$$

Each sustainability dimension (environmental, economic, social) was computed as the average of its HPI scores (Biswas and John, 2022):

$$\mathrm{TBL}_{dd} = \frac{\sum_{h=1}^{mm_{dd}} \mathrm{HPI}_{h-dd}}{\mathrm{m}_{dd}} \qquad \text{(Equation 5)}$$

Finally, the overall sustainability score (SS) was derived as the average of the three TBL scores (Biswas and John, 2022):

$$SSSS = \frac{\mathrm{Gap}_{eennee} + \mathrm{Gap}_{eeeeee} + \mathrm{Gap}_{sseeee}}{3} \qquad \text{(Equation 6)}$$

This method enabled the comparison of material configurations through a single composite sustainability score.

Results

Mechanical Performance

Mechanical testing revealed a progressive decline in performance with increasing rPLA content, primarily attributed to molecular chain degradation, reduced interlayer adhesion, and possible contamination from previous processing cycles. The tensile properties of the PLA blends exhibited a clear composition-dependent trend (Figure 2). The virgin blend (V100:R0) achieved the highest UTS of 59.05 MPa and yield strength of 37.69 MPa, while V75:R25 and V50:R50 maintained comparable strengths (53.45 MPa and 50.78 MPa), indicating adequate integrity up to 50% recycled content. Beyond this threshold, performance dropped sharply, with V25:R75 and V0:R100 recording UTS values of 37.64 MPa and 30.49 MPa, respectively. Similar declining trends were observed for modulus and elongation at break.

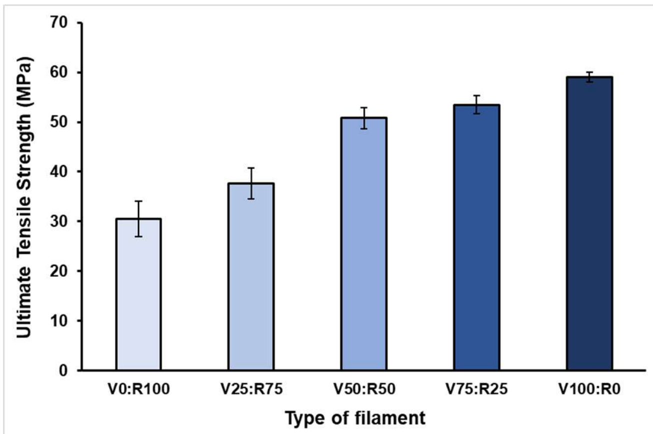


Figure 2. Ultimate tensile strength of the tested specimens

Gears printed from all blends performed well under test conditions. V100:R0 lasted 142 hours, while V50:R50 lasted 138 hours. The V0:R100 gear lasted 114 hours before showing tooth deformation. Additionally, wear patterns on gear teeth showed greater abrasion and localised plastic deformation in higher rPLA samples. These wear mechanisms are consistent with the previous studies on polymer recycling and surface integrity degradation (Polanec et al., 2023, Muratovic, 2025). These findings align with microstructural observations, where scanning electron microscopy (SEM) revealed voids and interlayer inconsistencies in rPLA-dominant prints. In contrast, the V50:R50 blend exhibited a uniform layered structure with fewer microcracks.

The performance of recycled blends suggests that while full substitution (V0:R100) may introduce dimensional or interfacial weaknesses, a balanced composition like V50:R50 demonstrates an optimal balance between mechanical integrity and material circularity. It retains sufficient interlayer bonding and minimises brittleness by compensating degraded molecular chains with more stable virgin segments. These results are consistent with literature findings showing that the adverse effects of recycled PLA degradation can be mitigated through blending strategies or the use of chain extenders.

LCSA Assessment

Life cycle sustainability assessment (LCSA) was conducted for all rPLA–based gear configurations after verifying their mechanical performance through tensile and functional testing. This approach integrates environmental, economic, and social criteria, enabling a holistic comparison of materials beyond technical performance. The results were synthesised using a weighted performance gap method to generate an overall sustainability score for each configuration.

Environmental Life Cycle Assessment (ELCA)

The ELCA showed that rPLA-rich blends had significantly lower global warming potential (GWP) and cumulative energy demand (CED) (Figure 3). V0:R100 produced 1.12 kg CO_2-eq, compared to 67 kg CO_2-eq for V100:R0. CED was 12.8 MJ for V0:R100 vs. 39.0 MJ for virgin PLA. Eutrophication and water use were slightly higher in rPLA-rich blends due to the water-intensive cleaning step, but the overall impact remained lower than virgin PLA. Abiotic resource depletion (ARD) showed considerable improvement with rPLA blends. V0:R100 reduced ARD by 62% compared to virgin PLA. Toxicity-related categories, such as human toxicity and terrestrial ecotoxicity, were also lower for rPLA due to the avoidance of new polymer synthesis. However, variability in source material and cleaning processes can affect consistency. These results highlight that even partial substitution of vPLA with rPLA yields substantial environmental benefits. V50:R50 achieved a 35-40% reduction in climate-related and resource depletion indicators, showing diminishing returns beyond 50% rPLA in terms of environmental impact per unit gear due to the extra energy required for processing poorly flowing rPLA.

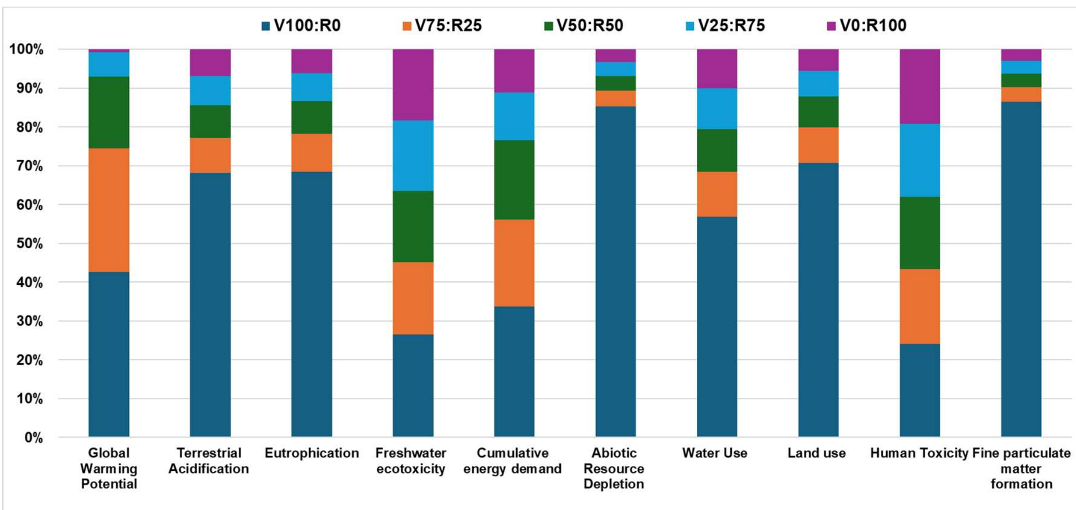


Figure 3. Environmental impact results for each material configuration

Life Cycle Costing (LCC)

Material cost for rPLA was AUD 2/kg, compared to AUD 29/kg for virgin PLA. The V50:R50 gear had the lowest total production and operational cost of AUD 10.43/unit. V100:R0 cost AUD 11.79/ unit, and V0:R100 was AUD 30.46/unit. Increased operational costs in rPLA-rich blends were due to energy use in extrusion and the replacement of increased number of gears during the 3D printing process. Labour cost contributed a significant share to rPLA production, as labour-intensive sorting and cleaning accounted for 25% of the labour time of the total production period. For V0:R100, repeated extrusions were needed to achieve filament uniformity, resulting in increased energy use, higher failed prints and nozzle clogs, so the increased operational expenditures increased, although the feedstock cost is low. In contrast, making blended solutions like V50:R50 is economically optimal. This reflects a break-even point where material savings offset the additional processing time, consistent with circular economy costing studies that stress the importance of balancing feedstock efficiency with production scalability.

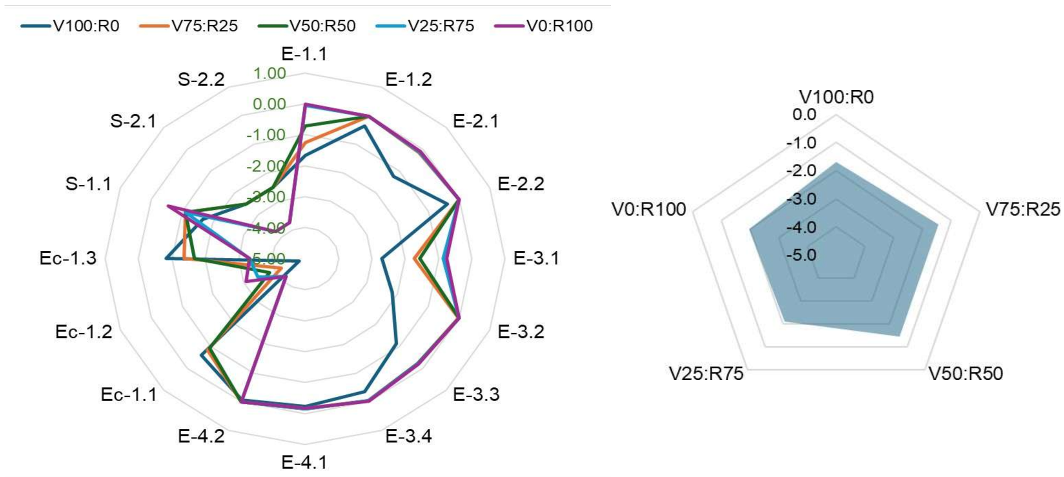
Social Life Cycle Assessment (SLCA)

The decentralised recycling process created jobs in collection, sorting, and filament production. Local employment (full-time equivalent- FTE) was the highest in V0:R100 due to increased labour inputs. However, workplace training scores for rPLA were lower, reflecting the limited formal training and reduced practical engagement associated with tasks like waste sorting and filament processing, which resulted in minimal skill development opportunities for workers. Indicators related to quality of life highlighted the need for enhanced social engagement and community empowerment, particularly through the provision of structured training programs, safety protocols, and pathways to long-term job stability for individuals involved in grassroots recycling initiatives. Qualitative interviews revealed that the workers involved in PLA collection and filament production perceived their roles as contributing positively to environmental stewardship, which fostered a sense of purpose and increased motivation despite the limited formal training received. Blended filament like V50:R50 offered the best balance between process complexity and job creation, with manageable training requirements and lower failure rates compared to full rPLA usage. Such setups are better suited for skill-building programs and regional sustainability hubs.

Integrated Sustainability Score

To consolidate findings across the environmental, economic, and social dimensions, an integrated sustainability score was computed using the weighted performance gap method. As outlined in Section 2.4.3, each KPI was assigned a Likert score (1-5) based on its position between a defined threshold (ideal) and minimum (worst-case) value. Gaps were calculated as the deviation from the optimal score (5), then weighted by stakeholder-assigned importance and aggregated through head performance indicators (HPIs) and sustainability pillars (Figure 4a).

The final score reflects the average of environmental, economic, and social performance gaps. Higher (less negative) scores indicate stronger overall sustainability. Among the five evaluated gear types, the V50:R50 blend achieved the most favourable overall score with reduced gap (-1.29) (Figure 4b), reflecting a well-balanced performance across all three dimensions. Its moderately high tensile strength (43.08 MPa), stable gear service life, lower embodied energy, and support for decentralised labour contributed to the high sustainability score. Additionally, V50:R50 benefited from lower failure rates and consistent extrusion quality, making it suitable for circular workflows with minimal process adaptation. In contrast, V0:R100, while achieving the lowest GWP and resource depletion scores, received the weakest integrated score (-1.89). This was due to the reduced level of mechanical performance, non-homogeneous filament quality, and higher replacements, which increased both economic and social impact. The V100:R0 gear, although mechanically robust, scored -1.57, reflecting its higher environmental footprint and minimal contribution to social indicators such as local employment and workplace training.



(a) (b)

Figure 4. (a) Gaps of KPIs, (E-1.1 Global Warming Potential, E-1.2 Acidification Potential, E-2.1 Eutrophication Potential, E-2.2 Freshwater Aquatic Ecotoxicity, E-3.1 Cumulative Energy Demand, E-3.2 Abiotic Resource Depletion, E-3.3 Water Consumption, E-3.4 Land Use, E-4.1 Human Toxicity, E-4.2 Particulate Matter Formation Potential, Ec-1.1 Life Cycle Cost, Ec-1.2 Carbon Tax Saving, Ec-1.3 Net Benefit, S-1.1 Local Employment, S-2.1 Quality of Life, S-2.2 Workplace Training and Skill Development),

(b) Radar chart illustrating the overall sustainability performance of each material configuration.

Radar chart analysis confirmed that V50:R50 had the most balanced profile across the 16 KPIs, avoiding extreme trade-offs. It demonstrated an effective compromise between mechanical reliability and circularity benefits, making it a practical choice for both industrial prototyping and community-based additive manufacturing ecosystems. These findings highlight the value of mid-range blends like V50:R50 and V75:R25, which offer scalable, low-barrier solutions for sustainable 3D printing. They support circularity without requiring significant changes to equipment or material handling practices, and align well with training, economic, and environmental priorities.

Implications for Industry and Policy

The findings of this study provide compelling evidence that incorporating recycled PLA into additive manufacturing workflows offers tangible sustainability benefits without compromising essential functionality. The successful performance of the V50:R50 blend highlights the potential for adopting mid-range rPLA ratios in practical applications, particularly in non-critical mechanical components such as gears, casings, and structural supports. From an industrial perspective, the transition to rPLA requires only modest adaptations to existing FDM setups. Equipment such as desktop extruders and consumer-grade 3D printers can be repurposed for filament recycling with minimal investment. However, the study revealed the importance of consistent feedstock quality and tight process control. Implementing standardised protocols for washing, drying, and re-extrusion can significantly improve filament consistency and reduce print failure rates.

For policymakers, these results underscore the value of supporting decentralised PLA recycling infrastructure. Incentives for community-led collection schemes, makerspaces, and training hubs can stimulate local economies while reducing landfill pressure. Furthermore, including rPLA as a recognised sustainable input in procurement and certification schemes can accelerate its adoption across sectors. Education and outreach also play critical roles. Awareness campaigns targeting students, designers, and engineers can cultivate a culture of material circularity. Integrating hands-on training in material recovery and digital fabrication into educational curricula will help mainstream sustainable design thinking in future generations.

Conclusion

This research confirms the technical and sustainability feasibility of incorporating recycled PLA (rPLA) into additive manufacturing workflows. Mechanical testing showed that PLA blends containing up to 50% rPLA maintained sufficient tensile strength (43.08 MPa for V50:R50 vs. 44.42 MPa for virgin PLA) and gear service life (138 hours vs. 142 hours), with only minor reductions in performance.

The LCSA revealed that rPLA-rich blends significantly reduced environmental impact. The V0:R100 configuration achieved the lowest global warming potential (1.12 kg CO_2-eq) and cumulative energy demand (12.8 MJ), although these gains were offset by higher operational complexity and lower mechanical reliability. Economically, rPLA lowered material costs dramatically, but increased labour and reprocessing demands raised total costs in high-rPLA scenarios. Socially, mid-range blends like V50:R50 created jobs while offering technical engagement and community awareness through recycling initiatives. Among all blends, V50:R50 emerged as the most balanced and sustainable option, achieving the best overall LCSA score (-1.29). It offered reduced emissions, the lowest unit cost (AUD 10.43), high gear reliability, and moderate social benefits, making it an ideal candidate for circular additive manufacturing in both industrial and community contexts.

The LCSA framework proved effective for holistic material evaluation, enabling stakeholders to assess sustainability trade-offs across environmental, economic, and social pillars. By integrating ELCA, LCC, and SLCA into a unified model, this study provides a practical tool for guiding sustainable material decisions in 3D printing. Future research should aim to improve the quality and consistency of high-rPLA blends through better sorting and controlled reprocessing. Expanding the scope of applications to structurally critical parts (support brackets, drone arms), environmentally safe medical products, or thermally demanding components will help further unlock the circular potential of recycled PLA and support the development of more sustainable manufacturing ecosystems.

References

- Ahmad, S. & Wong, K. Y. 2019. Development of weighted triple-bottom line sustainability indicators for the Malaysian food manufacturing industry using the Delphi method. *Journal of Cleaner Production,* 229**,** 1167-1182.
- Aybar, D. M. R., Biswas, W. & John, M. 2025. Development of a Life Cycle Sustainability Assessment Framework for Hemp-Based Building Materials in Australia. *Advances in Environmental and Engineering Research,* 06**,** 1-34.
- Biswas, W. K. & John, M. 2022. *Engineering for Sustainable Development: Theory and Practice,* Newark, United Kingdom, John Wiley & Sons, Incorporated.
- Chang, Y.-J., Neugebauer, S., Lehmann, A., Scheumann, R. & Finkbeiner, M. 2017. Life cycle sustainability assessment approaches for manufacturing. *Sustainable Manufacturing,* 221.
- Hasan, M. R., Davies, I. J., Pramanik, A., John, M. & Biswas, W. K. 2024a. Fabrication and Characterisation of Sustainable 3D-Printed Parts Using Post-Consumer PLA Plastic and Virgin PLA Blends. *Processes,* 12.
- Hasan, M. R., Davies, I. J., Pramanik, A., John, M. & Biswas, W. K. 2024b. Potential of recycled PLA in 3D printing: A review. *Sustainable Manufacturing and Service Economics,* 3.
- Hasan, M. R., Davies, I. J., Pramanik, A., John, M. & Biswas, W. K. 2025. Recycling Post-Consumed Polylactic Acid Waste Through Three-Dimensional Printing: Technical vs. Resource Efficiency Benefits. *Sustainability,* 17.
- Hsueh, M. H., Lai, C. J., Liu, K. Y., Chung, C. F., Wang, S. H., Pan, C. Y., Huang, W. C., Hsieh, C. H. & Zeng, Y. S. 2021. Effects of Printing Temperature and Filling Percentage on the

Mechanical Behavior of Fused Deposition Molding Technology Components for 3D Printing. *Polymers,* 13**,** 2910.

- Ipcc 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- Janjua, S. 2021. *Sustainability Implication of Residential Building Materials Considering Service Life Variability.* Doctor of Philosophy, Curtin University.
- Janjua, S. Y., Sarker, P. K. & Biswas, W. K. 2020. Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings. *J Environ Manage,* 264**,** 110476.
- Janjua, S. Y., Sarker, P. K. & Biswas, W. K. 2021. Sustainability implications of service life on residential
- buildings – An application of life cycle sustainability assessment framework. *Environmental and Sustainability Indicators,* 10.
- Javaid, M., Haleem, A., Singh, R. P., Suman, R. & Rab, S. 2021. Role of additive manufacturing applications towards environmental sustainability. *Advanced Industrial and Engineering Polymer Research,* 4**,** 312-322.
- Jayawardane, H., Davies, I. J., Gamage, J. R., John, M. & Biswas, W. K. 2023a. Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment. *The International Journal of Advanced Manufacturing Technology,* 126**,** 1471-1496.
- Jayawardane, H., Davies, I. J., Gamage, J. R., John, M. & Biswas, W. K. 2023b. Sustainability perspectives – a review of additive and subtractive manufacturing. *Sustainable Manufacturing and Service Economics,* 2.
- Khosravani, M. R., Berto, F., Ayatollahi, M. R. & Reinicke, T. 2022. Characterization of 3D-printed PLA parts with different raster orientations and printing speeds. *Scientific Reports,* 12.
- Lim, C. I. & Biswas, W. K. 2018. Development of triple bottom line indicators for sustainability assessment framework of Malaysian palm oil industry. *Clean Technologies and Environmental Policy,* 20**,** 539-560.
- Muratovic, E. 2025. Lifetime testing of polymer gears. *Polymer Gears.*
- Panagiotopoulou, V. C., Stavropoulos, P. & Chryssolouris, G. 2022. A critical review on the environmental impact of manufacturing: a holistic perspective. *The International Journal of Advanced Manufacturing Technology,* 118**,** 603-625.
- Polanec, B., Glodez, S. & Belsak, A. 2023. Noise Evaluation of Coated Polymer Gears. *Polymers (Basel),* 15.

The Effect of Upcycling and Downcycling on Emission Factors: A Semi-Qualitative Framework for Circular Economy in Industrial Waste Treatment

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Abstract:
The transition to a circular economy presents significant opportunities for reducing environmental impacts through improved waste management practices. This work explores the semi-qualitative effects of upcycling and downcycling on emission factors, focusing on the role of industrial waste treatment in supporting the circular economy. The primary question addressed is: How should emission factors in downstream waste management reflect the different scenarios of upcycling and downcycling within a circular economy framework? In the context of circular economy strategies, upcycling and downcycling represent key waste management pathways with varying environmental consequences. Upcycling, where waste is repurposed into higher-value products, typically leads to reductions in emissions by decreasing the need for raw material extraction and lowering energy consumption. In contrast, downcycling, which involves converting waste into lower-value products, may result in higher emissions, especially when secondary products require more energy-intensive processing or have shorter lifespans.

This paper presents a conceptual framework to guide the understanding of how emission factors should be adjusted in LCA studies to account for these upcycling and downcycling processes. The framework emphasises the importance of considering the full life cycle of both the waste treatment process and the final products, particularly in the context of varying material quality and processing requirements. The paper also highlights the need for consistent and reliable data to accurately reflect the impacts of these circular economy strategies. By offering a theoretical approach to understanding emission factors in the circular economy, this paper aims to support future research and policy development, providing a basis for companies and researchers to better integrate upcycling and downcycling into sustainable waste management practices.

Keywords: Upcycling, downcycling, emission factors, industrial waste treatment, circular economy, Life Cycle Assessment (LCA, sustainability

Literature Review

The circular economy departs from the linear "take-make-dispose" model, promoting regenerative systems that close material loops and minimize waste (Geissdoerfer et al., 2017. It redefines waste as a resource within strategies such as recycling, reuse, remanufacturing, upcycling, and downcycling (Kirchherr et al., 2017. Upcycling enhances material quality and lifespan while reducing reliance on virgin resources (McDonough & Braungart, 2002, whereas downcycling yields lower-quality outputs with diminished usability and higher energy demands (Geyer et al., 2016. Waste valorisation further supports circularity by transforming waste into valuable materials, energy, or products through recovery, recycling, and upcycling (van Fan et al., 2021. Upcycling remains the preferred route for maintaining material value and minimizing environmental impact (Rossi et al., 2020, while downcycling provides limited circular benefits and often leads to material degradation over successive cycles (Allwood et al., 2011. Life Cycle Assessment (LCA, standardized under ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b, evaluates environmental impacts across a product's life cycle using emission factors (EFs that quantify emissions per unit of activity. However, common databases such as Ecoinvent lack differentiation between upcycling and downcycling in terms of material quality, energy use, and longevity (Wernet et al., 2016. This uniform treatment misrepresents circularity assessments and overlooks the distinct environmental performance of upcycled versus downcycled materials (Laurent et al., 2012. Despite growing recognition of this issue, existing standards and studies offer no consistent method for integrating material value retention into EF calculations (Elia et al., 2017; Prendeville et al., 2014. To address this gap, this paper proposes a conceptual framework designed to adjust emission factors for downstream waste management by incorporating material quality, value retention, and potential for future loops. By differentiating upcycling and downcycling in emission factor reporting, this framework aims to support more precise environmental assessments, inform policy and industry practices, and promote higher-value circular strategies.

Conceptual Framework: Emission Factors in Upcycling and Downcycling

Current life cycle assessment (LCA) practices typically rely on standardized emission factors from databases such as ecoinvent to account for downstream waste management processes. While these datasets provide a consistent basis for assessing environmental impacts, they generally do not differentiate between upcycling and downcycling pathways in sufficient detail (Wernet et al., 2016; Weidema et al., 2013). This is appropriate when such processes are not the central focus of the study; however, when material recovery routes play a key role in the analysis, the aggregation of these pathways into generic emission factors can obscure the distinct environmental benefits or drawbacks associated with higher-value material recovery (upcycling) versus lower-value material reprocessing (downcycling). Such limitations can reduce the precision and policy relevance of LCA outcomes (Laurent et al., 2012). To address this gap, this paper proposes a semi-qualitative conceptual framework for adjusting emission factors in downstream waste management to better reflect these differences. By integrating scenario-specific factors into LCA, the framework aims to improve the representation of upcycling and downcycling in environmental assessments, thereby supporting future research, policy formulation, and practical decision-making in sustainable industrial waste treatment. This paper introduces a "composite emission factor (EF) score", which disaggregates the emission factors of recycled materials into three primary life cycle stages, upstream, core (processing), and downstream (end-of-life), and applies stage-specific weighting to better capture the influence of circularity within product LCAs. Disaggregating emission factors across life cycle stages improves transparency and identifies where environmental impacts are most concentrated, enabling targeted interventions and more accurate, credible LCAs that better inform circular economy decisions.

Three-Stage Disaggregation of Emission Factors: In life cycle assessment, emissions are categorized into upstream, core, and downstream stages. As shown in Table 1, upcycling reduces upstream emissions by displacing virgin material, while downcycling often requires virgin additives, offsetting benefits. At the core stage, downcycling is typically more energy-intensive than upcycling, which can rely on lower-energy remanufacturing. Downstream, upcycled materials retain value, re-enter circulation, and enhance recyclability, whereas downcycled materials degrade, increasing disposal impacts and limiting circularity. Disaggregating emissions in this way allows for more precise adjustment of emission factors (EFs) and supports strategies that better capture the environmental advantages of higher-quality recycling pathways.

Table 1: Key consideration for EF adjustment

Life Cycle Stage	Key Considerations for EF Adjustment
Upstream	In upcycling, virgin material extraction is avoided, which significantly reduces upstream emissions. Downcycling may require some virgin input (e.g., binders, stabilizers), resulting in partial upstream impacts.
Core (Processing)	Downcycling often involves **more energy-intensive processes** (e.g., melting, re-extrusion, or chemical transformation). Upcycling may involve **lower energy use** or simple remanufacturing, reducing core-stage emissions.
Downstream (EoL)	Upcycled materials often retain value longer and can re-enter the loop more easily. Downcycled materials may degrade beyond reuse, resulting in **higher disposal impacts** and lower recyclability at the next cycle.

The Role of Material Quality in Core and Use Phases

An often-overlooked aspect of LCA is the influence of material quality and performance on environmental outcomes. While functional equivalence is usually assumed during the use phase, variations in durability and behaviour can significantly alter life cycle impacts, particularly when comparing upcycled and downcycled materials. Upcycled materials offer greater durability and reuse potential, while downcycled materials have lower quality and shorter lifespans. To avoid double-counting, this approach does not recommend accounting for longevity through both explicit use-phase modelling and emission factor (EF) adjustments. Instead, it proposes context-sensitive EFs that reflect the heterogeneity of recycled outputs. For instance, a downcycled material that degrades quickly and requires frequent replacement inherently accrues higher emissions per functional unit. If not modelled dynamically, this can be represented through a "durability penalty factor." Conversely, upcycled materials used in higher-value, long-life applications may justify proportional EF reductions. The penalty factor may be positive or negative, depending on whether recycling outcomes improve or degrade quality. Downcycling often involves energy-intensive processing and yields inferior outputs, raising emissions per unit above baseline recycling pathways. The penalty factor accounts for this additional burden by increasing the adjusted EF. In contrast, upcycling extends product service life and reduces replacement needs, warranting lower attributed emissions. By contextualizing EFs in this way, LCAs more accurately reflect the real environmental consequences of material quality and recycling outcomes.

Proposed Approach

To better reflect the environmental distinctions between upcycling and downcycling pathways in LCA, we propose the introduction of a composite emission factor (EF) metric. This metric conceptualizes the total emission factor (EF_{total}) as a weighted sum of emissions from different lifecycle stages, expressed as:

$$EF_{total} = w1 \times EF_{up} + w2 \times EF_{core} + w3 \times EF_{down} \quad \text{Equation 1}$$

Here, w1, w2, and w3 represent weighting factors that can be adjusted based on specific process characteristics, such as process intensity, material quality degradation, or loop longevity. By allowing these weights to vary depending on the material fate; such as high-value closed-loop upcycling in construction materials versus low-grade downcycling in plastic fillers, this approach introduces a flexible and scenario-specific customization of emission factors. While this paper does not assign exact weightings, it establishes the foundation for a future scoring system that quantitatively integrates circularity considerations into LCA. Such a framework would enable more accurate comparisons of circular strategies and inform policy development, industrial decision-making, and sustainability reporting. The applicability of the proposed method lies in its ability to complement existing LCA practice where conventional database emission factors are insufficient to capture material quality differences within recycling systems. In many practical assessments, detailed process data for distinct upcycling and downcycling routes are unavailable, leading practitioners to rely on averaged or generic factors that obscure the effects of circularity performance. The proposed composite emission factor framework provides a transparent and adaptable approach to bridge this gap by introducing scenario-based adjustment coefficients that can be applied using readily available circularity indicators such as value retention, material quality, and loop longevity. Although the method is conceptual, it establishes a reproducible structure for integrating qualitative and semi-quantitative information into emission factor adjustments, enabling more differentiated and policy-relevant LCA outcomes across diverse industrial contexts.

Composite Emission Factor Discount Model

To operationalize the conceptual framework introduced in this study, a discount model was developed to reflect the environmental distinctions between upcycling and downcycling pathways. This model enables practitioners to adjust default emission factors (EFs) based on the circularity performance of recovered materials, thereby providing more accurate and scenario-sensitive life cycle assessments. The proposed composite emission factor (EF) metric disaggregates total emissions into upstream, core, and downstream life cycle stages. Each stage is assigned a weighting factor depending on the characteristics of the recovery process and the quality of the secondary material produced. To account for the varying environmental performance of upcycled and downcycled materials, the model introduces a discount (or penalty) factor, denoted as D, that adjusts the total emission factor according to circularity attributes such as value retention, material quality, and loop longevity. The adjusted emission factor is computed as:

$$EF_{adjusted} = EF_{total} \cdot (1 - D) \qquad \text{Equation 2}$$

Where:

- $D>0$: represents a discount for high-value upcycling (e.g., improved material quality, durability, or reuse potential)
- $D<0$: represents a penalty for downcycling outcomes (e.g., quality degradation, limited recyclability, or shorter product lifespan)

To reflect the heterogeneity of circularity outcomes, the discount factor D is defined as a weighted function:

$$D = \alpha \cdot VR + \beta \cdot MQ + \gamma \cdot RL \qquad \text{Equation 3}$$

Where:

- VR: Value retention score (0–1)
- MQ: Material quality retention (0–1)
- RL: Loop longevity or recyclability potential (0–1)
- $\alpha+\beta+\gamma=1$, with weightings selected based on material category or sectoral context.

To account for both positive (upcycling) and negative (downcycling) circularity outcomes, the discount factor D is defined relative to a neutral baseline value rather than as an absolute 0–1 index.

The revised equation is:

$$D = \alpha(VR - 0.5) + \beta(MQ - 0.5) + \gamma(RL - 0.5) \quad \text{Equation 4}$$

Where $\alpha + \beta + \gamma = 1$. In this formulation, $D > 0$ represents improvements beyond the baseline circularity level (upcycling), while $D < 0$ captures performance below the baseline (downcycling). For illustration, the model applies weighting coefficients ($\alpha = 0.3$, $\beta = 0.5$, $\gamma = 0.2$), yielding scenario-specific values consistent with Table 2. This adjustment ensures that the discount model can represent both credits and penalties within a continuous, normalized framework. To increase transparency, the weighting coefficients (α, β, γ) are not fixed but calibrated to reflect the sector-specific significance of each circularity dimension. For example, in durable construction materials such as metals, material quality retention (MQ) may be weighted more heavily (e.g., $\alpha = 0.3$, $\beta = 0.5$, $\gamma = 0.2$), whereas in packaging plastics, where recyclability potential plays a larger role, loop longevity (RL) may be prioritized (e.g., $\alpha = 0.25$, $\beta = 0.25$, $\gamma = 0.5$). For example, in durable construction materials such as metals, material quality retention (MQ) may be weighted more heavily (e.g., α=0.3, β=0.5, γ=0.2), whereas in packaging plastics, where recyclability potential plays a larger role, loop longevity (RL) may be prioritized (e.g., α=0.25, β=0.25, γ=0.5). By applying these weightings to the normalized scores (VR, MQ, RL), a composite discount factor D is derived. This approach enables the creation of scenario-specific discount factors that adjust the environmental profile of recycled materials in a transparent and reproducible manner. For example, a remanufactured high-quality aluminium panel with extended durability and high reuse potential might receive a discount factor of D=0.35, leading to a 35% reduction in its attributed EF. In contrast, a mixed plastic downcycled into a low-grade road filler might incur a penalty factor of D=−0.15, increasing the overall emissions attributed to the process. Table 2 illustrates typical values for upcycling and downcycling scenarios:

Table 2: values for upcycling and downcycling scenarios

Circularity Level	MQ	RL	Discount (D)	Adjusted EF Change
High (Upcycling)	0.85	0.8	+0.35	–35%
Medium (Marginal)	0.5	0.4	+0.18	–18%
Low (Downcycling)	0.2	0.1	–0.15	+15%

For the numerical examples shown (Table 2), the following weightings were used for illustration

Table 2a: Weightings (α, β, γ) values for upcycling and downcycling scenarios.

Scenario	α	β	γ	Resulting D
High (Upcycling)	0.3	0.5	0.2	+0.35
Medium (Marginal)	0.3	0.5	0.2	+0.18
Low (Downcycling)	0.3	0.5	0.2	–0.15

This discount model not only aligns emission factor modelling more closely with circular economy principles, but it also improves the granularity and credibility of comparative LCA outcomes. Importantly, it allows for more nuanced assessments of environmental trade-offs across different circular strategies and supports incentive structures that prioritize high-value material loops. The graphical representation in Figure 1 visualizes the operational logic of the discount model for both upcycling and downcycling scenarios.

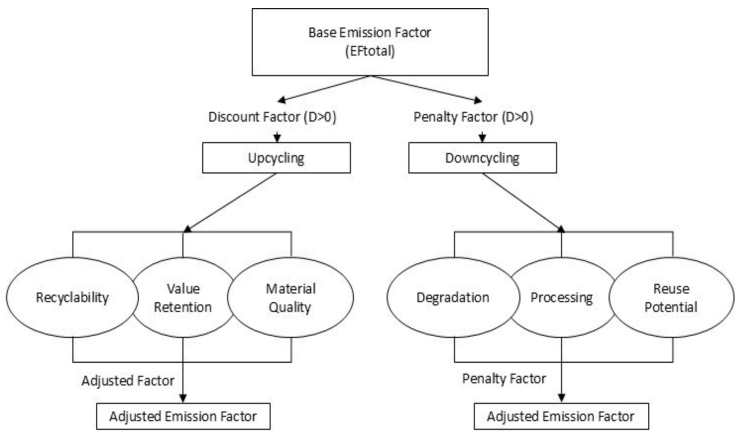

Figure 1: Discount Model for Upcycling and Downcycling

Upcycling Discount vs. Downcycling Penalty

To operationalize the conceptual model, this study introduces a qualitative scoring matrix that assigns discount or penalty factors based on the circularity level of material flows. The approach quantifies the environmental significance of upcycling and downcycling by evaluating three core dimensions: Value Retention (VR), Material Quality (MQ), and Loop Longevity (RL). Table 3 indicates examples for calculation of discount or penalty value.

Table 3: Examples for discount and penalty value calculations

Circularity Level	Description	Value Retention (VR)	Material Quality (MQ)	Loop Longevity (RL)	Discount (D)
High (Upcycling)	e.g. remanufactured aluminium panels	0.9	0.85	0.8	**+0.35**
Medium (Marginal Case)	e.g., mixed-material filler in concrete	0.6	0.5	0.4	**+0.18**
Low (Downcycling)	e.g., shredded plastics into road filler	0.3	0.2	0.1	**–0.15**
Residual Waste	e.g., incineration ash	0.0	0.0	0.0	**0.00**

Downcycling of Mixed Plastic into Construction Filler

This example demonstrates how the proposed discount model penalizes low-value recovery routes by adjusting the emission factor (EF) upward in response to poor circularity performance. Scenario: A post-consumer mixture of PET and HDPE plastics is downcycled into a low-grade construction filler used in road base layers. While this approach diverts waste from landfill, the material loses most of its functional properties, purity, and reusability.

Step 1 – Baseline Emission Factor: The default cradle-to-gate EF for recycled mixed plastic is

assumed to be: EF_total (base) = 2.5 kg CO_2e/kg plastic

Step 2 – Circularity Scoring: The product's circularity performance is evaluated based on three key indicators:

- Value Retention (VR) = 0.3 → minor utility retained
- Material Quality (MQ) = 0.2 → heavily degraded and contaminated
- Loop Longevity (RL) = 0.1 → short lifespan, not recyclable again Assuming equal

weighting:

D = (VR + MQ + RL) ÷ 3 = (0.3 + 0.2 + 0.1) ÷ 3 = 0.20

Since the overall circularity is poor, this results in a penalty of –0.15. Step 3 – Emission Factor

Adjustment

EF_adjusted = EF_total × (1 + 0.15) = 2.5 × 1.15 = 2.875 kg CO_2e/kg

Result: A 15% increase in the emission factor reflects the degradation of material quality and functionality during downcycling (shown in table 4).

Table 4: Examples for adjusted EF calculation

Case	Base EF Kg CO_2e/kg	Circularity Score	Discount/Penalty	Adjusted EF (kg CO_2e/kg)
Upcycled Aluminium Panels	9.00	High (0.85)	–35% (D = +0.35)	5.85
Downcycled Plastic Filler	2.50	Low (0.20)	+15% (D = –0.15)	2.88

This example highlights how the model enables transparent EF adjustments based on circularity metrics. It rewards high-performance strategies like aluminium remanufacturing and penalizes loss-heavy routes such as plastic downcycling. Ultimately, this supports more granular and decision-relevant LCA interpretations and encourages the selection of circular strategies with long-term environmental value.

Discussion

The proposed framework advances LCA by incorporating circularity through differentiated emission factors for upcycling and downcycling, addressing traditional models' neglect of material longevity and multi-cycle environmental benefits. The proposed semi-qualitative framework is particularly applicable in screening LCAs or early design stages where process-specific data are not yet available, and decisions must balance environmental outcomes with circularity considerations. This paper introduces the concept of circularity feedback loops to highlight these extended benefits. Upcycling processes typically preserve or enhance material quality, enabling further recycling or reuse in future cycles. This creates a "positive feedback loop" wherein upcycling leads to high-quality retention, increased recyclability, and longer persistence of materials within the system. In contrast, downcycling often results in quality degradation, reducing future recycling potential and accelerating the pathway to final disposal (shown in Figure 2).

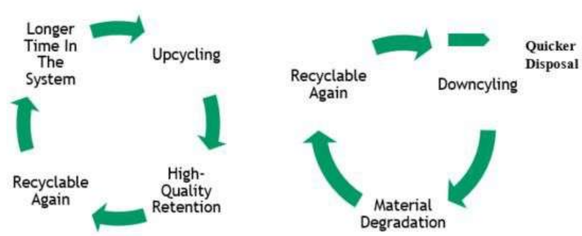

Figure 2: Upcycling vs Downcycling Feedback Loop

The proposed composite emission factor metric supports this systemic perspective by allowing future research and practitioners to assign scenario-specific weights reflecting the likelihood of material continuation in circular loops. While this conceptual framework does not prescribe exact numeric values, it establishes a foundation for developing more dynamic and forward-looking LCA models that align better with circular economy principles. Ultimately, integrating feedback loop thinking can inform more effective policy design, promote high-value recovery strategies, and drive innovation in sustainable industrial practices.

Conclusion and Recommendation

This paper presents a conceptual framework for adjusting emission factors (EFs) in life cycle assessments (LCAs) to distinguish between upcycling and downcycling. By integrating a composite

EF metric and circularity feedback loops, the framework addresses key limitations of current LCAs that rely on static emission factors. Looking forward, we recommend that LCA databases and practitioners adopt a more nuanced approach by reporting emission factors according to recycling or circularity category. This classification can help standardize how circularity is integrated into life cycle inventory (LCI) and life cycle impact assessment (LCIA) datasets, aligning with emerging circular economy (CE) assessment frameworks and policy directions. A suggested categorization is outlined below (shown in Table 5):

Table 5: Suggested categorization based on circularity level

Material Output	Circularity Level	Suggested EF Treatment
High-quality secondary material	Upcycling	Discounted EF reflecting value retention and loop longevity
Functional but degraded material	Downcycling	Penalty-adjusted EF for extra processing and reduced lifespan
Non-functional residue	Residual waste	Standard disposal EF

References

- Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper.
- *Resources, Conservation and Recycling, 55*(3), 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002
- Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production, 142*, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196
- Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048
- Geyer, R., Jambeck, J. R., & Law, K. L. (2016). Production, use, and fate of all plastics ever made. *Science Advances, 3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782
- ISO. (2006a). *ISO 14040: Environmental management — Life cycle assessment — Principles and framework*. International Organization for Standardization.
- ISO. (2006b). *ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines*. International Organization for Standardization.
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling, 127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
- Laurent, A., Olsen, S. I., & Hauschild, M. Z. (2012). Limitations of carbon footprint as indicator of environmental sustainability. *Environmental Science & Technology, 46*(7), 4100–4108. https://doi.org/10.1021/es204163f
- McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. North Point Press.
- Prendeville, S., O'Connor, F., & Bocken, N. (2014). Design for remanufacture: Barriers and opportunities in the design and business context. *Journal of Cleaner Production, 93*, 311–320. https://doi.org/10.1016/j.jclepro.2015.12.127

- Rossi, M., Germani, M., & Zamagni, A. (2020). Review of life cycle assessment in remanufacturing and circular economy: A new research agenda. *Sustainable Production and Consumption, 23*, 42–56. https://doi.org/10.1016/j.spc.2020.05.005
- Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., & Wernet, G. (2013). Overview and methodology: Data quality guideline for the ecoinvent database version 3. *Ecoinvent Report 1(v3)*. Swiss Centre for Life Cycle Inventories.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. P. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Life Cycle Assessment of Different Pathways for End-of-Life Management of LDPE Packaging Waste

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Abstract
Low-Density Polyethylene (LDPE) is widely used in the building and construction sector for packaging, protecting materials, and facilitating their handling and transportation. However, its use in Australia typically follows a linear 'take-make-dispose' model that results in significant environmental impacts. Properly managing this waste resource is essential, as it can reduce the environmental impacts of construction activities. One key step is ensuring LDPE remains within the economy as long as possible through effective End of Life (EoL) management to support a Circular Economy (CE). This study employed Life Cycle Assessment (LCA) to assess the Greenhouse Gas (GHG) emissions associated with three alternative EoL management scenarios for LDPE used as packaging for construction materials. These alternatives include waste-to-energy, mechanical recycling and chemical recycling and were compared to the business-as-usual practice of disposal in landfill. The study used waste management and resource recovery system in Victoria, Australia. The findings show that mechanical recycling is the most favourable option, followed by chemical recycling. Considering the offset that can be achieved by the avoided virgin polymer production in these scenarios, they present significant advantages compared to disposal in landfill. The suitability of these two pathways, however, depends on waste characteristics, with factors such as contamination, mixing with other waste, and the need for washing and sorting affecting both the choice of pathway and overall emissions. Additionally, among all activities within the life cycle, the production of LDPE packaging from virgin polymer accounted for over 50% of the total GHG emissions across all scenarios, highlighting the significance of this stage. The findings provide actionable recommendations for practitioners and policymakers in developing best practices for the life cycle management of LDPE packaging in construction, ultimately contributing to a CE and reduced GHG emissions.

Keywords: Circular economy; Construction and demolition waste; End of life management, Greenhouse gas emissions; Landfill; Waste to energy

Introduction

Low-Density Polyethylene (LDPE) is widely used in the construction industry for packing materials such as clay bricks or steel coils to preserve the quality of construction materials and simplify their transport (Pešta, Šerešová and Kočí, 2020). However, LDPE packaging is typically short-lived compared to construction materials, resulting in a significant amount of waste during construction activities. In Australia, the construction industry alone generated 54,996 tonnes of LDPE waste in 2018–2019, the majority of which ended up in landfill (Hossain *et al.*, 2022). Disposing of LDPE in landfill not only wastes the resources embedded in its production but also presents serious risks to both environmental and human health, given its prolonged degradation period. Therefore, proper management of this waste material is critically important.

The challenge of LDPE waste management reflects broader issues in the global plastics economy. While plastics offer undeniable benefits, they remain part of a predominantly linear economy that follows a 'take-make-dispose' model. This model is characterised by growing consumption and limited recovery, leading to the generation of massive amounts of waste. The rise in plastic use is expected to be mirrored by a corresponding tripling of Plastic Waste (PW), with nearly half of it still being disposed of in landfill if business continues as usual (OECD, 2022). Plastics now account for 12% of total global waste by weight, the vast majority of which ends up in landfill (Hossain *et al.*, 2022). A substantial portion of this PW is derived from polyolefins, including LDPE (Yang *et al.*, 2022). In recent years, the concept of a Circular Economy (CE) has gained traction as a potential solution. A CE fosters the efficient use of resources by creating cyclical supply chains, in which the notion of waste is eliminated (Shooshtarian *et al.*, 2021). By treating the End of Life (EoL) of products as a resource, a CE links waste management to resource circulation, ensuring that valuable materials remain in the economy while supporting environmental sustainability. For plastics such as LDPE, a CE involves reuse or recycling at their EoL to move away from the traditional linear 'take-make-dispose' model. However, the CE for plastics is still in its infancy, partly due to the low cost of polymers and their varying additives (Panthi and Zhang, 19-23 May, 2025).

Multiple EoL management options exist for plastics, including LDPE. These include recycling (mechanical, chemical or biological), incineration (with or without energy recovery) and landfilling (Hossain *et al.*, 2022). However, the use and scale of these options vary considerably across nations, depending on their available infrastructure and regulatory frameworks. In Australia, PW has predominantly been landfilled. According to the Australian Plastics Recycling Survey, only about 11.5% of PW is recovered, leaving the overwhelming majority disposed of in landfill (O'Farrell, 2020). However, Australia's approach to PW management is undergoing significant changes, driven by increasing investments in recycling and energy recovery infrastructure. By 2025, the country is set to benefit from new mechanical recycling facilities with a combined capacity of 300,000 tonnes per year, alongside chemical recycling plants capable of handling an additional 200,000 to 300,000 tonnes annually. Waste-to-energy (WtE) infrastructure is also advancing, with plastics serving as a key contributor to the energy value of waste streams (O'Farrell and Pickin, 2023). However, to improve the environmental performance of LDPE packaging waste management, it is essential to evaluate the environmental impacts of EoL management options. By employing LCA, one can assess the environmental impacts of LDPE throughout its life cycle and gain insights into the factors that influence the choice of EoL management options. The findings of such an analysis could support decision-making processes aimed at reducing environmental impacts.

While previous LCA studies have examined alternative packaging materials, they often featured varying functional units and system boundaries, primarily focusing on packaging used in the food processing industry (Gómez and Escobar, 2022). This study aims to provide a comprehensive analysis of the environmental impacts associated with EoL management of LDPE used as packaging for construction materials. The specific objectives of this study are as follows:

1. To quantify the life cycle GHG emissions associated with LDPE used as construction packaging across four EoL management scenarios: disposal in landfill (business-as-usual), WtE, mechanical recycling and chemical recycling
2. To identify the alternative that results in the lowest GHG emissions

Materials and methods

This study applied LCA to assess the GHG emissions associated with four EoL management scenarios of LDPE used as packaging for construction materials. LCA is a standard method for quantifying the environmental impacts of a given product across different stages of its life cycle (Rebizer *et al.*, 2004). As shown in Figure 1 (left), this study adopts ISO 14040 (2006) which establishes a four-step framework for conducting an LCA:

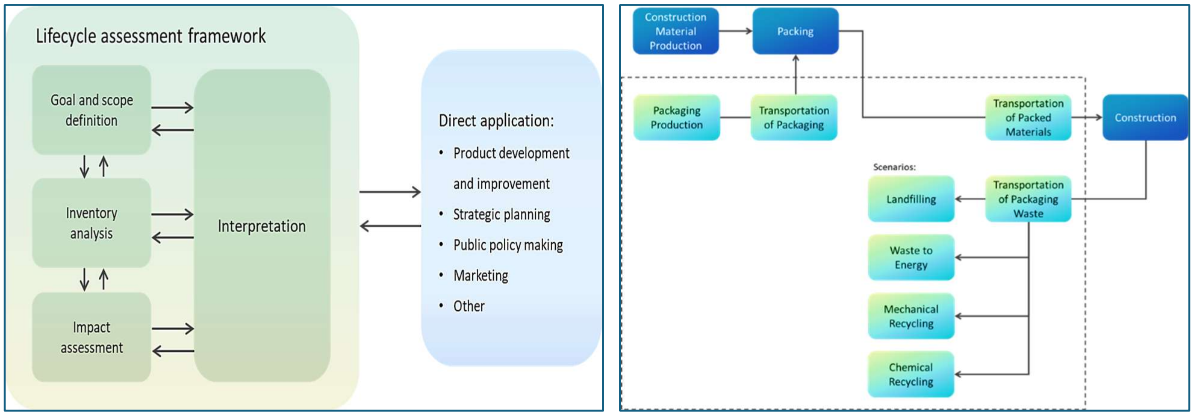

Figure 1. Left: Steps and applications of an LCA. Source: ISO 14040 (2006), Right: The system boundary of the study. Source: Authors

As shown in Figure 1 (right), the system boundary of this study includes LDPE packaging production, the transportation of the packaging to the construction material manufacturer, the transportation of packed materials to the construction site, the transportation of packaging waste from the construction site and the EoL management process of each scenario. It excludes the GHG emissions associated with the production of construction material, its packing and the construction process itself as these emissions are not pertinent to the life cycle of the packaging material. The geographical boundary of this study is Victoria, Australia. The Life Cycle Inventory (LCI) for estimating GHG emissions across the scenarios indicated above was developed using data from various sources including Australian government reports, established databases and existing literature as outlined below. Table 1 provides a summary of the process data used in the LCA analysis.

Table 1. A summary of the process data for the four study scenarios

Item	Value	Unit
Waste disposal		
Waste treatment emission factor	0.01[1]	$kgCO_{2}$-e/kWh
Waste conversion factor	0.00	$kgCO_{2}$-e/kWh
WtE		
Heating value	44.60[2]	GJ/t
Plant electricity use	260[2]	kWh/t
Electricity GHG emissions factor (Victoria)	0.92[3]	$kgCO_{2}$-e/kWh
Electricity export	2200[2]	kWh/t
Mechanical recycling		
Sorting electricity use	17[2]	kWh/t
Mechanical recycling into virgin equivalent flakes electricity use	1,480[2]	kWh/t
Mechanical recycling into virgin equivalent pellets electricity use	2,230[2]	kWh/t
Electricity GHG emissions factor (Victoria)	0.92[3]	$kgCO_{2}$-e/kWh
Chemical recycling		
Sorting electricity use	17.00[2]	kWh/t
Front-end pre-processing electricity use	80.00[2]	kWh/t
Reactor electricity use	210.00[2]	kWh/t
Plasticrude to ethene conversion electricity use	412.00[2]	kWh/t
Plasticrude to ethene conversion fuel use	35.60[2]	GJ/t
Fuel use GHGE factor	54.80[3]	kg CO_{2}-e/GJ
Electricity GHGE factor (Victoria)	0.92[3]	kg CO_{2}-e/kWh

[1] based on AusLCI database V1.42 Grant, T. (2023) AusLCI (V1.42) Carbon Emissions Factors. Melbourne. Available at: https://www.auslci.com.au/index.php/EmissionFactors..

[2] based on O'Farrell, K. and Pickin, J. (2023) Carbon emissions assessment of Australian plastics consumption–Project report. Available at: https://bit.ly/3ELB2Sa.

[3] emissions from consumption of purchased electricity from a grid, based on NGA (2022) Australian National Greenhouse Accounts Factors. [Online]. Available at: https://bit.ly/437QhyP.

Results and discussion

This study applied LCA to evaluate the GHG emissions associated with four EoL management scenarios for construction LDPE packaging: disposal in landfill (business-as-usual), WtE (thermochemical method), mechanical recycling and chemical recycling. By conducting a detailed process analysis, the study quantified emissions across the life cycle. Figure 2 presents the results of the analysis. Emissions are disaggregated by activity to enable a comparison of the contributions from production, transportation and EoL management processes.

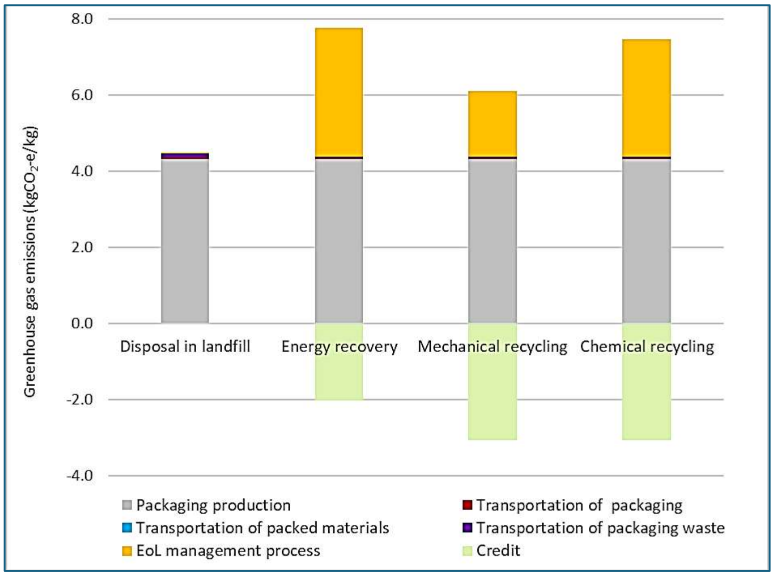

Figure 2. GHG emissions of construction LDPE packaging across four EoL management scenarios by activity Source: Authors

Among three alternatives to disposal in a landfill, the mechanical recycling scenario exhibits the lowest total GHG emissions, at 6.10 kgCO2-e/kg. This is primarily due to the relatively low energy requirements of the mechanical recycling process, making it the most favourable option. However, its effectiveness can be significantly reduced if the LDPE is contaminated or mixed with other waste, requiring additional washing or sorting steps (Ragaert, Delva and Van Geem, 2017). The chemical recycling scenario has the second-lowest GHG emissions at 7.46 kgCO2-e/kg. While this is about 22.3% higher than mechanical recycling, it may be a viable alternative for mixed or contaminated plastics that are unsuitable for mechanical recycling.

The WtE scenario has the highest GHG emissions at 7.77 kgCO2-e/kg among the three alternatives. This is primarily driven by the conversion of the polymer to CO2 during incineration, which releases its embedded carbon as CO_2 emissions, along with other GHGs. The disposal in landfill scenario generates 4.47 kgCO2-e/kg. This corresponds to approximately 4,137.79 kgCO2-e/m^3, using the average density of LDPE (925 kg/m^3) (PlasticsEurope, 2025). This volumetric perspective is particularly relevant as waste management companies typically charge for collection based on volume ($/m^3), while disposal cost and EPA landfill levies are mass-based ($/t). This creates an economic incentive structure where skip bin companies may preferentially recycle denser materials with established resale markets (like concrete and steel) while directing lighter materials like LDPE to landfill. Although the three alternatives to disposal in landfill result in an overall increase in GHG emissions, landfilling itself comes with a significant cost. In the landfill disposal scenario, the entire GHG associated with the polymer's production—estimated at 3.60 kgCO2-e/kg—is permanently lost as the material is removed from circulation. In contrast, mechanical and chemical recycling scenarios present an opportunity to offset much of the GHG emissions associated with polymer production through avoided virgin polymer production. At an 85% recycling efficiency, these scenarios can achieve an estimated savings of 3.06 kgCO2-e/kg, representing a significant offset against their GHG emissions. However, the market for recycled polymer in Australia is still developing (Shooshtarian *et al.*, 2022). In the 2018–19 financial year, locally processed recycled polymers accounted for only 4% of the national consumption (O'Farrell, 2020). Recycled polymers are not usually preferred over virgin ones due to their higher cost of production and unknown quality. They often face higher costs due to factors such as labour, transport and infrastructure (Ghafoor *et al.*, 2024). Their quality is also subject to debate with some standards prohibiting their use in certain applications (Santos, Esmizadeh and Riahinezhad, 2024). While mechanical recycling processes may degrade polymer quality over time, research suggests that polymers could be extruded up to 40 times without significantly altering their processability and long-term mechanical properties (Jin *et al.*, 2012). Meanwhile, chemical recycling offers the potential to restore polymers to their original quality; however, practical limitations such as process efficiency and material loss prevent infinite recyclability (Achilias *et al.*, 2007).

The WtE scenario also provides a credit for avoided electricity generation, offsetting emissions that would otherwise come from the current Victorian electricity grid, which relies on a mix of coal and natural gas. This credit, amounting to 2.02 $kgCO_2$-e/kg, offsets about 26% of the total scenario's GHG emissions. That said, the long-term viability of WtE is sensitive to the decarbonisation of national electricity grids. As grids increasingly rely on renewable energy sources, the relative carbon benefit of WtE will diminish, and its emissions profile will become less competitive compared to other EoL management options.

When looking at the activities within each scenario, packaging production — accounting for 4.31 $kgCO_2$- e/kg— is the dominant contributor. This activity alone accounts for more than 50% of total emissions across four scenarios. This is because LDPE as a fossil-based material has a high GHG coefficient and emphasises the importance of reducing emissions in LDPE production. Transportation, on the other hand, was found to contribute a relatively small share of total GHG emissions, approximately 3.4% in the disposal in landfill scenario and 1% in the other three alternatives to landfilling. The difference is mainly due to differences in travel distance and the type of truck used for transportation. This relatively low contribution might, to some extent, be attributed to the assumption that all activities are locally sourced. This finding, however, aligns with previous studies that found transportation's share of GHG emissions to be low (Tan *et al.*, 2023).

Conclusions

LDPE is widely used in the construction industry for packing construction materials, but its short lifespan contributes to a significant waste stream, much of which is traditionally sent to landfill. This practice not only squanders the resources embedded in the production of LDPE but also poses long-term environmental and health risks due to its lengthy decomposition process. This study utilised LCA to compare the environmental impacts of construction LDPE packaging across four EoL management scenarios, namely, disposal in landfill (business-as-usual), WtE, mechanical recycling and chemical recycling. The analysis revealed that while disposal in landfills has low GHG emissions during the EoL stage itself, it permanently loses the embedded resources in LDPE production. Considering the offset achieved by the avoided virgin polymer production, mechanical recycling is the most environmentally favourable option. However, its effectiveness may decrease when dealing with mixed or contaminated waste. In such cases, chemical recycling, despite its higher GHG emissions, presents a viable alternative. WtE, while useful in reducing waste volume, showed the highest GHG emissions, particularly as the decarbonisation of electricity grids reduces the relative benefit of its energy recovery. Among all activities, the production of LDPE packaging accounts for over 50% of the total GHG emissions across four scenarios, while transportation contributes a relatively low share, representing 1–3%. These findings provide the following recommendations for practitioners and policymakers:

- Minimise the use of LDPE packaging in construction.
- Prioritise upstream strategies such as reducing the reliance on fossil-based and virgin polymers to reduce production GHG emissions.

- Separate LDPE packaging waste on-site to improve the quality of recyclables and streamline downstream processing.
- Consider shifting waste disposal pricing and EPA levies for lightweight waste materials from weight-based ($/t) to volume-based ($/m³) to encourage their recovery.
- Maximise EoL recycling with a preference for mechanical recycling wherever feasible.

By implementing these recommendations, a more sustainable life cycle for LDPE packaging can be achieved, helping to mitigate its environmental impact within the construction industry.

Acknowledgement:
The authors gratefully acknowledge RecycleAll Pty Ltd for funding this study. We extend our sincere thanks to Mrs Damien Collins and Mr Dean Vella of RecycleAll, as well as Mr Matthew Grimm and Ms Laura Guccione of BlueScope Steel Australia, for their valuable insights and meaningful contributions throughout the research.

References

- Achilias, D.S., Roupakias, C., Megalokonomos, P., Lappas, A.A. and Antonakou, E.V. (2007) 'Chemical recycling of
- plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP)', *Journal of Hazardous Materials*,
- 149(3), pp. 536-542. Available at: 10.1016/j.jhazmat.2007.06.076
- Ghafoor, S., Shooshtarian, S., Udawatta, N., Gurmu, A., Karunasena, G. and Maqsood, T. (2024) 'Cost factors affecting
- the utilisation of secondary materials in the construction sector: A systematic literature review', *Resources, Conservation*
- *& Recycling Advances*, 23, p. 200230. Available at: 10.1016/j.rcradv.2024.200230
- Gómez, I.D.L. and Escobar, A.S. (2022) 'The dilemma of plastic bags and their substitutes: A review on LCA studies',
- *Sustainable Production and Consumption*, 30, pp. 107-116. Available at: 10.1016/j.spc.2021.11.021
- Grant, T. (2023) *AusLCI (V1.42) Carbon Emissions Factors*. Melbourne. Available at: https://www.auslci.com.au/index.php/EmissionFactors.
- Hossain, R., Islam, M.T., Ghose, A. and Sahajwalla, V. (2022) 'Full circle: Challenges and prospects for plastic waste management in Australia to achieve circular economy', *Journal of Cleaner Production*, 368, p. 133127. Available at: 10.1016/j.jclepro.2022.133127
- ISO 14040 (2006) *Environmental Management-Life Cycle Assessment-Principles and Framework*.
- Jin, H., Gonzalez-Gutierrez, J., Oblak, P., Zupančič, B. and Emri, I. (2012) 'The effect of extensive mechanical recycling on the properties of low density polyethylene', *Polymer Degradation and Stability*, 97(11), pp. 2262-2272. Available at: 10.1016/j.polymdegradstab.2012.07.039
- NGA (2022) *Australian National Greenhouse Accounts Factors*. [Online]. Available at: https://bit.ly/437QhyP. O'Farrell, K. (2020) *2018–19 Australian Plastics Recycling Survey: National Report - Final Report*. [Online]. Available at: https://bit.ly/4162Nwb.
- O'Farrell, K. and Pickin, J. (2023) *Carbon emissions assessment of Australian plastics consumption–Project report*. Available at: https://bit.ly/3ELB2Sa.
- OECD (2022) *Global plastics outlook: Policy scenarios to 2060* (9264832025). Available at: https://bit.ly/418tfVP.
- Panthi, S. and Zhang, F. (19-23 May, 2025) 'A comprehensive review of plastic recycling in the construction industry: Challenges and opportunities in the U.S', *CIB World Building Congress 2025: Sustainable built environment – the role of the construction community in meeting the UN SDGs*. West Lafayette, US. Purdue University. doi: 10.7771/3067-4883.2081

- Pešta, J., Šerešová, M. and Kočí, V. (2020) 'Carbon footprint assessment of construction waste packaging using the package-to-product indicator', *Sustainability*, 12(23), p. 10094. Available at: 10.3390/su122310094
- PlasticsEurope (2025) Polyolefins. Available at: https://bit.ly/3EWie2p (Accessed: 17/02/2025).
- Ragaert, K., Delva, L. and Van Geem, K. (2017) 'Mechanical and chemical recycling of solid plastic waste', *Waste Management*, 69, pp. 24-58. Available at: 10.1016/j.wasman.2017.07.044
- Rebizer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P. and Pennington, D.W. (2004) 'Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications', *Environment International*, 30(5), pp. 701-720. Available at: 10.1016/j.envint.2003.11.005
- Santos, G., Esmizadeh, E. and Riahinezhad, M. (2024) 'Recycling construction, renovation, and demolition plastic waste: review of the status quo, challenges and opportunities', *Journal of Polymers and the Environment*, 32(2), pp. 479-509. Available at: 10.1007/s10924-023-02982-z
- Shooshtarian, S., Caldera, S., Maqsood, T., Ryley, T., Wong, P.S.P. and Zaman, A. (2022) 'Analysis of factors influencing the creation and stimulation of the Australian market for recycled construction and demolition waste products',
- *Sustainable Production and Consumption*, 34, pp. 163-176. Available at: 10.1016/j.spc.2022.09.005
- Shooshtarian, S., Hosseini, M.R., Kocaturk, T., Ashraf, M., Arnel, T. and Doerfler, J. (2021) *The circular economy in the Australian built environment: The state of play and a research agenda* Deakin University.
- Tan, Q., Yang, L., Wei, F., Chen, Y. and Li, J. (2023) 'Comparative life cycle assessment of polyethylene agricultural mulching film and alternative options including different end-of-life routes', *Renewable and Sustainable Energy Reviews*, 178, p. 113239. Available at: 10.1016/j.rser.2023.113239
- Yang, R.X., Jan, K., Chen, C.T., Chen, W.T. and Wu, K.C.W. (2022) 'Thermochemical conversion of plastic waste into fuels, chemicals, and value-added materials: a critical review and outlooks', *ChemSusChem*, 15(11), p. e202200171 Available at: 10.1002/cssc.202200171

Future-oriented LCA of emerging SBC technology within transportation

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Abstract

The emerging technology of Structural Battery Composites (SBCs), when used in e-mobility, is expected to offer advantages due to its multifunctionality. Compared to lithium-ion (LiFePO4) batteries, SBC components designed to replace materials such as steel, aluminium or plastic in light electric vehicles show weight savings. LCA results of lab-scale SBC production, had in earlier studies highlighted hotspots in energy demand and generated waste due to auxiliary materials used in the lab. LCA case studies, that anticipated the impact when the emerging technology had been deployed was aided by computer aided design finite element method and scenarios. The focus of this conference paper is two different future-oriented LCA case studies, both done to explore the emergent technology in order to guide its further development. The first is on application in an electric vehicle in 2032 and the second is on SBC technology modelled at a more mature stage at higher Technology Readiness Level (TRL), approaching commercial scale production. The approach presented here benefited from participation of technology developers and showed further the importance of regionalised considerations, of data quality assessment and of broader life cycle environmental impacts assessment in addition to Climate Change impact in LCA. Summarising, the importance of continuing participatory approaches was highlighted in future-oriented LCA.

Keywords: prospective LCA, ecodesign, sustainable transportation, structural batteries

Introduction

The decarbonisation of transport is forecasted to increase demand in batteries for energy storage in the coming years (Carrara et al., 2023). Developments in energy storage are expected to encourage the transition towards sustainable transportation. New technological innovations in electric vehicle (EV) applications include structural batteries that offer potential for mass savings, advancing the state of the art in EV lithium-ion-based energy storage (Chaudhary et al., 2024; Hermansson et al., 2023). Based on early and preliminary assessments (Jin et al., 2023; Medicharla & Rao, 2024), structural batteries are expected to be part of improving the technical and environmental performance of EVs.

Due to their mechanical capacity and energy storage capacity, Structural Battery Composites (SBCs) can replace structural parts as well as parts of the battery in electric vehicles. SBCs are comprised of carbon fibres that when modified and further assembled in a certain way, with the presence of advanced semi-solid electrolyte design, turns the resulting composite into a lithium-ion battery (LIB). These SBCs are produced currently at laboratory scale, at Chalmers University of Technology, in Sweden. No-full-scale production yet exists. In initial efforts to this study, prospective Life Cycle Assessment (LCA) was done to reflect the technology's environmental performance at lab-scale, early stage (TRL 3-4), at a defined future (2-5 years), to identify hotspots and thereby direct efforts of technology developers for mitigation. Challenges with data gaps in direct energy consumption in SBC production and technical performance of the emerging SBC technology, were highlighted important in further SBC development work. A range of predictive scenarios with a long-term perspective (2030) later highlighted additional data requirements and increasing uncertainty in prospective evaluations of foreground and background changes, when modelling at higher TRLs (6-

9). In our earlier work, a participatory approach in developing future scenarios in LCA, as previously used also by others in mobility scenarios (Bouillass et al., 2021) highlighted the importance of stakeholder engagement in defining the future prospects of the technology in upscaling from the laboratory and low TRL state to a state that involved a higher level of manufacturability.
Data gaps, increased complexity with handling the multifunctional dimension of the technology, and comparing SBC to commercial alternative, were challenges identified due to the early TRL of SBC. These challenges have been pointed out in LCA literature of emerging technologies (Moni et al., 2020). Building further on earlier studies, this conference contribution reports on life cycle environmental impacts associated with SBC technology from two case studies, with advances in functional and scaling analysis of the emerging technology.

Material and methods
The LCA framework followed the ISO 14040/44 methodology, however the approach in this study applied life cycle thinking that considered possible scenarios, with a future-oriented perspective, to facilitate further the technology development. Thus, expanded the earlier approach of attributional LCA done at the lab-scale at a defined future, with prospective scenarios, in the context of ecodesign. LCA conducted at an early stage can have a significant influence on technology development (Arvidsson et al., 2018). However methodological challenges previously found in literature remain (Hetherington et al., 2014). Despite existing data and LCI databases, challenges emerge often found in ex-ante LCA (van der Giesen et al., 2020), where ex-ante considers technological maturity at an early stage, quantified by Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) or qualitatively considered (Arvidsson et al., 2023). Challenges include foreground data that might not be readily available, limited data availability of the lab-scale processes, or lack of representative information for the product system. Therefore, a starting point for upscaling methods was scenarios development. Due to the possible difference that scenarios modelling involves, studies have proposed constructing future scenarios with predictive or exploratory scenarios (Langkau et al., 2023), normative scenarios often resulting from sector roadmaps, or forecasting methods of relevant factors in technology development (Hummen & Kästner, 2014).

This conference contribution considers prospective scenarios in technology development and manufacturing development in two case studies. The effect of how the emerging SBC technology will perform in the future was assessed with screening LCA and scenarios developed, estimating: 1) GHG implications in vehicle application of ecodesign practice of lightweighting (e.g. kg CO_2-eq. per kWh of battery capacity); 2)environmental im-pacts of SBC technology development, in future production environment beyond lab-scale, for carbon fibres with a structural battery electrolyte (SBE) design. The first case study, combined greenhouse gas emission results, ‘from cradle to gate’, with sensitivity analyses in a streamlined prospective LCA aiming to quantify prospective scenarios of material substitution. This was put in the context of transportation, to understand how the technology will perform in the future. According to researchandmarkets.com, electric quadricycles are forecasted to grow in urban areas (by 2032), due to emission regulations and growing traffic congestion. Environmental im-pact results from earlier efforts to the study, in prospective LCA of SBC production in the laboratory, was combined with relevant literature data, computer aided design (CAD) and finite element method simulations (FEM), to indicate design specifications for electric quadricycles. The second case study, advanced the prospective scope of the assessment method with an anticipatory approach (Wender et al., 2014), where relevant parameters to the production and the technology itself identified in earlier prospective LCA of SBC production in the laboratory, were assessed in the context of upscaling. This was done within scenario development to understand the environmental impact of SBCs at a pilot production, to prepare for EV application, and is explained further in the next section. Alternative process scenarios within SBC production, and technology scenarios to the SBCs produced at Chalmers University of Technology were assessed. Energy modelling calculations were based on material and energy balances for scaled to a higher production environment, inventory data (per kg of production). Results from the screening LCA were compared to relevant literature reviewed to evaluate findings, with a focus on the environmental impacts and improvement opportunities for the technology. Finally, hotspots were identified.

Results

Assessing multifunctionality of SBC in EV re-design

Computer-aided design (CAD) and FEM simulations indicated that with correct design adaptations, SBC can match the strength of materials such as steel if the volume is increased. The first case study showed that replacing virgin-grade steel or aluminium with SBC resulted in weight savings for the vehicle in quadricycle parts (Table 1), including: chassis pipe and rims (steel), battery casing and roof (aluminium), and interior panels (ABS).

Table 1. SBC comparison to conventional materials in EV quadricycle design

Integrated re-design of components	Material 1: Aluminium	Material 2: Steel	Material 3: ABS plastic	Total:	Unit
Component weight reduction after structural performance considerations*	7.1	13.69	1.8	22.6	kg
Weight reduction comparing SBC to LFP battery	7.9	7.4	3.4	18.7	kg
SBC capacity in vehicle-integrated de-sign	1.2	1.1	0.5	2.8	kWh
Lightweighting, from both structural performance and energy storage on selected structural components	14.93	21.1	5.2	41.2	kg
Climate Change, Emissions	2606.5	763.1	1197.3	4566.9	kg CO_2 eq.

* Weight savings of material alternatives compared to the SBC when used in selected vehicle components. SBC weight modified with volume adjusted, to maintain the modular strength (MPa) of original materials.

Selected components can contribute meaningfully to energy storage displacing conventional $LiFePO_4$ (LFP) batteries (energy density, 150 Wh/kg). As a result, component re-design to SBC with energy density of 100 Wh/kg indicated 2.8 kWh capacity of energy storage for the EV quadricycle. In this case study, when life cycle thinking was applied with CAD and FEM, it provided valuable in-put for method development in LCA. Also, it illustrated for SBC technology investigation a value of kg CO_2 eq. per kWh of electricity storage, focused on a specific function of battery capacity performance with the aim of ecodesign. However, looking at the emissions avoided through lightweighting, the importance of the green-house gas intensity amongst material components was highlighted (Table 2). The weight shown in Table 1 decreased of 41.2 kg related to almost 9% of reference EV quadricycle weight (471 kg, Citroën AMI), including the battery (46 kg). However, 22.6 kg component weight reduction, corresponded to almost 5% of the vehicle weight (425 kg, excluding battery), while the 18.7 kg battery weight reduced represented 41% of the battery weight. This showed a potential for integrated components re-design for the use stage in ecodesign.

Table 2. Screening LCA results of SBC in EV quadricycle re-design scenario (kg CO_2 eq.).

Integrated components redesign	Climate Change impacts: structural components	Climate Change impacts: conventional LFP battery	Climate Change impacts: SBC	Total emissions change
Material 1: Aluminium	249.5	309.4	3165.4	2606.5
Material 2: Steel	102.8	288.6	2925.6	2587.9
Material 3 ABS plastic	26.7	132.6	1356.6	1197.3
Unit:	kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.	kg CO_2 eq.

The above-mentioned approach showed primarily the function of mechanical capacity and secondarily energy storage potential in the multifunctional performance of SBC in the selected vehicle application. When the use stage of the EV quadricycle was considered, in urban mobility, with an adjusted energy reduction value (0.83kWh/100 kg*100km for the quadricycle) under the Artemis Urban Cycle (DieselNet, 2025), bigger reductions in Climate Change emissions were anticipated. This was due to potential for energy storage in the integrated components re-design of EV application resulting to SBC capacity of 2.8 kWh that could represent 51% of the inherent battery capacity of the Citroën AMI quadricycle (5.5 kWh). However, for energy savings from lightweighting to be realised, the differences in GHG emissions intensity on regionalised scenarios and actual performance in the intended use are recommended for future research and development. The difference in the maturity of material com-ponents is also important, which is the focus in the next case study of the emerging SBC technology.

Design for the environment with LCA

The second case study was developed to analyse and understand challenges with future technology development routes. The following relevant parameters were identified and then quantified in screening LCA, with prospective scenarios: i) Laboratory and larger productions (beyond pilot to pre-production) and electricity demand estimates (to evaluate process-based upscaling with equipment nominal capacity); ii) structural battery electrolyte design and battery performance (to evaluate yield scenario and battery capacity gains in expected use, considering energy-based allocation); iii) specific heat capacity of car-bon fibre-structural battery electrolyte (to evaluate the End-of-Life management based on basic thermodynamic principle, considering exergy-based allocation).

The modelled inventory data represented a reduced scope of SBC production within carbon fibre-reinforced components. The focus was on the semi-solid electrolyte content in the SBE scenarios and the resulting battery capacity for ecodesign. Despite the fact that mechanical stiffness varied (400-100 MPa) amongst scenarios, but the epoxy resin content remained constant (Yu et al., 2017). This scenario explored both multifunctional performance and environmental performance of semi-solid electrolyte, onto carbon fibres found in SBC technology. In the energy modelling calculations, the heating capacity of the active materials was considered as well as differences in mass yields of the carbon fibre-electrolyte scenarios (i.e. 1 m^2 corresponding to electrolyte layered onto four carbon fibre layers). However, electricity demand calculations were constant to the equipment capacity. Within all devel-oped scenarios, output-based definitions of functional units were considered (per 1 kg and 1 m^2). LCA results showed that data that had the most impact resembling the technology at differing scales, related to energy use for infusion and curing, and carbon fibres production. Hotspot analysis of laboratory and larger production identified the energy intensive processes in SBE production (i.e. curing and resin-infusion preparation). Laboratory production showed to be less energy-intensive than the (mid-scale) industrial due to equipment capacity calculations. However, LCA results still showed lower overall lab-scale impacts than the industrial alternative. This was anticipated as inventory data scaled linearly to the equipment size which showed a significant energy contribution. Additionally, differences in the electrolyte yields (SBE scenarios) showed reduction in impacts with higher yield scenario. Finally, lower overall impacts were observed for 1 m^2 of potential application compared to 1 kg of production. LCA results explored the impact of alternative process and technology scenarios within SBC pro-duction, confirming the relevance of energy demand and thus fuel mix contribution, in the future development of the emerging technology. The significant contribution from carbon fibres production, highlighted the importance of energy mix and regionalised scenarios. Finally, the importance of full LCA was illustrated in future-oriented LCA.

Lastly, despite the focus put of the SBE scenarios, assessed with LCA, hence the resin-infusion process, the resin-infusion process yields and battery performance however there were differences highlighted to the SBC production in the laboratory, at Chalmers University of Technology, in Sweden. Additionally, scenarios explored in this case study do not represent a full SBC technology nor the SBCs produced currently at laboratory scale, at Chalmers University of Technology, in Sweden.

Discussion

Experiences gained from the case studies were valuable in method development with LCA. This conference contribution composed of case studies using prospective LCA in technology development, aimed at generating insights into SBC advancements.

The first case study provided insights in multifunctionality and lightweighting. Findings complement previous studies regarding potential for mass savings of structural batteries (Hermansson et al., 2023). However, LCA results of SBC production in the laboratory from earlier LCA study showed high-er environmental impact, associated with the production process also found in literature (Botejara-Antúnez et al., 2024; Ellingsen et al., 2017; Kim et al., 2023). Intended use in the quadricycle application scenario demonstrated battery capacity specifications in the EV quadricycle. However, it also showed dependence on regionalised scenarios for use stage of components providing an overview of challenges for future research within energy consumption and GHG emissions. The understanding of environmental impacts of production in the context of light-weight structures with mechanical performance, has been previously assessed in the environmental impacts of carbon fibres with regionalised scenarios (Prenzel et al., 2024). Additionally, possible future research in SBC technology development and environmental impacts should assess additional structural performance considerations (i.e. elastic modulus) to build more precise case studies representing actual applications. Despite limited use stage performance data, the EV scenario used streamlined prospective LCA and informed how SBC technology at early-stage, can be used based on different assumptions over its lifetime.

The second case study considered different plant sizes (beyond laboratory) and technological variations (SBE design) and estimates of energy used in larger production were quantified and used as life cycle inventory data (LCI). Findings provided insights for SBE production as scenarios directed attention to energy demand, in the future development of the emerging technology. The environmental and technical performance of the SBC technology was analysed in the context of scaled life cycle inventory data per kg and per 1 m^2. Initial LCA results before these case studies sought to understand further the influence of energy demand in SBC production and the battery performance within EV transition. Additional process-based energy modelling of this study considered scaled up equipment characteristics into the industrial scale, following the laboratory process, resulted in increased LCA results. Future LCA studies should integrate LCA findings in the development of SBC technology, although in the light of SBC production output as variable; for example, considering further production characteristics, and material properties including their variation and trade-offs of ionic conductivity, mechanical stiffness, and battery capacity. These in the context of technology functionality for EV application, with the importance of battery conditioning and cycling is suggested in TRL advancing, and future LCAs, as additionally researched for multifunctional carbon fibres in lightweighting (Jacques et al., 2012) and in-vehicle battery technologies (Porzio & Scown, 2021). Although the second case study considered encapsulation requirements for ecodesign, assumptions in anticipatory scenarios do not currently cover the full SBC technology, therefore data requirements for completeness stand out in future research. Nevertheless, the importance of applying life cycle thinking is shown in this study that considered possible scenarios to facilitate the technology development.

Based on the above case studies, the importance of regionalised scenarios in the context of up scaling the emerging technology were highlighted for future work. Finally, the importance of assessing wider environmental impacts in full LCA of technology advancing, additional to energy use and Climate Change, is recommended also as part of future work.

Conclusion

The first case study aimed to investigate future impacts of electric quadricycles based on scenarios intended to inform SBC technology development. However, as the LCA was conducted at early TRL, and at lab-scale, it is currently difficult to anticipate how this emerging technology will compare to commercial technology alternatives.

In the second case study, prospective parameters introduced within scenario development in the context of upscaling production, and of ionic conductivity of the structural electrolyte, proved useful in highlighting the importance of energy demand in larger production and also considered a wider analysis of life cycle environmental impacts assessed with LCA in addition to energy use and Climate Change. Furthermore, changes suggested in an ex-ante manner, supporting scale-up (Arvidsson et al., 2018, 2023) into future LCA studies included; dynamic LCA considerations, to overcome the challenge of in-creased uncertainty in LCA of SBC technology upscaling, data quality requirements for completeness and representativeness, and the effect of regionalised scenarios. Finally, this study benefited from a life cycle perspective about ecodesign and is encouraged in future stakeholder participation and future SBC technology development (Hauschild et al., 2017; Wender et al., 2014).

Acknowledgements

The authors are very grateful to Funding from Chalmers Area of Advance Transport and from Åforsk Foundation (grant no 23-491).

References

- Arvidsson, R., Svanström, M., Sandén, B. A., Thonemann, N., Steubing, B., & Cucurachi, S. (2023).
- Terminology for future-oriented life cycle assessment: review and recommendations. *International Journal of Life Cycle Assessment*, *29*, 607–613. https://doi.org/10.1007/s11367-023-02265-8
- Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286–1294. https://doi.org/10.1111/jiec.12690
- Botejara-Antúnez, M., Prieto-Fernández, A., González-Domínguez, J., Sánchez-Barroso, G., & García-Sanz-Calcedo, J. (2024). Life cycle assessment of a LiFePO4 cylindrical battery. *Environmental Science and Pollution Research*, *31*(46), 57242–57258. https://doi.org/10.1007/s11356-024-32543-3

- Bouillass, G., Blanc, I., & Perez-Lopez, P. (2021). Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. *International Journal of Life Cycle Assessment*, *26*(12), 2408–2435. https://doi.org/10.1007/s11367-021-01988-w
- Carrara, S., Bobba, S., Blagoeva, D., Dias, A., Cavalli, P., Georgitzikis, A., Grohol, K., Kuzov, A., Latunussa, T., Lyons, C., Maury, G., & Somers, T. (2023). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU - A foresight study, JRC Science for Policy Report. In *Eu Crm*. https://doi.org/10.2760/334074
- Chaudhary, R., Xu, J., Xia, Z., & Asp, L. E. (2024). Unveiling the Multifunctional Carbon Fiber Structural Battery. *Advanced Materials*, *2409725*. https://doi.org/10.1002/adma.202409725
- DieselNet. (2025). *Common Artemis Driving Cycles (CADC)*. https://dieselnet.com/standards/cycles/artemis.php
- Ellingsen, L. A. W., Hung, C. R., & Strømman, A. H. (2017). Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment*, *55*, 82–90. https://doi.org/10.1016/j.trd.2017.06.028
- Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2017). Life Cycle Assessment: Theory and Practice.
- Life Cycle Assessment: Theory and Practice, 1–1216. https://doi.org/10.1007/978-3-319-56475-3 Hermansson, F., Edgren, F., Xu, J., Asp, L. E., Janssen, M., & Svanström, M. (2023). Climate impact and
- energy use of structural battery composites in electrical vehicles—a comparative prospective life cycle assessment. International Journal of Life Cycle Assessment, 28(10), 1366–1381. https://doi.org/10.1007/s11367-023-02202-9
- Hetherington, A. C., Borrion, A. L., Griffiths, O. G., & McManus, M. C. (2014). Use of LCA as a development tool within early research: Challenges and issues across different sectors. International Journal of Life Cycle Assessment, 19(1), 130–143. https://doi.org/10.1007/s11367-013-0627-8
- Hummen, T., & Kästner, F. (2014). Evaluating existing methodological approaches for prospective LCA at early technology development stages. LCA XIV San Francisco Proceedings from the LCA XIV International Conference, American Center for Life Cycle Assessment, San Francisco, 19–30.
- Jacques, E., Kjell, M. H., Zenkert, D., Lindbergh, G., Behm, M., & Willgert, M. (2012). Impact of electrochemical cycling on the tensile properties of carbon fibres for structural lithium-ion composite batteries. Composites Science and Technology, 72(7), 792–798. https://doi.org/10.1016/j.compscitech.2012.02.006
- Jin, T., Singer, G., Liang, K., & Yang, Y. (2023). Structural batteries: Advances, challenges and perspectives. Materials Today, 62(February), 151–167. https://doi.org/10.1016/j.mattod.2022.12.001
- Kim, H. C., Lee, S., & Wallington, T. J. (2023). Cradle-to-Gate and Use-Phase Carbon Footprint of a Commercial Plug-in Hybrid Electric Vehicle Lithium-Ion Battery. Environmental Science and Technology, 57(32), 11834–11842. https://doi.org/10.1021/acs.est.3c01346
- Langkau, S., Steubing, B., Mutel, C., Ajie, M. P., Erdmann, L., Voglhuber-Slavinsky, A., & Janssen, M. (2023). A stepwise approach for Scenario-based Inventory Modelling for Prospective LCA (SIMPL). International Journal of Life Cycle Assessment, 28(9), 1169–1193. https://doi.org/10.1007/s11367-023-02175-9
- Medicharla, H., & Rao, S. (2024). A Critical Review on Structural Battery Composites : Current State , Challenges , and Future Prospects. https://doi.org/10.31031/PSPRJ.2024.05.000624

- Moni, S. M., Mahmud, R., High, K., & Carbajales-Dale, M. (2020). Life cycle assessment of emerging technologies: A review. Journal of Industrial Ecology, 24(1), 52–63. https://doi.org/10.1111/jiec.12965
- Porzio, J., & Scown, C. D. (2021). Life-Cycle Assessment Considerations for Batteries and Battery Materials. Advanced Energy Materials, 11(33). https://doi.org/10.1002/aenm.202100771
- Prenzel, T. M., Hohmann, A., Prescher, T., Angerer, K., Wehner, D., Ilg, R., von Reden, T., Drechsler, K., & Albrecht, S. (2024). Bringing Light into the Dark—Overview of Environmental Impacts of Carbon Fiber Production and Potential Levers for Reduction. Polymers, 16(1). https://doi.org/10.3390/polym16010012
- Wender, B. A., Foley, R. W., Hottle, T. A., Sadowski, J., Prado-Lopez, V., Eisenberg, D. A., Laurin, L., & Seager, T. P. (2014). Anticipatory life-cycle assessment for responsible research and innovation. Journal of Responsible Innovation, 1(2), 200–207. https://doi.org/10.1080/23299460.2014.920121
- Yu, Y., Zhang, B., Feng, M., Qi, G., & Tian, F. (2017). Multifunctional structural lithium ion batteries based on carbon fiber reinforced plastic composites. Composites Science and Technology, 147, 62–70. https://doi.org/10.1016/j.compscitech.2017.04.031

Life Cycle Assessment of Waste Tyre Recycling in Australia

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Abstract

Australia produces approximately 537 thousand tonnes of waste tyres (WTs) each year, with only about 66% recovered for civil engineering applications; the remainder is either landfilled or stock-piled. In civil engineering, tyre-derived granules and crumbs are limited to 5–10% binder substitution in road construction due to structural performance constraints. Additionally, substituting sand with granules in concrete increases the carbon footprint. These challenges underscore the need for more sustainable management strategies. To address this, the present study applies a Life Cycle Assessment (LCA) using SimaPro to compare pyrolysis to current practices, such as landfilling and crumb rubber production, in Australia. The assessment uses 1 tonne of WTs as its functional unit, with inventory data sourced from Tyre Stewardship Australia and published studies, adapted for Australian conditions. The results show that pyrolysis emits (255 kg CO2eq per tonne), which is lower than crumb rubber production (278 kg CO2eq per tonne) and landfilling (598 kg CO2eq per tonne) under the current electricity generation scenario. It is important to note, however, that crumb production will have a comparable GWP to WT pyrolysis due to the absence of direct greenhouse gas emissions. Looking ahead, the electrification of pyrolysis is expected to be the most sustainable pathway, given its lower electricity consumption compared to crumb production. Therefore, based on these findings, pyrolysis is recommended for treating WTs in Australia.

Key words: Waste tyre, Recycling, Pyrolysis and Life Cycle Assessment

Introduction

Waste tyres (WTs) represent a significant global environmental challenge due to their durability, complex composition, and high annual generation rate (Pei et al., 2025). These tyres are composed of heterogeneous materials, including natural and synthetic rubber, carbon black, textile fibres, steel wires, zinc oxide, and various chemical additives that enhance mechanical strength and durability (Pei et al., 2024). The structural components include the tread, carcass, bead, and inner liner. WTs differ from new tyres primarily because of tread mass loss resulting from road wear, up to 20% of the tread (Abdullah, 2024), which is rich in natural rubber, may be lost through surface erosion (Han et al., 2024). This material complexity hinders recycling and energy recovery efforts, contributing to environmental issues such as particulate matter emissions (Kumar et al., 2025).

Each year, approximately 1.5 billion tyres reach the end of their life globally, with over 4 billion estimated to be stockpiled or landfilled, a figure projected to increase to 5 billion by 2030. Waste tyres are classified as non-hazardous and non-biodegradable, persisting for centuries in landfills and stockpiles. Leachates from tyres can contaminate soil and water, while stockpiles elevate fire risks and serve as breeding grounds for disease vectors (Xiao et al., 2022). In Australia, Tyre Stewardship Australia (TSA) reports that approximately 537,000 tonnes of WTs are generated annually, with a recovery rate of 66% (TSA, 2024a). Of these, about 95% are on-road tyres for cars and trucks. Car tyres are predominantly shredded and exported, accounting for up to 56% of total WTs in 2019, whereas truck tyres are recycled domestically into crumb rubber and granulates (1–8%) for civil engineering applications (TSA, 2019). The production of crumb rubber for civil engineering applications has resulted in 345.67 kg CO2eq /t emissions, but it has also saved valuable resources (steel and asphalt binder) worth $16 billion in Australia (Tushar et al., 2022). The TSA has recently reported that the use of WT-derived rubber products in asphalt is generally limited in quantity, with crumb rubber typically replacing 5-10% of the bitumen binder by weight in asphalt mixtures. Similarly, in concrete, rubber granules sourced from WTs are used to substitute an equivalent proportion of sand by weight, generally within the 5-10% range (TSA, 2024b). Despite these applications, further uptake is limited by performance requirements and market demand. Retreading constitutes approximately 6% and pyrolysis less than 1% of the total in Australia (TSA, 2024c, TSA, 2019). WTs are retreated to extend their service life by 2–4 times, depending on the application, but this option is not indefinite (Qiang et al., 2020). Despite these efforts, around 30% of ELTs are still landfilled, either in monofills (7%) or through on-site disposal (23%) (TSA, 2024b). The landfill of WT averages 439 kg CO2eq/t in Australia due to the biodegradation of natural rubber (TSA, 2024b), while the treatment of WTs in monofilaments emitted 1,230.88 kg CO2eq/t (Tushar et al., 2022). Similarly, the incineration of WT in cement kilns and thermal power plants has emitted (2,720 kg CO2eq/t), which is worse than retreading, landfill and crumb production in Australia (TSA, 2024b). Export bans and waste trade restrictions in China, India, and Southeast Asia between 2017 and 2022 have created significant challenges, leading the Australian government to establish a national target of 80% recovery across all WT streams (Hoogzaad, 2024).

Several waste tyre treatment (WTT) technologies have been developed to address global waste management and environmental challenges. (Kumar et al., 2025) has recently conducted a comprehensive literature review on different WTT technologies. The results revealed that pyrolysis is the most sustainable option among the selected technologies, with a maximum GHG savings of 1,298 kg CO2eq/t and resource recovery of 60 eco-points/t, generating a profit of $133/t due to revenue from steel wire, carbon black, pyro-oil, and textile fibres. The analysis was limited to the maximum and minimum values of environmental impact categories to avoid the uncertainties associated with changes in technical and geological boundaries. However, pyrolysis technology has been compared against other treatment technologies in the USA (Feraldi et al., 2013), Turkey (Banar, 2015), Germany (Maga et al., 2023), Europe (Duval et al., 2024) and China (Li et al., 2010, Qi et al., 2025) with accurate measurement, verification, and reporting of input and output inventories to avoid uncertainties and inaccuracies in LCA-based decisions. These studies have found that pyrolysis technology offers better environmental and economic performance than landfilling, incineration, retreading, pulverisation, and devulcanization technologies. Besides pyrolysis advantages, its adoption remains marginal (<1% of current WT recovery) in Australia (TSA, 2024b).

To date, no studies have comprehensively assessed the environmental performance of waste tyre pyrolysis technologies and products in Australia. Although previous research has examined waste tyres for energy recovery and civil engineering, detailed carbon footprint comparisons between pyrolysis and other management options are limited. This study uses a Life Cycle Assessment (LCA) with SimaPro software, applying one tonne of waste tyres as the functional unit. Inventories for collection, transport, and landfill disposal are provided by TSA. Data for commercial crumb rubber production in Melbourne are sourced from (Tushar et al., 2022), while pyrolysis data are adapted from a published scientific study that measures the materials and energy flow and emissions (Banar, 2015) that reflects a Victorian pilot facility. All process inventories are harmonised with Australian conditions as specified in the TSA report. The study compares the carbon footprint of pyrolysis, landfill, and crumb rubber production to determine the most sustainable option for WTs management in Australia.

Material and methods

Goal and Scope

This study aims to calculate the environmental impacts of WT pyrolysis and compare it with landfill and crumb rubber production in Australia. It uses SimaPro Software to develop an LCA model, following the attributional approach and the ISO 14040 guideline. The attributional LCA is the most suitable method for evaluating and comparing the current environmental performance of WT pyrolysis with existing disposal options. It provides a baseline assessment using average data and quantities of direct environmental impacts from material and energy recovery. This study does not include indirect effects of substitutional benefits of steel wire, pyro-oil, and carbon black. Moreover, it does not consider the system expansion that includes the distillation of pyro-oil into diesel and petrol, tar into carbon black, and the recycling of steel wires and chips (Nordenstam, 2021). Therefore, the attributional LCA modelling is a better option than consequential LCA modelling under the given assumptions.2.2. Technical system boundary and life cycle inventory

The selected pyrolysis technology is a pilot-scale system with a daily capacity of 12t (Figure 1). This reflects the currently under-construction facility at Geelong, Australia. It has two main processes. Firstly, a multi-stage pretreatment process (debeader, shredder and granulator) that converts WT to rubber granules of ~20 mm. It is equipped with a magnetic separator which removes steel scrap from granules up to 12% of WT. It consumes 155.51 kWh of electricity per tonne of WT. Rubber granules are fed into a horizontal rotary batch pyrolysis reactor that is heated at 400 °C using heating oil and pyro-gas with a heating value of 42.54 MJ/kg. It takes 11 hours per batch (12 tonnes), including 3 hours of preheating on heating oil and 8 hours of operation, as given in Table 2. Granules are converted into pyrolysis vapour that is further distilled and condensed into pyro-oil (41%), pyro-gas (15%) and coke (32%). Pyro-oil is stored for sale, while pyro-gas passes through a scrubber and demister that remove particulates and moisture for efficient combustion in the pyrolysis reactor. The plant emits CO_2, SO_2, NO_x and Particulate Matters by 68.06 kg, 3.55 kg, 1.40 kg and 0.58 kg/t, respectively. Moreover, the inventory of WT landfill and crumb rubber production in Australia is given in Table 1 *(Tushar et al., 2022, TSA, 2024b).*

Table 1. Inventory of transportation and pretreatment process

Process	Input				Output		
	Material Flow		Energy Use		Product	By-Products	
	Tyre (ton)	Other	Fuel (L)	Electricity (kWh)	Tyre	Steel	Fibres
Collection and Transportation (TSA, 2024b)							
Transportation	1.25	-	8.28	-	1.25	-	-
Pretreatment (Tushar et al., 2022)							
Shredding Process	1.25	-	2.1	28.25	1.25		0.05
Chipping Process	1.25		1.88	45.75	1.00	0.2	-
Granulating process	1.00	-	-	28.75	1.00	-	-
Cracking Process	1.00	-	0.1	303.5	1.00	0	0

Table 2. Inventory of pilot-scale pyrolysis plant (Banar, 2015).

Parameter	**Data**	Unit
Waste Tyre Chips Feed rate	1.00	Tonne
Operating hours	0.92	h
Total CO_2 emissions	5.67	Kg CO2
Pre-heating duration	0.25	h
Light fuel oil consumption	7.75	Kg
Heating oil-based CO_2 emissions	2.02	Kg CO2
Operating hours with pyrolysis gas	0.67	h
The heating energy of pyrolysis gas	69.90	MJ
Volumetric pyrolysis gas production	13.96	m^3
The percentage of recovered pyrolysis gas	13.14	%
CO_2 generation from the combustion of pyrolysis gas	3.66	Kg CO2

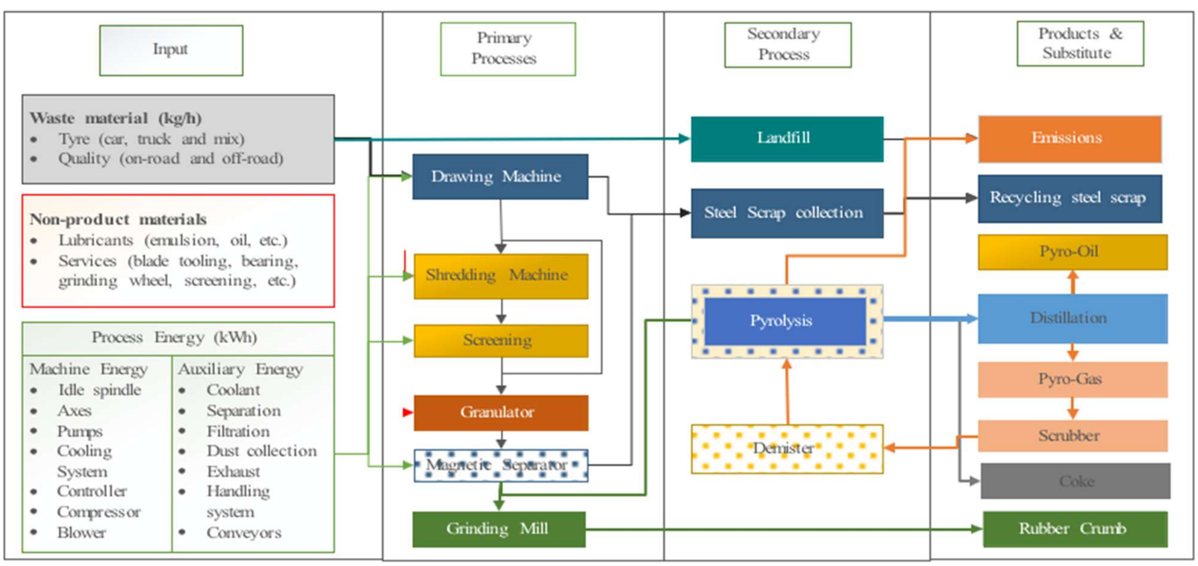

Figure 1. Technical system boundary of WT landfill, crumb rubber production and pyrolysis.

Impact assessment methodology

This study uses the Australian Life Cycle Assessment Society (ALCAS) Best Practice LCIA recommendations methodology to investigate selected categories (Renouf, 2015). This selects global warming potential (GWP), Eutrophication (EU), freshwater eco-toxicity (FE), water scarcity (WS) and resource use-fossil (RUf), which TSA reports (TSA, 2024b).

Results

Environmental impacts of WT pyrolysis

The environmental impacts of waste tyre (WT) pyrolysis were assessed using life cycle assessment (LCA) methodology. Figure 2 presents the relative contributions of pyrolysis emissions, transportation, pretreatment, and fuel oil to selected environmental impact categories. The total global warming potential (GWP) was calculated as 255 kg CO2eq per tonne, with pyrolysis emissions accounting for 85.1 kg CO2eq per tonne, primarily due to the combustion of pyro-gas and fuel oil in the reactor. Embodied emissions from light fuel oil were estimated at approximately 6.41 kg CO2eq per tonne, resulting from its production and transportation to the regional storage facility. Electricity consumption for operating reactor auxiliaries contributed 76.2 kg CO2eq per tonne of WT. Rubber chips, with an average particle size of 20–25 mm, emitted approximately 70 kg CO2eq per tonne during processing. The pyrolysis process was identified as the major contributor to GWP, accounting for up to 65%, followed by pretreatment at approximately 20%. Transportation contributed less than 10%, as 50% of tyres were collected from the regional area and 50% from within Geelong, an intermediate location close to collection sites. Maximum fossil fuel resource depletion was 2900 MJ net calorific value (NCV), with electricity consumption in pretreatment and the reactor contributing 70%, reflecting the dominance of fossil fuels in Australian electricity generation. Negligible resources were consumed in the pyrolysis reactor itself due to the use of internally produced pyro-gas, which supplied up to 89% of the reactor's heating demand, while fuel oil accounted for only 20%. Regarding eutrophication, the combustion of pyro-gas and light fuel oil in the reactor had the highest impact, contributing 80% (0.227 kg PO4 3- eq), primarily due to the high sulphur content in tyres. Freshwater ecotoxicity (2.65 × 10^6 comparative toxic unit equivalents, CTUe) was mainly influenced by transportation and light fuel oil, with minimal contributions from pyro-gas combustion and electricity use.

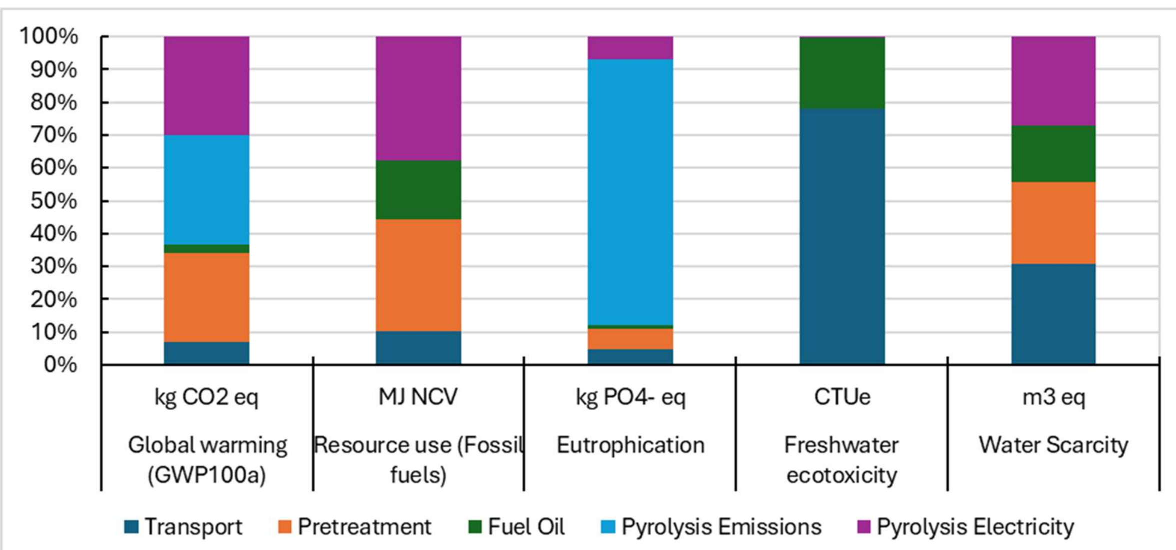

Figure 2. Environmental impact of WT pyrolysis.

Comparative environmental impact assessment with energy transition

The environmental performance of landfill, crumb production, and pyrolysis of waste tyres (WTs) was evaluated using life cycle assessment (LCA). Table 3 summarises the results for both the current electricity mix and the projected transition to renewable energy. Under current conditions, pyrolysis demonstrates the lowest global warming potential (GWP) at 255 kg CO_2eq per tonne, followed by crumb production at 278 kg CO_2eq per tonne and landfill at 598 kg CO_2eq per tonne (TSA, 2024b). The reduced impact of pyrolysis is attributed to its low electricity consumption and the use of pyro-gas for reactor heating. Pyrolysis requires 81 kWh of electricity to convert chips into pyro-oil, whereas pulverising chips into crumb rubber consumes 350 kWh per tonne of WT. Consequently, crumb production results in the highest fossil fuel resource depletion (4120 MJ NCV per tonne), followed by the pyrolysis reactor (2320 MJ NCV per tonne). Landfilling WTs leads to the lowest fossil fuel depletion (158 MJ NCV per tonne), as only transportation is considered. Both crumb production and pyrolysis exhibit substantially higher fossil fuel depletion compared to landfill. Pyrolysis meets approximately 89% of its heating demand with recovered pyro-gas, thereby reducing external energy requirements relative to crumb production. However, the sulphur content in pyrolysis emissions can contribute to eutrophication. Freshwater ecotoxicity burdens are primarily influenced by electricity-related emissions. Pyrolysis (2.65×10^6 CTUe) is lower than crumb production (5.54×10^6 CTUe) but higher than landfill (9.17×10^5 CTUe). Pyrolysis also achieves the lowest water scarcity footprint (0.164 m^3-eq per tonne), outperforming landfill (0.244 m^3-eq per tonne) and crumb production (0.259 m^3-eq per tonne). Currently, pyrolysis offers an acceptable environmental profile, mitigates the impacts of climate change, and facilitates the recovery of materials and energy. Nevertheless, decarbonising electricity remains essential for minimising ecotoxicity. The energy transition could reduce fossil fuel depletion by up to 53% in mechanical processing and 45% in chemical processing of WTs. It also decreases GWP by 40% in crumb production, a greater reduction than observed for pyro-oil generation (31%). The shift to renewable energy by 2050 is projected to have minimal effects on eutrophication or freshwater ecology. However, it increases water scarcity in crumb production by 12% due to reliance on hydropower and biomass-based electricity. In the energy transition scenario, crumb production exhibits the lowest GWP because it depends primarily on grid electricity and does not generate direct emissions, in contrast to pyro-gas combustion.

Table 3. Environmental impacts of landfill, crumb production and pyrolysis.

Impact category	Unit	Landfill	Crumb Production		Pyrolysis	
		Baseline	Present	2050	Present	2050
Global warming potential	kg CO2 eq	598	278	167	255	175
Resource Use (Fossil fuels)	MJ NCV	158	4120	1920	2900	1570
Eutrophication	kg PO4-eq	0.0000971	0.08	0.0542	0.281	0.279
Freshwater ecotoxicity	CTUe	917,000	5,546,000	2,600,000	3,310,000	3,260,000
Water Scarcity	m3 eq	0.244	0.259	0.291	0.205	0.204

Discussion

Comparison with existing studies

Life cycle assessment shows that pyrolysis of WTs yields the lowest GWP at 255 kg CO_2-eq per ton, lower than crumb rubber production (278 kg CO_2-eq per ton) and landfill disposal (598 kg CO_2-eq per ton). This aligns with previous research, which identifies pyrolysis as a lower-emission pathway, ranging from -1,298 to 1,560 kg CO_2-eq per ton (Kumar et al., 2025), compared to incineration and landfilling (Maga et al., 2023, Clauzade et al., 2010). The reduced GWP primarily results from substitution credits for recovered pyro-oil and carbon black, as well as the use of internally generated pyro-gas, which supplies nearly 90% of the reactor's heating needs.

Fossil fuel depletion mainly resulted from transportation and pretreatment processes. Both crumb rubber production (4120 MJ per ton) and pyrolysis (2320 MJ per ton) were dominated by electricity consumption. In contrast, landfill disposal required minimal external energy (158 MJ per ton). These

results are consistent with previous studies (Tushar et al., 2022, Pei et al., 2025). Such studies examined the sensitivity of tyre recycling to grid electricity and the influence of mechanical process parameters on environmental impacts. Pyrolysis showed the highest eutrophication potential (0.227 kg PO_4-eq per ton) due to nitrogen oxides (NO_x) and sulfur dioxide (SO_2) emissions. This is consistent with reported impacts (Banar, 2015, Meng et al., 2023). Freshwater ecotoxicity was also notable (2.65×10^6 CTUe), though lower than crumb rubber production (5.54×10^6 CTUe) (Neri et al., 2018).
The results align with existing studies; however, the primary limitation is the reliance on adapted secondary inventory data, which introduces uncertainty. Future research should incorporate operational data from local facilities and examine scenarios with increased renewable energy integration to more accurately assess the effects of energy transition on the environmental impacts of waste tyre management in Australia.

Policy Consideration

The life cycle results confirm that waste tyre pyrolysis provides the lowest GWP among existing disposal routes in Australia in the present circumstances. However, realising these environmental benefits requires policy alignment. Although end-of-life tyres are recognised as a priority by the National Waste Policy Action Plan, the absence of a coherent regulatory framework and lack of carbon-credit recognition for pyrolysis-derived fuels limit market incentives (GoA, 2019). Policy development should prioritise consistent regulation and clear carbon-credit mechanisms to support investment and implementation.

Australia's limited pyrolysis infrastructure constrains large-scale adoption, emphasising a need for policy-driven investment in capacity expansion. Addressing high capital costs and logistics for dispersed feedstock collection is critical for scaling. Furthermore, policy measures should aim to strengthen domestic markets for recovered carbon black and pyro-oil by updating fuel standards and supporting the energy industry (TSA, 2018). Strategic investment in emission controls and advanced reactor technologies, guided by policy incentives, can further minimise eutrophication and optimise environmental outcomes as the share of renewable energy increases.
While attributional LCA benchmarks existing practices, shaping effective policy requires understanding broader market responses. Future studies employing consequential LCA can inform policymakers about the system-wide impacts of large-scale adoption, such as the substitution of pyro-oil, carbon black, and steel, as well as market displacement. Integrating these insights with national energy-transition planning will better support strategic policy decisions.

Conclusion

This study evaluates the environmental impacts of waste tyre (WT) pyrolysis in comparison with landfill disposal and crumb rubber production in Australia. An LCA model was developed using SimaPro software, with 1 tonne of WT as the functional unit. The results indicate that pyrolysis yields the lowest global warming potential at 255 kg CO_2-eq per tonne, outperforming crumb rubber production and landfilling under the current electricity generation mix. Under a renewable energy transition, crumb rubber production becomes similarly favourable due to its dependence on electricity. Electrification of the pyrolysis reactor is projected to be the most sustainable future option, as it requires less electricity by utilising tyre chips rather than crumb rubber. Eutrophication and ecotoxicity impacts remain considerable, primarily due to electricity consumption during pretreatment and emissions from pyro-gas combustion. Overall, the findings identify pyrolysis as a promising strategy for sustainable waste tyre management in Australia and underscore the importance of enhanced emission controls and increased renewable energy integration to optimise environmental outcomes.

Acknowledgements

This research was funded through the Australian Government's inaugural Trailblazer Universities Program as part of Deakin University's Recycling and Clean Energy Commercialisation Hub (REACH) and by industry partner Clean Energy Resources Geelong (CERG). Deakin has conducted this research in its REACH partnership with CERG for The EoL Tyres to Green Hydrogen Project.

References

- Abdullah, Z. T. 2024. Remanufactured waste tire by-product valorization: Quantitative–qualitative sustainability-based assessment. *Results in Engineering,* 22**,** 102229.
- Banar, M. 2015. Life cycle assessment of waste tire pyrolysis. *Fresenius Environmental Bulletin,* 24**,** 1215-1226.
- Clauzade, C., Osset, P., Hugrel, C., Chappert, A., Durande, M. & Palluau, M. 2010. Life cycle assessment of nine recovery methods for end-of-life tyres. *The International Journal of Life Cycle Assessment,* 15**,** 883-892.
- Duval, L., Majeau-Bettez, G., Saunier, F., Maréchal, F. & Margni, M. 2024. Optimization of the end-of-life tire repartition within the European treatment system to minimize its environmental impacts. *Journal of Industrial Ecology,* 28**,** 512-526.
- Feraldi, R., Cashman, S., Huff, M. & Raahauge, L. 2013. Comparative LCA of treatment options for US scrap tires: material recycling and tire-derived fuel combustion. *The International Journal of Life Cycle Assessment,* 18**,** 613-625.
- GOA 2019. 2018 National Waste Policy: From waste to resource. *In:* Climate Change, E., The Environment And Water (Ed.). Australia.
- Han, B., Kumar, D., Pei, Y., Norton, M., Adams, S. D., Khoo, S. Y. & Kouzani, A. Z. 2024. Sustainable transformation of end-of-life tyres into value-added products using thermochemical processes. *Carbon Research,* 3.
- Hoogzaad, J. 2024. *Chinese waste ban forcing a breakthrough in circular economy ambitions in Australia*
- [Online]. [Accessed 13/09/2024].
- Kumar, D., Pei, Y., Han, B., Khoo, S. Y., Norton, M., Adams, S. D. & Kouzani, A. Z. 2025. Comparative analysis of waste tyre treatment technologies: Environmental and economic perspectives. *Renewable and Sustainable Energy Reviews,* 216.
- Li, X., Xu, H., Gao, Y. & Tao, Y. 2010. Comparison of end-of-life tire treatment technologies: a Chinese case study. *Waste Manag,* 30**,** 2235-46.
- Maga, D., Aryan, V. & Blömer, J. 2023. A comparative life cycle assessment of tyre recycling using pyrolysis compared to conventional end-of-life pathways. *Resources, Conservation and Recycling,* 199.
- Meng, X., Yang, J., Ding, N. & Lu, B. 2023. Identification of the potential environmental loads of waste tire treatment in China from the life cycle perspective. *Resources, Conservation and Recycling,* 193.
- Neri, E., Berti, B., Passarini, F., Vassura, I., Giorgini, L., Zattini, G., Tosi, C. & Cavazzoni, M. 2018. Application of lca methodology in the assessment of a pyrolysis process for tyres recycling. *Environmental Engineering and Management Journal,* 17**,** 2437-2445.
- Nordenstam, L. 2021. Attributional or consequential assessments in a cyclic greenhouse gas management process – Comparison of guidance on use and production of electricity and district heating. *Journal of Cleaner Production,* 317**,** 128214.
- Pei, Y., Han, B., Kumar, D., Adams, S. D., Khoo, S. Y., Norton, M. & Kouzani, A. Z. 2024. Mechanical processes for recycling of End-of-Life Tyres. *Sustainable Materials and Technologies,* 41.

- Pei, Y., Kumar, D., Han, B., Adams, S. D., Khoo, S. Y., Norton, M. & Kouzani, A. Z. 2025. Environmentally informed modelling and optimisation of shredding performance for recycling waste tyres. *Journal of Cleaner Production*, 145696.
- Qi, J., Wang, Y., Xu, P., Hu, M., Huhe, T., Ling, X., Yuan, H., Li, J. & Chen, Y. 2025. Coupling of molten salt heating tire pyrolysis process with carbon black modification process: Technical economic evaluation and life cycle assessment. *Journal of Cleaner Production,* 486.
- Qiang, W., Li, J., Yunlong, W., Xiaojie, Q. & Guotian, W. 2020. Discussion on Tire Retreading and Reuse Technology. *IOP Conference Series: Earth and Environmental Science,* 512**,** 012146.
- Renouf, M. A., Grant, T., Sevenster, M., Logie, J., Ridoutt, B., Ximenes, F., Bengtsson, J., Cowie, A., Lane, J. 2015. Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia. The Australian Life Cycle Assessment Society.
- TSA 2018. Tyre pyrolysis and gasification technologies a brief guide for government and industry. *In:*
- TSA (ed.). Australia.
- TSA 2019. Retreading The repeated benefits. *In:* AUSTRALIA, T. S. (ed.).
- TSA. Life Cycle Assessment of Agriculture and Mining Off-the-Road (OTR) Tyres. 2024a. 4-43. TSA 2024b. Life Cycle Assessment of End-of-Life Tyres. Australia: Tyre Stewardship Australia.
- TSA 2024c. Pyrolysis of end-of-life tyres Review of pyrolysis technologies and product opportunities for Australia.
- Tushar, Q., Santos, J., Zhang, G., Bhuiyan, M. A. & Giustozzi, F. 2022. Recycling waste vehicle tyres into crumb rubber and the transition to renewable energy sources: A comprehensive life cycle assessment. *J Environ Manage,* 323**,** 116289.
- Xiao, Z., Pramanik, A., Basak, A. K., Prakash, C. & Shankar, S. 2022. Material recovery and recycling of waste tyres-A review. *Cleaner Materials,* 5.

Unveiling Hydrogen's Hidden Footprint: A Comparative LCA of Green Hydrogen Production Pathways in India

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Abstract

Green hydrogen as an energy carrier is key to transition to sustainable energy systems and global decarbonization. However, since environmental impacts vary with technology and energy source, a life cycle assessment (LCA) is essential to holistically assess and compare hydrogen production pathways. This study conducts LCA of hydrogen generation employing grid, solar-powered battery energy storage systems (Li-ion and lead-acid), solar photovoltaics, and wind as electricity sources for electrolysis technologies. A cradle-to-gate framework is applied using OpenLCA 2.3 with the ecoinvent database and ReCiPe Midpoint (H) and Endpoint (H/A) methods, assessing 18 midpoint and 3 endpoint environmental indicators.

Results indicate that SOE shows the highest climate (5.44, 3.11 kg CO_2-eq) and AEM the highest water depletion (37, 19 L) impacts when powered by solar or wind. but the lowest (57.49 kg CO_2-eq, 213 L) when powered by the SOE grid. Conversely, AWE exhibits the lowest climate impact (4.28, 1.12 kg CO_2-eq) under renewables, but its impact rise sharply to (74.77kg CO_2-eq) when grid-supplied, second only to PEM at (74.99 Kg CO2-eq). End-point analysis reveals grid-powered hydrogen has greater overall impacts, dominated by human health, followed by resource depletion and ecosystem quality. These findings emphasize the decisive role of renewable integration in achieving sustainable hydrogen pathways, particularly for emerging economies like India.

Keywords: Hydrogen, Life Cycle Assessment (LCA), Electrolysis Technologies.

Introduction

The global surge in energy demand, environmental degradation, and depletion of conventional fossil fuel re-serves have necessitated a transition toward sustainable, renewable energy sources (Kalinci et al., 2012; Surya-wanshi et al., 2023). This imperative aligns closely with Sustainable Development Goal 7, "Affordable and Clean Energy," motivating nations to adopt policies that enhance renewable energy production. A key development in this global transition is the growing emphasis on green hydrogen (H_2), as reflected in India's National Green Hydrogen Mission, which targets the indigenous production of 5 million metric tons of green H_2 by 2030 (National Green Hydrogen Mission | MNRE, n.d.). Green hydrogen is defined as hydrogen produced through water electrolysis using electricity exclusively derived from renewable energy sources such as solar, wind, or hydropower, resulting in negligible greenhouse gas emissions throughout its life cycle. This ambitious initiative aims to reduce energy import dependency, decarbonize critical sectors like manufacturing and transportation, and foster a self-reliant, low-carbon economy in pursuit of net-zero emissions by 2070.

Historically, hydrogen has been primarily utilized as a commodity gas and feedstock in oil refining and fertilizer manufacturing (Hassan, 2020; Zheng et al., 2019). However, it is now recognized as a versatile and environmentally friendly energy vector that can be derived from water, methane, and biomass using thermal, electrical, bio-chemical, and photonic processes (Dincer, 2012). Hydrogen enhances the flexibility of energy systems by enabling synchronization between energy production and demand (Hassan, Jaszczur, Abdulateef, et al., 2022), while its storability and transportability make it suitable for applications ranging from daily to seasonal storage and global trade. Despite these advantages, conventional hydrogen production —predominantly from natural gas (75%) and coal (23%)—emits substantial greenhouse gases, contributing to climate change (Hurtubia & Sauma, 2021).

Prior LCA studies on hydrogen generation have primarily focused on a single electrolysis method or a specific regional location, usually ignoring comparison assessments across multiple production pathways and energy sources. This study contributes to the field by conducting a complete, India-specific life cycle assessment of four electrolysis technologies while including renewable and grid-based electricity scenarios to provide precise in-sights for maximising sustainable hydrogen pathways. To address these challenges, this study employs a com-prehensive life cycle assessment (LCA) framework to evaluate the environmental impacts of multiple hydrogen production pathways. The research identifies sustainable hydrogen production pathways aligned with climate and resource-efficiency goals, providing policy-relevant insights for India and other emerging economies pursuing green energy transitions.

Material and methods

Life cycle assessment:

Life cycle assessment (LCA) is one of the most established methods for estimating the environmental performance associated with the life cycle of products and services. LCA assesses the environmental impact of a product, process, or service over its entire life cycle, from raw material extraction to disposal. The first LCA framework was published by the Society of Environmental Toxicology and Chemistry (Consoli F. SETAC, 1993). After many modifications, the practice of LCA was regulated, and nowadays, its application follows the ISO 14040 and 14044 standards (ISOa, 2006 and ISOb, 2006). The LCA comprises four phases: 1. Goal and Scope Definition, 2. Inventory of Inputs and Outputs, 3. Impact Assessment, and Interpretation of Results.

System Description

The system for hydrogen generation via electrolysis consists of a sequence of integrated processes designed within a defined life cycle assessment (LCA) boundary. The system begins with the construction of a power plant, involving the use of materials such as metals, concrete, plastics, and raw material inputs for production of electricity. The electricity generated is then utilised for multiple downstream processes, starting with water purification, where tap water is pumped into an ion exchange system to remove salts and impurities, producing deionized water suitable for electrolysis. The purified water is fed into an electrolyzer, where one of four electrolyzer technologies Alkaline Electrolyzer (AWE), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), or Solid Oxide Electrolyzer (SOE) is used to split water into hydrogen and oxygen using the solar-generated electricity. In the electrolysis process, hydrogen is produced at the cathode while oxygen is released at the anode and vented into the atmosphere as an elementary flow.

The resulting hydrogen gas contains trace water vapour, which is removed through a gas-water separation step involving condensate traps. The dry hydrogen is then compressed for storage using a compressor and subsequently stored in Type III storage tanks, which consist of metal liners wrapped with composite materials. The system's electricity requirements cover the electrolysis, gas separation, hydrogen compression, and water pumping processes. The system boundary includes these energy and material flows but excludes the impacts from manufacturing of machinery, infrastructure, system decommissioning, recycling, and potential leakage losses.

The functional unit is defined as the production of 1 kg of hydrogen, with the overall system designed to maximise resource efficiency while minimising environmental impacts relative to conventional hydrogen production methods. Figure 1 shows the Process flow and system boundary of the study.

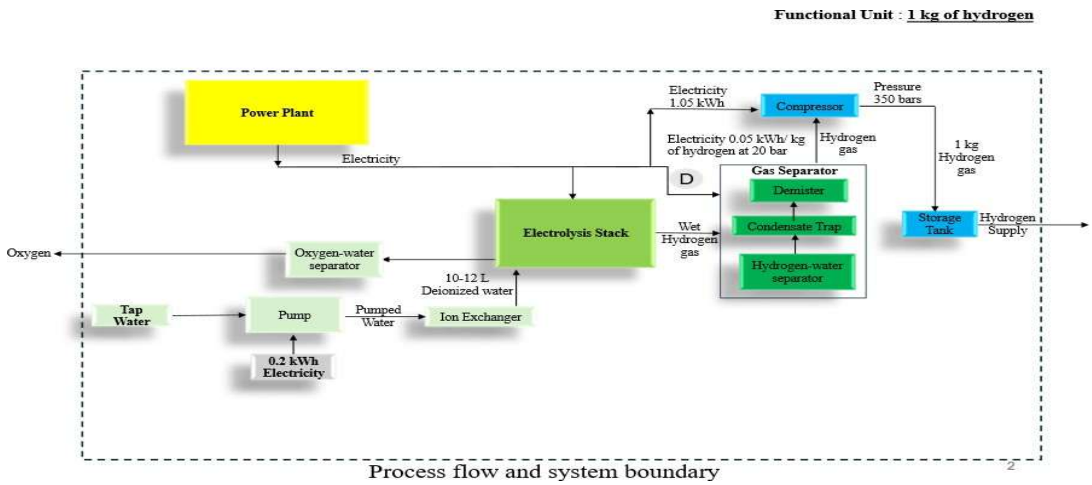

Figure 1Process flow and system boundary

Results

This study adopts a cradle-to-gate life cycle assessment (LCA) approach using OpenLCA version 2.3, the ecoinvent database, and the ReCiPe Midpoint (H) and Endpoint (H/A) methodologies. The analysis covers 18 midpoint and 3 endpoint environmental impact categories, providing a comprehensive environmental profile of hydrogen production via electrolysis using different electricity sources solar, wind, grid-mix, and Battery Energy Storage Systems (BESS) Li-ion and Lead Acid in the Indian context. The findings not only deepen the understanding of environmental trade-offs associated with different electrolysis technologies but also offer broader insights for policy and strategic planning in developing economies of the Global South striving for a sustainable energy transition.

Life Cycle Impact Assessment (Mid-Point Indicator)

The life cycle impact assessment (LCIA) of hydrogen production via electrolysis technologies Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), Alkaline Water Electrolyzer (AWE), and Solid Oxide Electrolyzer (SOE) evaluated across various electricity sources including grid, solar PV, wind, and Battery Energy Storage Systems (BESS) with Li-Ion and Lead Acid batteries, reveals critical insights into their environmental performance. The climate change impact, represented by global warming potential (GWP100), is highest when hydrogen is produced using grid electricity, where PEM records 74.99 kg CO_2-equivalent per kg of hydrogen, AEM at 67.46 kg, AWE at 74.75 kg, and SOE at 57.49 kg CO_2-equivalent. In contrast, wind and solar PV scenarios yield the lowest emissions, with AWE powered by wind having the least impact at 1.12 kg CO_2-equivalent per kg of hydrogen. Water depletion also mirrors this trend, being highest in the grid, while renewable energy sources lead to minimal water consumption, with AWE under wind power consuming just 15 litres of water.

Toxicity-related impacts, such as human toxicity and ecotoxicity across freshwater and marine ecosystems, are significantly amplified under BESS Li-Ion scenarios due to the high environmental costs associated with battery production and usage. For example, PEM powered by BESS Li-Ion incurs a human toxicity impact of 91.004 kg 1,4-DCB-equivalent per kg of hydrogen. Similarly, metal depletion is substantially higher in BESS Li-Ion cases, reflecting the heavy reliance on critical metals like lithium and cobalt, with PEM recording 77.85 kg Fe-equivalent under this configuration. Land occupation impacts, both agricultural and urban, remain minimal in renewable-powered scenarios, where PEM with solar PV occupies merely 8.69E-04 m²a of agricultural land per kg of hydrogen, indicating a very low spatial footprint compared to grid or battery-powered pathways. Overall, the LCA underscores that renewable energy sources such as solar PV and wind are essential for minimizing the environmental burdens of hydrogen production. In contrast, grid electricity and BESS Li -Ion configurations are associated with heightened impacts, especially in carbon -intensive energy contexts like India's grid mix. SOE emerges as a particularly sustainable electrolyzer technology when paired with renewables, while PEM's performance is notably dependent on the carbon intensity of the electricity source. These findings highlight the pivotal role of clean electricity in enabling truly sustainable hydrogen pathways, essential for supporting global decarbonization efforts. The Global Warming Potential (GWP) analysis reveals that hydrogen production's climate impact varies significantly with both the electrolysis technology and the electricity source. The highest emissions occur when grid electricity powers the electrolyzers, with PEM showing the maximum impact at 74.99 kg CO_2-equivalent per kg of hydrogen, followed by AWE, AEM, and SOE. In contrast, the lowest GWP values are achieved when renewable sources like wind and solar PV are used. For example, AWE powered by wind yields only 1.12 kg CO_2-equivalent, the lowest among all configurations. These results highlight the critical influence of electricity source selection in reducing the carbon footprint of hydrogen production. The detailed comparison of GWP across all electrolyzers and energy sources is shown in Figure 2.

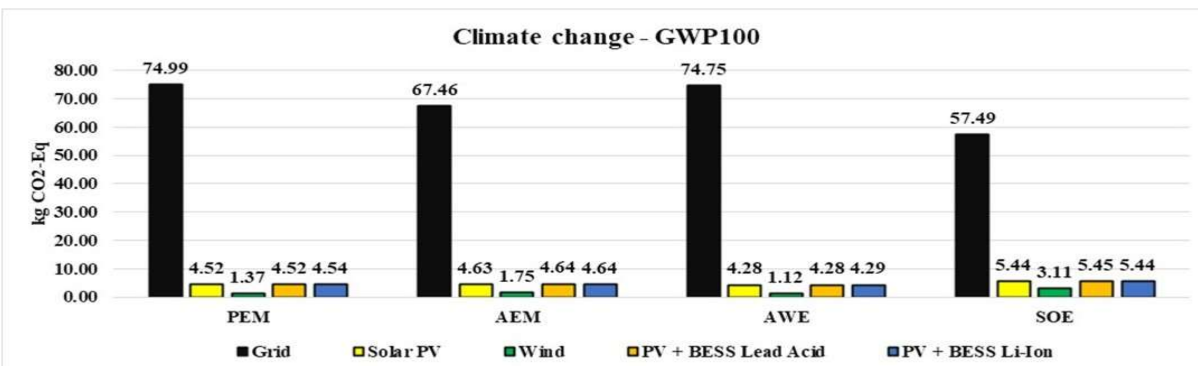

Figure 2 Global Warming Potential (GWP)

The Water Depletion Potential (WDP) assessment indicates that hydrogen production is water-intensive when relying on grid electricity and BESS, particularly with Li-Ion batteries. PEM powered by the grid depletes 280.7 l of water per kg of hydrogen, whereas renewable sources such as wind and solar significantly reduce this burden as PEM using wind energy consumes only 16.7 l of water per kg of hydrogen, demonstrating the efficiency of renewable-powered systems in conserving water resources. The environmental advantage of integrating hydrogen production with renewable energy is clearly reflected in the water depletion outcomes presented in Figure 3.

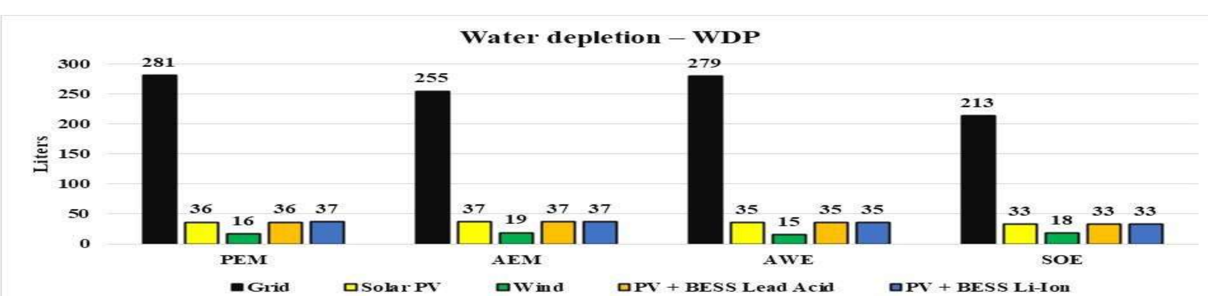

Figure 3 Water Depletion Potential (WDP)

In terms of land use, particularly agricultural and urban land occupation, the results show that solar and BESS solar powered hydrogen production systems have the highest land footprint. Wind powered PEM occupies lowest agricultural and urban land per kg of hydrogen, while grid powered systems lead to substantially lower urban land use while highest agriculture land use. This trend is consistent across all electrolyzers, affirming that wind minimize the spatial impact of hydrogen production infrastructure. The comparison of land occupation impacts across different technologies and power sources is depicted in Figure 4.

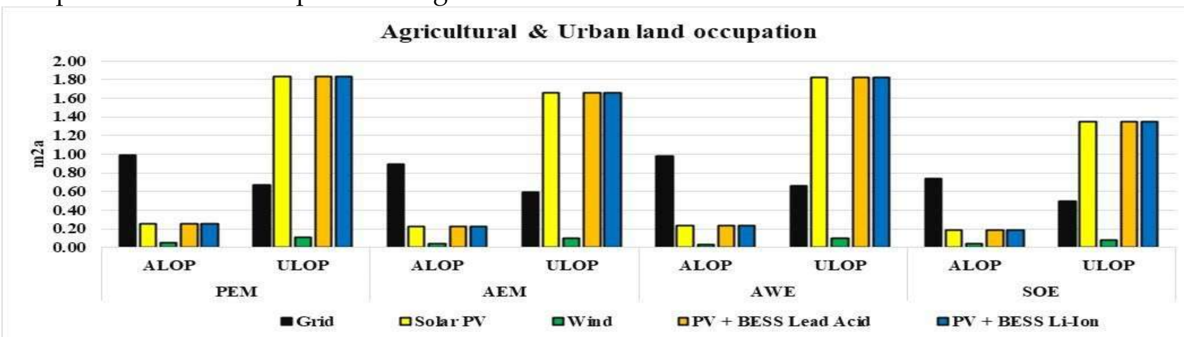

Figure 4 Land Use

Regarding Metal Depletion Potential (MDP), the study finds that scenarios involving Solar and Wind result in significantly higher metal resource consumption. PEM powered by solar depletes 1.03 kg Fe-equivalent per kg of hydrogen, reflecting the resource-intensive nature of solar panels due to the demand for critical metals like silicon, cobalt, and nickel. In contrast, hydrogen production powered by grid energy drastically lowers metal depletion, especially with SOE technology. This stark difference underscores the importance of LCA for installation of hydrogen production plant. The complete analysis of metal depletion across the assessed configurations is illustrated in Figure 5.

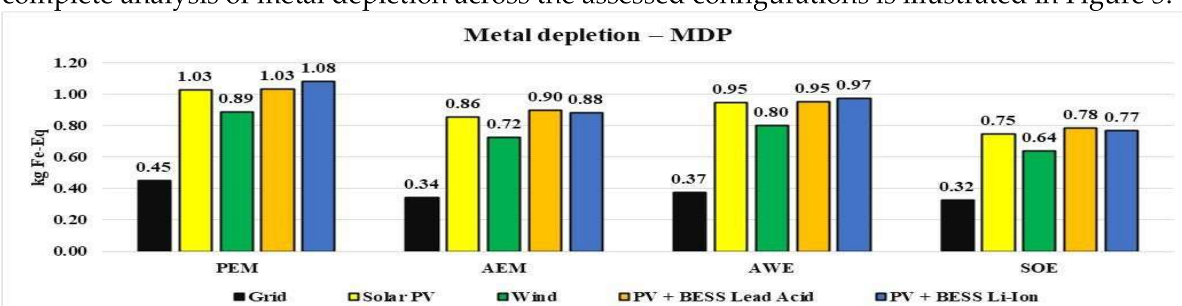

Figure 5 Metal Depletion Potential

End Point Assessment

The endpoint impact analysis of hydrogen production technologies presents insights into three critical sustainability dimensions: ecosystem quality, human health, and resource depletion, cumulatively influencing the overall environmental footprint. Across all electrolyzers AWE, PEM, AEM, and SOE when powered by renewable sources such as wind and solar, the impacts on all three endpoint categories remain minimal. For instance, the overall total impact for SOE powered by wind is just 0. 41 points, while PEM and AEM using wind energy have even lower overall impacts of 0.30 and 0.28 points, respectively. Conversely, the environmental impacts spike when electrolysis technologies are powered by Battery Energy Storage Systems (BESS) Li-Ion and grid electricity, with PEM and AWE recording overall totals of 7.75 and 7.2 points, respectively. This heightened impact is primarily driven by resource depletion and human health damages, reflecting the intensive material requirements and emissions associated with battery production and fossil-fuel dominant grid mixes.

This positions renewable hydrogen as a superior alternative for minimizing ecosystem degradation, reducing health risks, and conserving resources. The endpoint analysis reinforces that the choice of both electrolysis technology and energy source critically determines the sustainability outcomes of hydrogen production pathways. The detailed comparison of endpoint category impacts across all assessed technologies and energy sources is summarized in Figure 6.

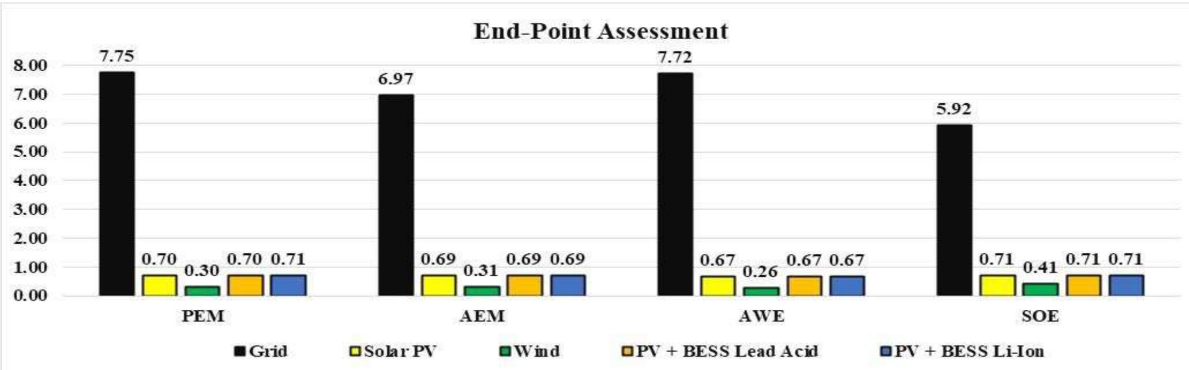

Figure 6 End Point Assessment

Discussion

This study presents a comprehensive Life Cycle Assessment (LCA) of various hydrogen generation technologies, specifically examining the environmental impacts of different electrolysis methods PEM, AEM, AWE, and SOE under diverse energy sources including solar PV, wind, battery energy storage systems (Li-Ion and Lead Acid), and grid electricity. The analysis covers both midpoint and endpoint indicators, providing critical insights into climate change potential, water depletion, land use, resource depletion, human health, and ecosystem quality. The results demonstrate that hydrogen production is highly sensitive to the electricity source used, with renew-able energy-powered electrolysis (wind and solar PV) consistently showing the lowest environmental impacts across all categories. Conversely, hydrogen generated through grid electricity and battery storage systems (particularly Li-Ion) imposes a significant burden on human health, resource consumption, and global warming potential, primarily due to the fossil-fuel-based composition of the grid and the material intensity of battery pro-duction.

Conclusion

The outcomes of this LCA provide a valuable foundation for developing tailored pathways for a sustainable energy transition, essential for addressing escalating climate change, pollution, and environmental degradation. By understanding the full environmental footprint of hydrogen production routes, this work enables the identification of strategies that balance energy demands with environmental sustainability, particularly in contexts like India and the Global South. Importantly, the findings can inform policy frameworks that prioritize the integration of green hydrogen with renewable energy, encourage innovation in electrolyzer efficiency, and support the development of cleaner battery technologies. Given the urgent global mandate to decouple economic growth from environmental harm, this study contributes to broader research and policy efforts aimed at making economic growth cleaner, controlling environmental externalities, and protecting human populations from environmental risks. Moving forward, the insights from this LCA will be instrumental in guiding policymakers, industries, and researchers to align hydrogen production pathways with the goals of a sustainable, low-carbon, and resource-efficient future, while maintaining economic competitiveness and ensuring environmental protection.

References

- Behroozsarand, A., Zamaniyan, A., & Ebrahimi, H. (2010). Industrial hydrogen production and CO2 management. Journal of Natural Gas Science and Engineering, 2(4), 192–196. https://doi.org/10.1016/j.jngse.2010.06.001 Catumba, B. D., Sales, M. B., Borges, P. T., Ribeiro Filho, M. N., Lopes, A. A. S., Sousa Rios, M. A. de, Desai, A. S., Bilal , M., & Santos, J. C. S. dos. (2023). Sustainability and challenges in hydrogen production: An advanced bibliometric analysis. International Journal of Hydrogen Energy, 48(22), 7975–7992. https://doi.org/10.1016/j.ijhydene.2022.11.215
- Ceran, B., Mielcarek, A., Hassan, Q., Teneta, J., & Jaszczur, M. (2021). Aging effects on modelling and operation of a photovoltaic system with hydrogen storage. Applied Energy, 297, 117161.
- https://doi.org/10.1016/j.apenergy.2021.117161
- Chi, J., & Yu, H. (2018). Water electrolysis based on renewable energy for hydrogen production. Chinese Journal of Catalysis, 39(3), 390-394. https://doi.org/10.1016/S1872-2067(17)62949-8
- Consoli, F. (1993). Guidelines for Life-cycle Assessment: A Code of Practice ; SETAC Workshop Held at Sesimbra,
- Portugal, 31 March - 3 April 1993. Society of Environmental Toxicology and Chemistry
- Dincer, I. (2012). Green methods for hydrogen production. International Journal of Hydrogen Energy, 37(2), 1954–1971. https://doi.org/10.1016/j.ijhydene.2011.03.173
- Elke Schropp, Felipe Campos-Carriedo, Diego Iribarren, Gabriel Naumann, Christian Bernäcker, Matthias Gaderer, Javier Dufour (2024) Environmental and material criticality assessment of hydrogen production via exchange membrane electrolysis, Applied Energy, Volume 356, 2024, 122247, ISSN 0306-2619,
- https://doi.org/10.1016/j.apenergy.2023.122247.
- Hassan, Q. (2020). Optimisation of solar-hydrogen power system for household applications. International Journal of Hydrogen Energy, 45(58), 33111–33127. https://doi.org/10.1016/j.ijhydene.2020.09.103
- Hassan, Q., Jaszczur, M., Abdulateef, A. M., Abdulateef, J., Hasan, A., & Mohamad, A. (2022). An analysis of
- photovoltaic/supercapacitor energy system for improving self-consumption and self-sufficiency. Energy Reports, 8, 680–695. https://doi.org/10.1016/j.egyr.2021.12.021
- Hassan, Q., Jaszczur, M., Hafedh, S. A., Abbas, M. K., Abdulateef, A. M., Hasan, A., Abdulateef, J., & Mohamad, A. (2022). Optimizing a microgrid photovoltaic-fuel cell energy system at the highest renewable fraction. International Journal of Hydrogen Energy, 47(28), 13710–13731. https://doi.org/10.1016/j.ijhydene.2022.02.108
- Hassan, Q., Pawela, B., Hasan, A., & Jaszczur, M. (2022). Optimization of Large-Scale Battery Storage Capacity in Conjunction with Photovoltaic Systems for Maximum Self-Sustainability. Energies, 15(10), Article 10. https://doi.org/10.3390/en15103845
- Ho, W. S., Hashim, H., Lim, J. S., Lee, C. T., Sam, K. C., & Tan, S. T. (2017). Waste Management Pinch Analysis (WAMPA): Application of Pinch Analysis for greenhouse gas (GHG) emission reduction in municipal solid waste management. Applied Energy, 185, 1481– 1489. https://doi.org/10.1016/j.apenergy.2016.01.044
- Hurtubia, B., & Sauma, E. (2021). Economic and environmental analysis of hydrogen production when complementing renewable energy generation with grid electricity. Applied Energy, 304, 117739. https://doi.org/10.1016/j.apenergy.2021.117739
- Jaszczur, M., Rosen, M. A., Śliwa, T., Dudek, M., & Pieńkowski, L. (201). Hydrogen production using high temperature nuclear reactors: Efficiency analysis of a combined cycle. International Journal of Hydrogen Energy, 41(19), 7861–7871. https://doi.org/10.1016/j.ijhydene.2015.11.190

- Jinxu Zhang, Bo Ling, Yong He, Yanqun Zhu, Zhihua Wang (2022). Life cycle assessment of three types of hydrogen production methods using solar energy, International Journal of Hydrogen Energy, Volume 47, Issue
- 2022, Pages 14158-14168, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2022.02.150.
- Kalinci, Y., Hepbasli, A., & Dincer, I. (2012). Life cycle assessment of hydrogen production from biomass gasification systems. International Journal of Hydrogen Energy, 37(19), 14026–14039. https://doi.org/10.1016/j.ijhydene.2012.06.015
- Mehmeti, A., Angelis-Dimakis, A., Boigues Muñoz, C., Graziadio, M., & McPhail, S. J. (2018). Eco-thermodynamics of hydrogen production by high-temperature electrolysis using solid oxide cells. Journal of Cleaner Production, 199, 723-736. https://doi.org/10.1016/j.jclepro.2018.07.166
- Muhammed Iberia Aydin, Ibrahim Dincer (2022)An assessment study on various clean hydrogen production methods, Energy, Volume 245, 2022, 123090, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.123090. National Green Hydrogen Mission | Ministry of New and Renewable Energy | India. (n.d.). Retrieved July 5, 2024, from https://mnre.gov.in/national-green-hydrogen-mission/
- Rossi, F., Li, Y., & Gambelli, A. M. (2021). Thermodynamic and Kinetic Description of the Main Effects Related to the Memory Effect during Carbon Dioxide Hydrates Formation in a Confined Environment. *Sustainability*, *13*(24), 13797. https://doi.org/10.3390/su132413797
- Sato, T., Qadir, M., Yamamoto, S., Endo, T., & Zahoor, A. (2013). Global, regional, and country level need for data on wastewater generation, treatment, and use. Agricultural Water Management, 130, 1–13. https://doi.org/10.1016/j.agwat.2013.08.007.
- Suryawanshi, S. J., Shewale, V. C., Thakare, R. S., & Yarasu, R. B. (2023). Parametric study of different biomass feedstocks used for gasification process of gasifier—A literature review. Biomass Conversion and Biorefinery, 13(9), 7689–7700. https://doi.org/10.1007/s13399-021-01805-2.
- Yang, S., Mao, D., Yu, Z., Ma, W., Ma, L., Li, X., & Xi, F. (2024). Comparison of life cycle assessment between hydrogen production from silicon waste and alkaline water electrolysis. Science of The Total Environment, 920, 171065. https://doi.org/10.1016/j.scitotenv.2024.17106.
- Zheng, X., Streimikiene, D., Balezentis, T., Mardani, A., Cavallaro, F., & Liao, H. (2019). A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. Journal of Cleaner Production, 234, 1113–1133. https://doi.org/10.1016/j.jclepro.2019.06.140.

Decarbonising Electricity for Recycling: Impacts on Municipal Waste Glass Recovery in Victoria

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Abstract

Australia's electricity generation remains dominated by coal, which accounted for 46 percent of output in 2023. With the Australian Energy Market Operator's "Step Change" scenario targeting 82% renewables by 2030, this study examines how electricity decarbonisation may influence emissions from municipal waste glass recycling. Piloted in Yarra City Council, Melbourne, the study compares life cycle emissions from two systems: mixed kerbside recycling bin (MKRB) and separate municipal waste glass bin (SKGRB), both supplying recycled glass for asphalt production. A hypothetical scenario was modelled in which 50% of coal-fired electricity in Victoria's 2022 mix was replaced with zero-emission renewables. Under this cleaner mix, emissions from the sorting stage fell by approximately 26% in the SKGRB system and 37% in the MKRB system, due to higher electricity intensity in the latter. The total emissions decrease to 93.58 kg CO_2-eq for SKGRB and 131.29 kg CO_2-eq for MKRB. This corresponds to reductions of 1.35 kg CO_2-eq and 23.15 kg CO_2-eq per ton of asphalt. Findings highlight the importance of coordinating recycling strategies with electricity transition planning to ensure consistent climate benefits.

Keywords: Municipal waste glass, electricity decarbonisation, LCA, asphalt, recycling infrastructure

Introduction

The global effort to address climate change has placed increasing importance on reducing greenhouse gas (GHG) emissions from all sectors of the economy. In addition to direct emissions, embodied carbon, which refers to the emissions generated throughout the life cycle of products and systems, has become a key focus in environmental policy, infrastructure planning, and material management (Gillespie and McIlwaine, 2021; Drewniok et al., 2022).

At the same time, growing volumes of municipal solid waste (MSW) are placing mounting pressure on collection and processing systems. As urban populations expand, so does the quantity of packaging and container waste. Without effective recovery systems, this waste contributes to landfill demand, resource loss, and broader environmental degradation.

Glass represents a high-value material within the waste stream. It is chemically inert, non-biodegradable, and logistically heavy, yet it can be indefinitely recycled. Across Australia, policies have encouraged the use of recycled glass in civil construction, particularly as an aggregate substitute in asphalt (Australian Government, 2022). While this practice shows promise in both environmental and economic terms, the carbon implications of different glass recovery systems remain insufficiently quantified (Arulrajah et al., 2018). In Victoria, two primary household glass recovery methods are currently in use. The mixed kerbside recycling bin (MKRB) combines glass with other recyclable materials such as paper, metals, and plastics. In contrast, the separate kerbside glass recycling bin (SKGRB) collects glass alone, allowing for cleaner input into secondary applications. Although the SKGRB system is generally assumed to improve material quality, its comparative environmental benefits, especially in terms of embodied carbon, require closer evaluation (Harrison et al., 2020).

A critical factor influencing the carbon intensity of glass recovery and reuse is the electricity required during sorting and processing. Australia's electricity grid has historically been dominated by coal-fired generation, resulting in higher emission intensity per unit of energy compared with electricity systems in regions such as Europe, where natural gas and other lower-emission sources are more prevalent (Gutai et al., 2024). As Australia increases its share of renewable energy, emission reductions are expected across energy-dependent stages of material recovery (Zhang et al., 2024).

This study investigates how the introduction of renewable energy into the electricity grid affects the embodied energy of asphalt containing recycled glass derived from different municipal recovery systems. By modelling a scenario in which coal-based generation is reduced by 50% and replaced by renewable sources, the analysis quantifies changes in emissions during the sorting stage and assesses their implications for overall life cycle performance (Jiang et al., 2025).

The findings fill a critical empirical gap and provide a foundation for future scenario analysis and policy development (Anwar et al., 2024; Liu et al., 2022). This study does not include sensitivity or uncertainty analysis. Rather, it provides a deterministic comparison between different electricity grid conditions and waste recovery systems.

Materials and Methods

Goal and scope definition

This study applies a life cycle assessment (LCA) approach consistent with ISO 14040 and ISO 14044 to evaluate the greenhouse gas (GHG) emissions associated with using recycled municipal solid waste (MSW) glass in asphalt production. The method is selected due to its ability to make evidence-based environmental performance analysis (Subal et al., 2024; Akintayo et al., 2024).

The system boundary includes five life cycle stages: street collection, sorting, asphalt production, asphalt distribution (in-use), and demolition or end-of-life. It reflects cradle-to-cradle (Požarnik et al., 2023). Emissions are quantified in kilograms of carbon dioxide equivalent (kg CO_2-eq) per functional unit. The functional unit is defined as 1 ton of asphalt containing recycled MSW glass. This reference frame reflects the practical application of recovered glass in road construction and allows for consistent comparison across systems and scenarios.

The central focus of this study is to assess how changes in the electricity grid influence the embodied energy of asphalt made with recycled glass. Two electricity grid scenarios are examined:

a. Current grid scenario, based on Victoria's existing electricity mix, which includes a high share of coal-fired generation and therefore has relatively high carbon intensity per unit of electricity.
b. Decarbonised grid scenario, in which 50% of coal-based electricity is replaced with renewable energy sources. This adjustment is applied only to the sorting stage, which is the most electricity-intensive process in the system.

In both grid scenarios, two types of municipal glass recovery systems are evaluated:

c. Mixed kerbside recycling bin (MKRB), in which glass is collected together with paper, plastic, and metal recyclables.

d. Separate kerbside glass recycling bin (SKGRB), in which glass is collected on its own in a dedicated bin.

Both systems are currently in operation in Victoria and serve as supply pathways for recycled glass used in asphalt production. They differ in collection design and sorting requirements, which leads to differences in total emissions across life cycle stages.

Life Cycle Inventory

Inventory data and emission factors are based on previously published and peer-reviewed work by Zhang et al. (2022, 2024a, 2024b).

Stage-level emissions from the two recovery systems

Life cycle inventory data for each stage were sourced from Zhang et al. (2022, 2024a, 2024b), which provided emission estimates for both the MKRB and the SKGRB systems. **Table 1** presents the greenhouse gas emissions for each life cycle stage, expressed in kilograms of CO_2-equivalent per ton of asphalt produced.

Table 1. Life cycle GHG emissions by system and stage (kg CO_2-eq/ton asphalt)

Stage	SKGRB	MKRB
Street collection	0.99	2.95
Sorting	5.20	62.57
Asphalt production	81.92	81.92
Asphalt in-use	1.89	1.89
Demolition/End-of-life	4.93	4.93
Total	94.93	154.44

The sorting stage is energy-intensive and contributes significantly to total emissions, particularly in the MKRB system. **Table 2** summaries the energy consumption per kilogram of glass input during sorting, along with the associated emission factors under current grid conditions.

Table 2. Energy use and emission factors in sorting (per kg of input glass)

Scenario	Energy Type	Energy Use (MJ/kg)	Emission Factor (kg CO_2/MJ)	Source
SKGRB	Electricity	0.081	0.0570	AusLCI v1.42
	Natural Gas	0.033	0.0561	AusLCI v1.42
	Diesel	0.011	0.0741	AusLCI v1.42
MKRB	Electricity	1.486	0.0570	AusLCI v1.42
	Natural Gas	0.050	0.0561	AusLCI v1.42
	Diesel	0.066	0.0741	AusLCI v1.42

The electricity emission factor under current grid conditions reflects Victoria's existing generation mix, which is highly reliant on coal.

Grid decarbonisation scenario and emission factor adjustment

To evaluate the potential influence of electricity decarbonisation, the study models a scenario in which 50% of coal-fired electricity is replaced by renewable energy sources. The composition of Victoria's electricity grid under current conditions is based on Australian Energy Market Operator (AEMO) (2022) data: Coal is 46%, Natural gas is 17%, Oil is 2%, Renewable energy is 35%.

Corresponding emission factors are generated through SimaPro with AusLCI database using ReCiPe (2016) as follows: Coal = 0.1000 kg CO_2/MJ, Natural gas = 0.0561 kg CO_2/MJ, Oil = 0.0741 kg CO_2/MJ, Renewables = 0 kg CO_2/MJ.

The adjusted emission factor for electricity in the decarbonised scenario is calculated by reducing the coal share from 46% to 23% and reallocating the difference to renewables. So the emission factor for the 50% coal reduction electricity grid is 0.034 kg CO_2/MJ. This new electricity emission factor is then used to recalculate emissions from the sorting stage. **Table 3** summarises the results.

Table 3. Sorting emissions under original and decarbonised grid (kg CO_2-eq/kg glass)

Scenario	Electricity Emission Factor	Total Sorting Emissions (decarbonised)	% Reduction
SKGRB	0.0570 → 0.0340	0.00542194	26%
MKRB	0.0570 → 0.0340	0.058237	37%

Results

The results indicate a clear difference in total greenhouse gas (GHG) emissions between the two glass recovery systems, both under current electricity grid conditions and under a decarbonised scenario in which coal-based electricity is reduced by 50%.

Under current conditions, the separate kerbside glass recycling bin (SKGRB) system generates 94.93 kg CO_2-eq per ton of asphalt, while the mixed kerbside recycling bin (MKRB) system generates 154.44 kg CO_2-eq per ton. The most significant difference between the two systems arises in the sorting stage, where emissions for MKRB are more than twelve times higher than those for SKGRB, primarily due to the greater complexity and energy intensity of sorting mixed recyclables.

When electricity grid decarbonisation is applied, the sorting stage emissions are reduced by 26% for SKGRB and by 37% for MKRB, reflecting their respective energy profiles. As a result:

- The total emissions for SKGRB decrease from 94.93 to 93.58 kg CO_2-eq, resulting in a modest reduction of 1.35 kg CO_2-eq per ton of asphalt.
- The total emissions for MKRB decrease from 154.44 to 131.29 kg CO_2-eq, representing a substantial reduction of 23.15 kg CO_2-eq per ton of asphalt.

These results highlight the dual role of energy system transformation and waste system design. While both systems benefit from electricity decarbonisation, the MKRB system shows a greater absolute reduction due to its heavier dependence on electricity during sorting. However, even after adjustment, MKRB remains significantly more emission-intensive than SKGRB.

Discussion

The results of this study demonstrate that electricity grid decarbonisation can lead to measurable reductions in life cycle greenhouse gas (GHG) emissions from asphalt incorporating recycled municipal solid waste (MSW) glass. However, the magnitude of these reductions varies significantly depending on the recovery system used.

The mixed kerbside recycling bin (MKRB) system shows a greater absolute reduction in emissions (23.15 kg CO_2-eq per ton of asphalt) compared to the separate glass bin (SKGRB) system (1.35 kg CO_2-eq per ton). This difference reflects the much higher electricity demand associated with sorting mixed recyclables. In the MKRB system, the sorting stage alone originally contributed over 40 percent of total emissions. As such, reducing the carbon intensity of electricity has a proportionally larger impact. However, even with a 50 percent reduction in coal-based power, the MKRB system remains substantially more emission-intensive than SKGRB overall.

These findings underscore the importance of considering both energy system transformation and waste recovery system design in efforts to reduce embodied carbon (Colangelo, 2024; Caudle et al., 2023). While electricity decarbonisation can enhance the environmental performance of existing systems, it cannot fully compensate for structural inefficiencies such as high sorting burdens or cross-contamination (Wilkinson, 2023; Hsieh and Tsai, 2023). In contrast, the SKGRB system performs more efficiently across all stages and benefits from a cleaner input stream that requires less energy to process (Qin et al., 2024).

The analysis also highlights the sorting stage as a critical intervention point. Since this stage is highly electricity-dependent, it represents a strong candidate for targeted decarbonisation policies. For example, facilities processing high volumes of mixed recyclables could be prioritised for renewable electricity (Peng et al., 2021), while investments in material separation at source could reduce dependence on energy-intensive downstream sorting altogether (Anwar et al., 2024; Lu and Poon, 2019).

From a methodological standpoint, this study contributes empirical data that links waste recovery pathways with energy transition scenarios. By integrating real energy use profiles with adjusted emission factors based on Victoria's electricity mix, it provides a grounded baseline for future scenario modelling and sensitivity analysis (Papadogeorgos, 2019). While this study adopts a deterministic approach, its results lay the foundation for expanded modelling under probabilistic frameworks, particularly in the context of long-term energy system change and policy uncertainty (Hu et al., 2018).These deterministic results therefore provide a foundational reference for future dynamic and prospective LCA studies, which could explicitly model time-dependent decarbonization pathways and their potential impacts on the comparative outcomes between separate and mixed glass recovery systems.

Conclusion

This study investigates how the introduction of renewable energy into the electricity grid affects the embodied energy of asphalt containing recycled glass derived from different municipal recovery systems. By modelling a scenario in which coal-based generation is reduced by 50% and replaced by renewable sources, the analysis quantifies changes in emissions during the sorting stage and assesses their implications for overall life cycle performance.

The baseline total GHG emissions of producing one ton of asphalt with recycled glass are 94.93 kg CO_2-eq for the SKGRB system and 154.44 kg CO_2-eq for the MKRB system, based on current electricity grid conditions in Victoria.

Applying a decarbonised electricity grid scenario, where 50% of coal-based electricity is replaced by renewables, reduces the sorting stage emissions by 26% for SKGRB and 37% for MKRB.

The total emissions decrease to 93.58 kg CO_2-eq for SKGRB and 131.29 kg CO_2-eq for MKRB. This corresponds to reductions of 1.35 kg CO_2-eq and 23.15 kg CO_2-eq per ton of asphalt.

Despite greater absolute reductions in the MKRB scenario, its total emissions remain 40% higher than those of the SKGRB system after electricity decarbonisation.

These results confirm that grid carbon intensity directly affects the embodied emissions of recycling processes, but also demonstrate that system design (e.g., source separation) plays a larger role in determining overall environmental outcomes.

Acknowledgements
This paper was conducted with the support of the Australian Research Council Training Centre for Whole Life Design of Carbon Neutral Infrastructure (project number IC230100015) as well as the Centre for Future Construction, RMIT. The authors would like to acknowledge Yarra City Council, Victoria, Australia for providing support to this research.

References

- Adedara, M.L., Taiwo, R. and Bork, H.R., (2023), April. Municipal Solid Waste Collection and Coverage Rates in Sub-Saharan African Countries: A Comprehensive Systematic Review and Meta-Analysis. In Waste (Vol. 1, No. 2, pp. 389-413). MDPI.
- Akintayo, B. D., Babatunde, O. M., & Olanrewaju, O. A. (2024). Comparative Analysis of Cement Production Methods Using a Life Cycle Assessment and a Multicriteria Decision-Making Approach. Sustainability, 16(2), 484.
- Anwar, M. K., Zhu, X., Gilabert, F. A., & Siddiq, M. U. (2024). Recycling and optimum utilization of CRT glass as building materials: An application of low CO2 based circular economy for sustainable construction. Construction and Building Materials, *453*, 138798.
- Arulrajah, A., Imteaz, M., Horpibulsuk, S., Du, Y. J., & Shen, J. S. L. (2018). Recycled concrete aggregate/municipal glass blends as a low-carbon resource material for footpaths. Road Materials and Pavement Design, 19(3), 727-740.
- Australian Energy Market Operator (AEMO) (2022). Integrated System Plan. Retrieved from https://aemo.com.au/energy-systems/major-publications/integrated-system-plan-isp/2022-integrated-system-plan-isp
- Australian Government, (2022). National Waste Report 2022. Department of the Environment and Energy.
- Hu, P., Li, Y., Zhang, X., Guo, Z., & Zhang, P. (2018). CO2 emission from container glass in China, and emission reduction strategy analysis. Carbon Management, 9(3), 303-310.
- Drewniok, M., Cruz Azevedo, J., Dunant, C., Allwood, J., Cullen, J., Ibell, T., & Hawkins, W. (2022). Mapping material use and embodied carbon in UK construction. engRXiv.
- Gillespie, D., & McIlwaine, S. (2021, September). Reducing embodied carbon in the construction sector. In Proceedings of the 37th Annual ARCOM Conference (pp. 744-753). Association of Researchers in Construction Management.

- Gutai, M., Mok, B., Cavana, G., & Kheybari, A. G. (2024). Global carbon viability of glass technologies: Life-cycle assessment of standard, advanced and water-filled glass (WFG) building envelopes. Applied Energy, 367, 123281.
- Papadogeorgos, I. (2019). Decarbonisation of the Dutch container glass industry by 2050.
- Harrison, E., Berenjian, A., & Seifan, M. (2020). Recycling of waste glass as aggregate in cement-based materials. Environmental Science and Ecotechnology, 4, 100064.
- Hsieh, C. L., & Tsai, W. H. (2023). Towards carbon neutrality and circular economy in the glass industry by using the production decision model. Energies, 16(22), 7570.
- Jiang, B., Huang, H., Ge, F., Huang, B., & Ullah, H. (2025). Carbon Emission Assessment During the Recycling Phase of Building Meltable Materials from Construction and Demolition Waste: A Case Study in China. Buildings, 15(3), 456.
- Liu, Z., Shi, C., Shi, Q., Tan, X., & Meng, W. (2022). Recycling waste glass aggregate in concrete: Mitigation of alkali-silica reaction (ASR) by carbonation curing. Journal of Cleaner Production, 370, 133545.
- Lu, J. X., & Poon, C. S. (2019). Recycling of waste glass in construction materials. In New trends in eco-efficient and recycled concrete (pp. 153-167). Woodhead Publishing.
- Peng, Z., Lu, W., & Webster, C. J. (2021). Quantifying the embodied carbon saving potential of recycling construction and demolition waste in the Greater Bay Area, China: Status quo and future scenarios. Science of The Total Environment, 792, 148427.
- Požarnik, M., Mohar, L. R., & Kosi, D. (2023). Evaluating environmental impacts with LCA to achieve carbon neutral societies. Journal of Human, Earth, and Future, 4(3), 316-331.
- Qin, B., Wang, C., Lu, J., Zhu, J., & Ruan, J. (2025). Action mechanism of iron on the carbon dioxide emission reduction and methyl methacrylate generation during anhydrous cleaning process for waste glass recovery. Waste Management, 193, 62-69.
- Subal, L., Braunschweig, A., & Hellweg, S. (2024). The relevance of life cycle assessment to decision-making in companies and public authorities. Journal of Cleaner Production, 435, 140520.
- Wilkinson, C. (2024). Glass and a carbon-free United States: What is glass's role in the upcoming green revolution?. Journal of the American Ceramic Society, 107(3), 1533-1542.
- Zhang, J., Bhuiyan, M., Zhang, G. and Sandanayake, M., (2024a). Life cycle assessment of kerbside waste material for an open-looped and closed-loop production–towards circular economy designs. Journal of Cleaner Production, 434, p.139991.
- Zhang, J., Bhuiyan, M., Zhang, G., Sandanayake, M., & Navaratnam, S. (2024b). Circular economy life cycle cost for kerbside waste material looping process. Waste Management, 186, 307-317.
- Zhang, J., Zhang, G., Bhuiyan, M.A. and Agostino, J., (2022). Comparative life cycle assessment of kerbside collection methods for waste glass cullet for asphalt production. Journal of Cleaner Production, p.134055.
- Zhang, Z., Lei, Y., Liew, J. R., Liu, M., Wong, G., & Du, H. (2024). Embodied carbon saving potential of using recycled materials as cement substitute in Singapore's buildings. Npj Materials Sustainability, 2(1), 27.

Domain-Specific Large Language Model for Environmental Product Declaration Review Report Verification

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Abstract

Environmental Product Declaration (EPDs) are becoming the 'gold standard' in communicating and verifying the environmental impact performance of products. However, the preparation and verification process of EPDs can be cumbersome and resource-intensive, necessitating efficient tools to support Life Cycle Assessment (LCA) practitioners. This study presents the development and application of an innovative automated review approach utilising Large Language Models (LLMs) explicitly adapted for EPD documents. A specialised Low-Rank Adaptation (LoRA) method was implemented to fine-tune Google's open-source generative model, Gemma-3, to perform automated reviews of draft EPDs. This adapter (EPDRev) was trained on a carefully curated dataset comprising detailed, page-level comments from human experts on previous EPD submissions across multiple product categories. Using examples of human-expert reviewed EPD drafts, EPDRev was trained to understand the nuanced context within EPD documentation, enabling it to identify inconsistencies, omissions, and potential errors in preliminary EPD submissions. Additionally, a multi-label text classification model, EPDMclass, was trained to classify EPDRev-generated comments into four categories: "Adopt best practice", "Correct wrong information", "Provide more details", and "Others". Leveraging the capabilities of both models, an AI-assistant has been developed to generate page-level review comments with classifications. Additionally, a user can ask follow-up questions to clarify the review comments. Human review of the generated comments showed that they were moderately relevant to the context of the reviewed EPDs. This automated review approach would assist LCA practitioners by identifying potential issues and improving initial compliance checks, thus enhancing subsequent human reviews. EPDRev highlights the potential for technology to enhance traditional LCA methods and tools, contributing to more efficient environmental reporting practices. The current version of EPDRev was trained using a limited number of human-reviewed EPDs; hence, increasing the training examples would enhance the quality of generated reviews.

Keywords: Artificial Intelligence, Environmental Product Declaration, Verification

Introduction

Environmental product declarations have been used by life cycle assessment (LCA) professionals to transparently report and compare the environmental performance of building products because it allows professionals to use direct data (Palumbo et al., 2020) published by the manufacturers which guarantees the reliability of sustainability assessment. As a requirement, EPDs must comply with the ISO14040 (2020) standards and developed according to a pre-specified product category rule (PCR) (Minkov et al., 2015). EPDs help enhance the quality, credibility and transparency of environmental information to both businesses and consumers (Bergman and Taylor, 2011). EPDs that are intended for business-to-business communications do not require a third-party verification.

Recent estimates by Anderson (2020) suggest that there are around 23,000 Verified EPDs to EN15804 globally as of early 2024. This is a significant gap compared to over 250,000 building products available globally. Furthermore, there have been massive increase in the number of EPD schemes since 2002, when only seven operators existed (Minkov et al., 2015). More specifically, the construction sector has witnessed higher demand for quantification of the environmental performance (Jorba et al., 2025) and constitutes up to 75% of published EPDs across multiple programme operators.

EPD verification must be conducted by independently accredited experts who are expected to understand the LCA methodology intricately and attuned to the compliance framework for a particular study. The philosophy of verification is attuned to the premise of logical positivism and modernism (Johnsen et al., 2022). In a previous review of EPDs, over 82% were found to be lacking at least one piece of required information (Gelowitz and McArthur, 2017)

EPDs verification is expected to assuage persistent discrepancies in life cycle inventory methodology, incomparability of studies produced with same Product Category Rules (PCR) and allow for fair and equitable comparison across similar products (Gelowitz and McArthur, 2017). However, EPD verification happens in the context of time-pressure, minimal budget and unclear tasks. Johnsen et al., (2022) reckons that EPD verification combines some aptitude from critical review and compliance efficiency. Grahl and Schmincke (2023) reckons that verification is a conformity check but requires clear definition of requirements and objectives.

Poor verification practices have resulted in self-contradictory data and omitted information mandated by relevant PCRs (Hunsager et al., 2014; Gerlowitz and McArthur, 2017). Verifiers are also not perfect repositories of knowledge, and in many cases make subjective evaluation that may lack practical relevance (Johnsen et al., 2022). Nevertheless, EPD verification is only one of the quality-control mechanism to ensure the credibility of disclosed environmental information (Bergman and Taylor, 2011). Nevertheless, EPD verification process could become so formalistic that it dims focus on the environmental areas of protection (Johnsen et al., 2022). The verification process, however, seems to have stemmed as a support mechanism to curtail blind spot of LCA practitioners. This objective seems to have been lost in the wake of work pressure on verifiers due to trade barriers on the market (Del Borghi et al., 2020).

Reliable EPDs help communities make informed decisions regarding the environmental impact of construction products incorporated into building design. The use of generic datasets to develop EPDs has been found to result in up to 500% variation in results across environmental impact categories, in comparison to EPDs developed by specific datasets (Palumbo et al., 2020). Jorba et al., (2025) therefore concluded that EPD data from manufacturers can significantly reduce uncertainties in LCA outcomes. Moreover, the appetite to digitise EPDs have led to complex challenges with intellectual property, data compromise and hastened harmonisation of processes (Del Borghi et al., 2020).

Material and methods

Dataset

The model training and evaluation dataset in the research included seven draft EPDs reviewed by professional EPD assessors. Two-hundred and twenty-five (255) page-level EPD information (text, tables, and images) and matching review comments were extracted for model training and evaluation based on a data split ratio of 80:20 respectively. Subsequently, three pairs of draft and final EPDs were used for comparative analysis of model-generated review comments.

EPD Review Model Training and Evaluation

The EPD review (EPDRev) model was trained using a Low-Rank Adaptation (LoRA) approach to fine-tune Gemma-3-4b-it, Google's 4 billion parameter instruction-tuned multimodal model, handling image and text inputs and returning text output (Gemma Team et al., 2025), for EPD document analysis. The base model was enhanced with LoRA adapters, configured with a rank of

16, an alpha of 32, and a 10% dropout rate, targeting attention projection layers to achieve parameter-efficient fine-tuning (Hu et al., 2022). This configuration resulted in only 0.276% of the total model parameters being trainable, significantly reducing computational requirements while maintaining model performance (Hu et al., 2022). The training dataset consisted of page-level extracted EPD content and corresponding reviewer comments. Training proceeded for 2 epochs using a batch size of 256KB, learning rate of 2e-5, and bfloat16 precision (Devlin et al., 2018; Kalamkar et al., 2019; Liao et al., 2024). The model employed flash attention optimization and gradient checkpointing for memory efficiency (Dao et al., 2022). Evaluation was conducted on a held-out test set using ROUGE-L and BERTScore metrics to assess the quality of generated comments, providing quantitative measures of the model's ability to produce relevant EPD review content (Lin, 2004; Zhang et al., 2019).

Comments Classification Model Training and Evaluation

The Bi-directional Encoder Representation from Transformers (BERT) (Devlin et al., 2018), the predominant text classification model (Zhou et al., 2023), was employed to train a multi-label classification model for EPD review comments (EPDMClass). The training dataset consisted of manually labelled EPD review comments. The labelling processing was completed using the Labelbox platform (https://labelbox.com/) and involved a labeller and a label reviewer, resulting in consensus on labelling 244 review comments. The dataset was partitioned into 80% training and 20% testing subsets with random stratification (Uçar et al., 2020). The BERT model was configured for multi-label classification by setting the problem type parameter, and trained utilising the AdamW optimizer, a learning rate of 5e-5, a batch size of 16, and three epochs (Devlin et al., 2018). Performance assessment utilized classification report metrics including precision, recall, and F1-scores for each label category (Powers, 2020), providing a comprehensive evaluation of the model's ability to accurately predict multiple EPD characteristics simultaneously across the test dataset. The classes included "Adopt best practice" - comments recommending the implementation of industry standards or established methods; "Correct wrong information" - identifying inaccuracies, errors, or incorrect data that require correction to ensure EPD accuracy and compliance; "Provide more details" - requesting additional information or elaboration where existing content is insufficient; and "Others - not fit within the three primary categories above. The core classes were limited to three due to the limited number of training data in this research.

Comparative Analysis of Draft and Final EPD

A comparative protocol was developed to quantify the semantic and structural divergence between review comments generated by EPDRev for matched draft and final EPDs. For each document, comments were segmented by page, embedded with a sentence-transformer (Reimers & Gurevych, 2019), and treated as multivariate observations. Cross-document cosine distances provided a visual evaluation of semantic shift, while the Energy Distance test (5000 permutations) supplied an exact p-value for distributional differences (Rizzo & Székely, 2016), thereby controlling for unequal page counts. Complementary histograms of comment counts and word counts per page identified shifts in editorial density. Two-dimensional t-distributed stochastic neighbour embedding (t-SNE) projections provided an intuitive visual check of clustering behaviour across versions (Balamurali, 2021). This combination of distribution-based inference and descriptive graphics provides a balanced assessment of whether substantive revisions occurred between the draft and final texts, without relying on parametric assumptions or opaque model internals.

Results

EPDRev Model Evaluation Metrics

The effectiveness of EPDRev in generating review comments for Environmental Product Declarations was evaluated using ROUGE-L and BERTScore metrics. The ROUGE-L score, which assesses the longest common subsequence between generated and reference texts, was 0.08, indicating limited lexical similarity, reflecting the diverse ways expert reviewers may phrase similar content. In contrast, BERTScore, which evaluates semantic similarity using contextual embeddings, demonstrated more substantial alignment, with a precision of 0.79, a recall of 0.83, and an F1 score of 0.81. These results suggest that while the generated comments may differ lexically from the references, they are generally semantically aligned with the expert-authored comments. The relatively high BERTScore supports the model's ability to capture the contextual intent and meaning of review comments, even when exact wording varies. This highlights the suitability of EPDRev for assisting with preliminary EPD reviews, where semantic understanding is critical, rather than relying on strict textual replication. Below is a sample EPDRev generated comments extracted from detailed page comments.

*"The initial sentence stating the EPD scope as "Cradle to gate with options, modules C1–C4, module D and with optional modules (A1–A3, A4 (option) + C + D)" requires clarification. It should explicitly state *what* "options" refers to – are these different product variations or scenarios? The reference to PCR 2019:14 needs to be more directly linked to the scope definition."*

EPDMclass Model Evaluation Metrics

The overall accuracy of EPDMclass was 65% and **Error! Reference source not found.** generally indicates a strong performance in categorising model-generated review comments across three of the four predefined classes. The model achieved the highest effectiveness for the label "Provide more details", with a precision of 0.76, perfect recall of 1.00, and an F1-score of 0.86. These results suggest that the model reliably identified comments requiring additional information, with minimal false positives or missed instances.

Table 1. Evaluation metrics for EPDm class

Label	Precision	Recall	F1-score
Adopt best practice	0.32	0.80	0.46
Correct wrong information	0.51	1.00	0.68
Provide more details	0.76	1.00	0.86
Weighted average	**0.57**	**0.91**	**0.69**

For "Correct wrong information", EPDMclass performed effectively with precision of 0.51, recall of 1.00, and F1-score of 0.68, demonstrating high sensitivity in detecting inaccuracies despite some incorrect classifications. The "Adopt best practice" label yielded moderate results (precision 0.32, recall 0.80, F1-score 0.46), reflecting a tendency to over-predict this category that may be addressed through improved class balance or threshold tuning. The "Others" category achieved zero scores across all metrics, suggesting the model requires further exposure to diverse examples or additional clarification of this label's scope during training. The weighted average metrics (precision 0.57, recall 0.91, F1-score 0.69) demonstrate that EPDMclass effectively identifies the most relevant labels, particularly for critical categories related to content accuracy and completeness, though targeted improvements may enhance precision and support more balanced classification across all label types.3.3. Comparative Analysis of Draft and Final EPD

Table 2 summarises the processing times and number of comments generated for draft and final EPDs. The number of pages processed relates to the core EPD content, excluding references and appendices. Figure 1 presents graphical comparisons of review comments generated for Draft A and Final A. Across all four panels; broadly consistent commenting behaviour is evident with several noteworthy refinements. Panel A indicates that both documents concentrate most pages within six to eight comments, demonstrating similar review intensity. However, the draft includes outliers at the lower (three comments) and upper (eleven comments) extremes, whereas the final version exhibits tighter clustering, suggesting that revisions standardized the distribution of feedback across pages.

Table 2. Summary of EPD processing times and number of comments generated

Documents	Number of pages	Processing time	Comments generated	Energy Distance	P-value
Draft A	18	4.48	117	-0.04309	1.0000
Final A	16	5.31	107		
Draft B	18	4.54	117	0.136879	0.0003
Final B	20	7.55	128		
Draft C	75	14.33	504	0.031007	0.0167
Final C	17	4.32	100		

The comparative analysis reveals contrasting revision patterns between the two EPD pairs. For Draft A and Final A (Figure 1), Panel B shows modest comment length reduction, with the draft displaying a heavier tail beyond 300 words per page while the final clusters around 250-300 words, indicating concise rephrasing rather than wholesale rewrites. Panel C demonstrates extensive overlap in t-SNE projections, confirming thematic continuity, though several final pages occupy distinct positions suggesting localized content adjustments. Panel D quantifies changes through cosine-distance distribution centered at $\mu = 0.555$, with most distances between 0.4 and 0.7, reflecting moderate semantic divergence where comments were refined rather than fundamentally altered. Overall, Final A retains the draft's comment volume and thematic scope while achieving greater conciseness.

In contrast, Draft B and Final B (Figure 2) exhibit opposite trends. Comment counts per page remain comparable but are more evenly distributed (Panel A). Word counts shift upward from 150-250 to 260-340 words, indicating substantive elaboration (Panel B). Embedding projections reveal tighter thematic clustering (Panel C), while a higher mean cosine distance ($\mu = 0.606$) confirms deeper semantic changes (Panel D). Final B expanded whereas Final A became concise, with greater semantic divergence (0.606 versus 0.555).

The energy distance test (Table 2) corroborates these findings. Draft A-Final A records an energy-distance statistic near zero (-0.043) with $P = 1.0000$, indicating no statistically detectable shift in review-comment embeddings. Conversely, Draft B-Final B shows a substantially larger statistic (0.137) with $P = 0.0003$, confirming meaningful redistribution consistent with increased comment length, more even per-page allocation, and greater semantic divergence.

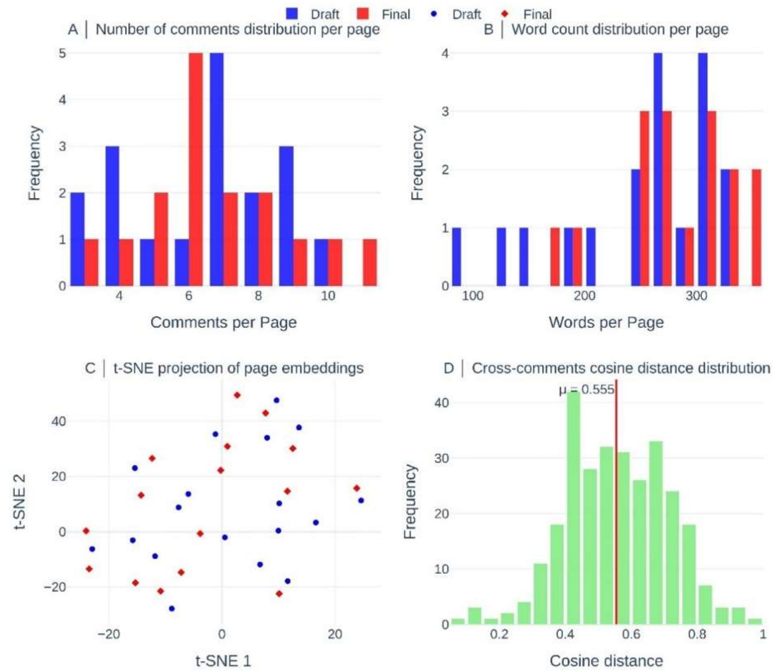

Figure 1: Graphical comparison of generated review comments for Draft A and Final A EPD

Discussion

The EPDRev model's BERTScore performance (F1: 0.81) demonstrates substantial semantic alignment with expert-generated comments, indicating the model successfully captures contextual intent despite lexical variations. This semantic coherence is particularly valuable given the subjective nature of EPD review practices, where experts may express similar concerns through diverse phrasing. The relatively low ROUGE-L score (0.08) further supports this interpretation, suggesting that effective review comment generation prioritizes meaning over exact wording replication.

To the best of the authors' knowledge, this study is the first of its kind to develop an LLM for generating EPD review comments based on real-world data. However, findings align with emerging research demonstrating LLM capabilities across the EPD lifecycle. Castle et al. (2025) applied LLMs for entity linking in EPD carbon-footprint estimation, while MacMaster and Sinistore (2024) demonstrated LLM effectiveness in evaluating EPD background data quality across multiple dimensions. Phan et al. (2024) explored long-context LLMs for environmental document comprehension, finding promise in retrieval-augmented generation approaches for complex EPD content. Olanrewaju et al. (2025) identified the potential for LLM-based quality assurance systems within EPD digital repositories. These complementary applications suggest a growing ecosystem of AI-supported EPD processes, with this study contributing the novel capability of automated review comment generation.

The EPDMClass model's strong performance in identifying content requiring additional details (F1: 0.86) addresses a critical gap, given that over 82% of EPDs lack necessary information. However, the model's inability to classify the "Others" category and moderate performance for "Adopt best practice" comments indicate limitations in handling diverse or less frequent review scenarios.

The key limitation of this study is the relatively small training dataset (255 page-level instances). Future research should expand volume and diversity of training data, incorporate multi-domain EPD types to enhance robustness, and explore integration with existing EPD management systems to facilitate practical application and generalizability across different verification frameworks.

Conclusion

This study demonstrates the feasibility of automated EPD review comment generation through artificial intelligence approaches, with EPDRev achieving substantial semantic alignment (BERTScore F1: 0.81) with expert reviewers despite lexical variations. The model's capacity to generate contextually appropriate feedback addresses a critical bottleneck in EPD verification processes, where time constraints and limited expert availability may compromise review quality. The complementary EPDMClass model effectively identifies content requiring additional details and corrections, categories that directly correspond to the most frequent deficiencies identified in existing EPD literature. The practical implications are significant given the substantial gap between available building products and verified EPDs. Automated review systems could enhance verification consistency, reduce expert workload, and accelerate EPD publication cycles. The models developed in this research would support broader sustainability objectives by facilitating more comprehensive environmental disclosure across construction supply chains.

The robustness of semantic understanding over lexical matching suggests these models can accommodate diverse expert communication styles while maintaining review quality standards. However, implementation would require careful consideration of verification framework integration and expert oversight protocols. Future development should prioritize expanding training and validation datasets across diverse EPD domains and product categories. Additionally, exploring hybrid human-AI verification workflows could optimize both efficiency and quality assurance. These developments would position automated EPD review as a viable solution for scaling environmental transparency in the construction industry while maintaining verification integrity.

References

- Anderson, J., 2021. Construction LCA's 2020 Guide to Environmental Product Declarations. *https:/ infogram. com/constructionlcas-2020-guide-to-epd-1h7g6kgqx9zo4oy*.
- Balamurali, M. (2021). T-distributed stochastic neighbor embedding. In *Encyclopedia of mathematical geosciences* (pp. 1–9). Springer.
- Castle, S., Schneider, J. M., Hennig, L., & Rehm, G. (2025). Entity Linking using LLMs for Automated Product Carbon Footprint Estimation. *arXiv preprint arXiv:2502.07418*.
- Dao, T., Fu, D., Ermon, S., Rudra, A., & Ré, C. (2022). Flashattention: Fast and memory-efficient exact attention with io-awareness. *Advances in neural information processing systems*, *35*, 16344–16359.
- Devlin, J., Chang, M.-W., Lee, K., & Toutanova, K. (2018). Bert: Pre-training of deep bidirectional transformers for language understanding. *arXiv preprint arXiv:1810.04805*.
- Gemma Team, Kamath, A., Ferret, J., Pathak, S., Vieillard, N., Merhej, R., Perrin, S., Matejovicova, T., Ramé, A., & Rivière, M. (2025). Gemma 3 technical report. *arXiv preprint arXiv:2503.19786*.
- Hu, E. J., Shen, Y., Wallis, P., Allen-Zhu, Z., Li, Y., Wang, S., Wang, L., & Chen, W. (2022). Lora: Low-rank adaptation of large language models. *ICLR*, *1*(2), 3.
- Kalamkar, D., Mudigere, D., Mellempudi, N., Das, D., Banerjee, K., Avancha, S., Vooturi, D. T., Jammalamadaka, N., Huang, J., & Yuen, H. (2019). A study of BFLOAT16 for deep learning training. *arXiv preprint arXiv:1905.12322*.
- Liao, B., Herold, C., Khadivi, S., & Monz, C. (2024). Apiq: Finetuning of 2-bit quantized large language model. *arXiv preprint arXiv:2402.05147*.
- Lin, C.-Y. (2004). Rouge: A package for automatic evaluation of summaries. Text summarization branches out,

- MacMaster, S., & Sinistore, J. (2024). Testing the use of a large language model (LLM) for performing data quality assessment. *The International Journal of Life Cycle Assessment*, 1–12.
- Olanrewaju, O. I., Enegbuma, W. I., Donn, M., & Oyefusi, O. N. (2025). Assessment of environmental product declaration and databases: Towards ensuring data quality assurance practices. *Environmental Impact Assessment Review*, *112*, 107803.
- Phan, H., Acharya, A., Meyur, R., Chaturvedi, S., Sharma, S., Parker, M., Nally, D., Jannesari, A., Pazdernik, K., & Halappanavar, M. (2024). Examining long-context large language models for environmental review document comprehension. *arXiv preprint arXiv:2407.07321*.
- Powers, D. M. (2020). Evaluation: from precision, recall and F-measure to ROC, informedness, markedness and correlation. *arXiv preprint arXiv:2010.16061*.
- Reimers, N., & Gurevych, I. (2019). Sentence-bert: Sentence embeddings using siamese bert-networks. *arXiv preprint arXiv:1908.10084*.
- Rizzo, M. L., & Székely, G. J. (2016). Energy distance. *wiley interdisciplinary reviews: Computational statistics*, *8*(1), 27–38.
- Uçar, M. K., Nour, M., Sindi, H., & Polat, K. (2020). The effect of training and testing process on machine learning in biomedical datasets. *Mathematical Problems in Engineering*, *2020*(1), 2836236.
- Zhang, T., Kishore, V., Wu, F., Weinberger, K. Q., & Artzi, Y. (2019). Bertscore: Evaluating text generation with bert. *arXiv preprint arXiv:1904.09675*.
- Zhou, C., Li, Q., Li, C., Yu, J., Liu, Y., Wang, G., Zhang, K., Ji, C., Yan, Q., & He, L. (2023). A comprehensive survey on pretrained foundation models: A history from bert to chatgpt. *arXiv preprint arXiv:2302.09419*.
- https://doi.org/10.1007/s13042-024-02443-6

Tackling Uncertainties in the Life Cycle Assessment of Relocatable Modular Buildings Using Machine Learning Techniques

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Abstract

As the building sector transitions toward decarbonisation, there is a high demand for analytical tools that assess the long-term environmental impacts in the built environment. The aim of the study is to appraise uncertainties in the life cycle assessment (LCA) of modular buildings, and identify key parameters associated with global warming potential (GWP) to help designers understand which parameters are important for the climate change impacts at the early design stage. The study commences with conducting the LCA of a conventional building and reports on the most optimal machine learning (ML) algorithm for improving life cycle-based exploration methods by coupling sensitivity analysis (SA). This study utilises Sobol indices which are computed to estimate the contributions of the different parameters to results' uncertainties, more precisely to the variance of the results that is induced by input parameters' uncertainties. The analytical framework for sensitivity analysis consists of SALib- a python-based library, Saltelli sampling technique and Ishigami function. In this study three ML algorithms, namely Artificial Neural Networks (ANN), Random Forest (RF) and Support vector Machine (SVM), were chosen among several reviewed techniques. They are tested, with the aim of finding out if they can predict the climate change impact accurately, while being less computationally expensive than the original model. It was found that ANN model trained on the data generated by the SA was used to predict the Climate Change impact of new design alternatives in a small amount of time, and with a coefficient of determination higher than 0.9. Additionally, Sobol method delivered satisfying results with the computation of quantitative indices. The outcome from the studies can assist optimal decision-making choices for relocatable buildings in Australia and support improved sustainability transition in the built environment.

Keywords: Machine Learning (ML), Modular buildings, Uncertainties

Introduction

Relocatable modular buildings (RMB) combine the essence and functionality of mobile and modular buildings towards enhancing circularity potentials. RMBs are crucial because they can address the disproportionate spread in population distribution such that they can be moved between urban and rural destinations (Kyrö et al. 2019). Furthermore, experience has shown that RMBs could be deployed to resolve temporary accommodation needs and are better at dealing with acute moisture problems in housing units. RMBs has been found attractive due to its potential to prolong a product's service life (Bakker et al. 2021). The Modular Building Institute (2021) retorts that RMB provide flexible spaces that are usually quick to produce and ready to install in a relatively short period, with the potential for future relocation due to the ease of transportation and re-installation. RMBs have also been found to be promising circular economy applications due to the recurrence and unpredictability of natural disasters, and the potential for addressing regional disparities in demand. The potentials of RMBs have therefore been found attractive for achieving long-term sustainability and circularity in the built environment sector.

There has been interest across the literature in conducting the LCA of RMBs. Hao et al. (2020), for instance, conducted the LCA of an office building in China, and found that material production accounts for 90% of carbon emission. Minunno et al. (2020) also conducted LCA on a modular office and recognised the potential to reduce climate change impact by 88%. Another study conducted by Dragonetti et al. (2025) in Greece on student housing found that the climate change impact of the building can account for up to 74% of emissions across the life cycle. Based on studies across the extant literature, RMBs have potential to reduce environmental emissions especially across the material production, transportation and end-of-life phases. End of life phases impact significantly influences outcomes as the assessment of different variations of buildings (Schneider-Marin and Lang 2020). Equally, material circularity tends to be intrinsically linked with end-of-life options such as relocation and re-use of building components (Gallo et al. 2021).

Uncertainties in LCA models are often attributable to variability and lack of precision and potential inaccuracies in the modelling framework (Hansen et al., 2024). Other sources of uncertainties include boundary choices, inconsistencies in goal and scope, allocation principles, time horizon and faulty implementation of LCA model in software (Trigaux et al. 2021). Common techniques for uncertainty analyses include sensitivity analyses and Monte Carlo simulation. Some modern LCA studies have considered Machine Learning (ML) techniques in dealing with uncertainties across modelling assumptions and data gaps (Duprez et al. 2019). ML models can learn from vast datasets, capturing intricate relationships between design variables and performance outcomes. This has led to more accurate predictions compared to simplified analytical models thereby enabling architects and engineers to design buildings with a higher degree of certainty regarding their energy consumption, thermal comfort, and environmental impact (Yao, 2020).

Material and methods

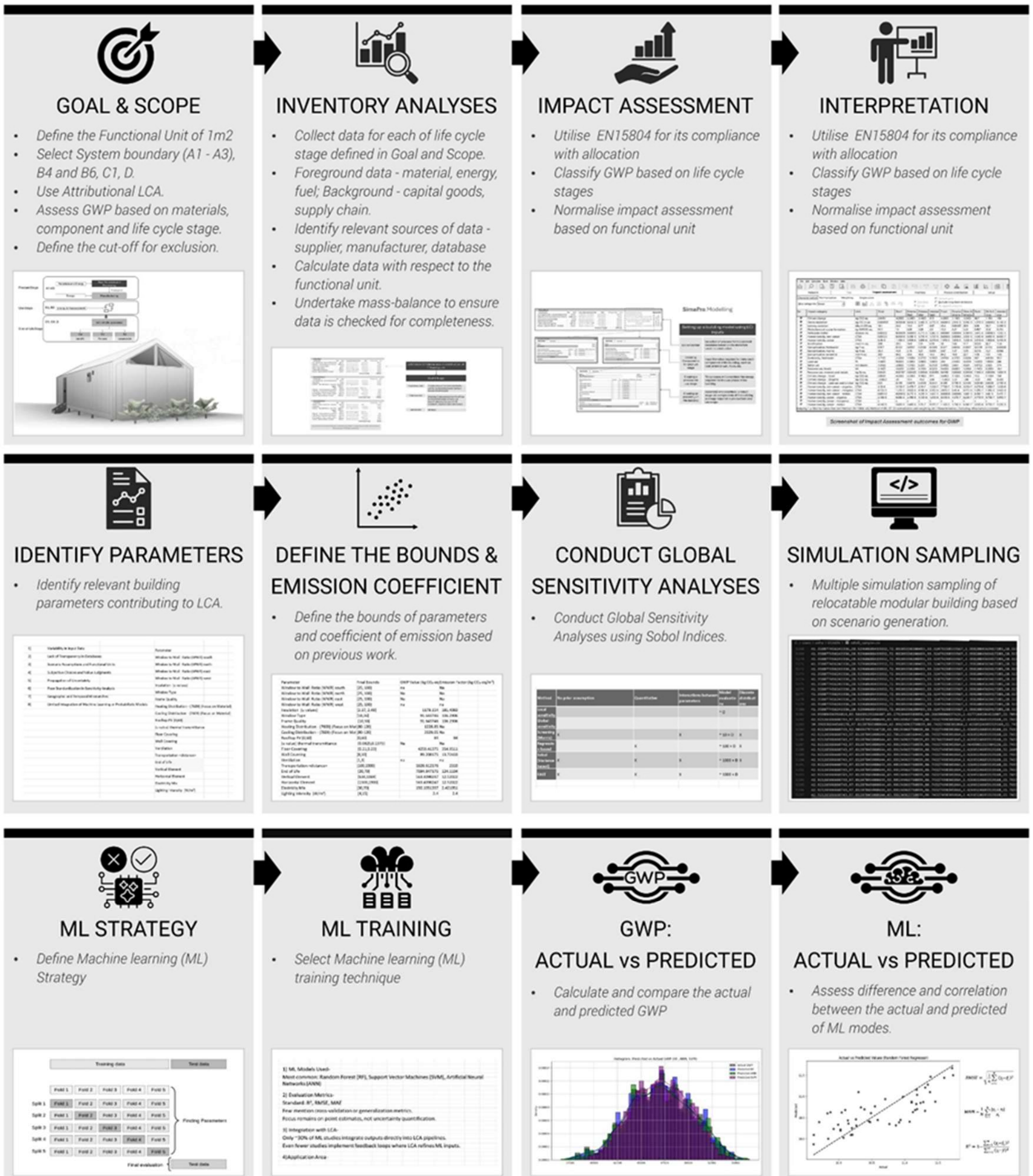
Figure 1 describes the overall research process involving three stages, as described in the section below. The intention of this approach was to evaluate the crucial uncertainties based on an integration of LCA and ML techniques. An attributional Life Cycle Assessment (LCA) of relocatable modular buildings (RMBs) is the first step in the technique, which establishes the environmental profile in terms of Global Warming Potential (GWP) and other indicators. However, for the purposes of this study, GWP will be the primary focus. Using a global sensitivity analysis (SA) the impact of variability in important design parameters are examined. The results of these simulations can serve as the basis for the last phase, in which ML algorithms are used to create predictive models that can quickly estimate the Climate change impacts. This integrated approach allows the identification of parameters with the highest impact on environmental outcomes and facilitates the creation of computationally efficient tools for early design-stage decision-making. The methodology seeks to consider uncertainties and improves the reliability of environmental performance assessments.

Conduct Life Cycle Assessment of Relocatable Modular Building (RMB)

The LCA followed the standard four-stage process of goal and scope definition, inventory analyses, impact assessment and interpretation of results. The LCA is undertaken to the EN 15804+A2 standard. The functional unit of the project is 1kg of material used. The system boundary covers A1 to A3 modules (material extraction, transportation and production), B1 (Use) and B4 (replacement), C1 – C4 (Demolition, Transportation, waste processing, and disposal) and finally D1 (benefits for re-use) and D2 (benefits from exported energy). The key environmental impacts are associated with raw materials (construction products), as the assembly of the units is a largely manual process. The inventory analyses are obtained from Bill of Quantities, Electricity logbook and supplemented with information from the literature. The impact assessment method used is the Environmental Footprint (EF 3.0) approach and the interpretation uses contribution analyses.

Evaluate Uncertainty Indices in LCA Outcomes

The second step focuses on simulation and scenario analysis to quantify uncertainties in LCA results. Relevant building design parameters, such as window-to-wall ratios (north, south, east, and west), heating and cooling distribution, thermal transmittance, roof covering, vertical and horizontal structural elements, and lighting intensity, are identified based on their influence on embodied and operational carbon emissions. For each parameter, realistic bounds and CO_2 emission coefficients are determined from the literature and empirical studies (Duprez et al., 2018; Martínez-Rocamora et al., 2021; Liu et al., 2024). To quantify both first-order and total-order effects, a global sensitivity analysis



is conducted using the Sobol method, which decomposes the variance of the model output to determine the relative importance of each input parameter.

Figure 2. Research Methodology Incorporating LCA, Sensitivity Analyses and Machine Learning

The SALib Python library's Saltelli sampling technique is used to implement the analysis. It produces a quasi-random and effective sample set that guarantees thorough exploration of the multidimensional input space, thereby enhancing the sensitivity estimates' robustness and dependability. This captures parameter interactions and their contributions to the variance in Climate change impact results. After that, several simulation runs are carried out to provide an extensive dataset that reflects a variety of parameter value combinations within the predetermined constraints. Thus, allowing for a thorough investigation of scenario variability.

Assess the Global Warming Potential of the RMB using ML technique

To predict Climate Change Impact outcomes using the scenario dataset created in Section 2.2, the third step focuses on integrating machine learning (ML) approaches. The dataset is separated into subsets for testing and training in order to facilitate the building and assessment of models. Three supervised learning algorithms Artificial Neural Networks (ANN), Random Forest (RF), and Support Vector Machines (SVM)] are selected due to their established effectiveness in environmental modelling tasks (Feng et al., 2018). Hyperparameter tuning is performed to optimise model performance, and k-fold cross-validation is applied to improve generalisation and minimise overfitting. Standard performance evaluation metrics, including the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE), are used to ensure consistent and comparable assessment across the algorithms. In line with accepted best practices for ML integration into LCA workflows, developed method offers a methodical framework for creating predictive models that may effectively estimate Climate Change Impacts while preserving methodological rigor.

Results

LCA of RMB

The overall climate change impact of the RMB based on the LCA was estimated at 24, 598 KgCO2e. 23% of these was apportioned to the End-of-Life (EoL) stage, while 33% was attributable to the Product Stage. The LCA revealed that the Use phase (B4 & B6) was the most significant life cycle stage accounting for 45% of Climate Change impact. The structural element of the building also contributed significantly to the Climate Change impact, with Steel accounting for 57%, while the Window frame and glass insulation accounted for 21% and 17% respectively. The corrugated iron sheet used for the shell of the building only accounts for about 15% of the Climate Change impact. Lastly, the approximate savings in Climate Change Impact can be up to 20% depending on the choices made for the end-of-life. In essence, downcycling had potentials to reduce the total Climate Change impact by 14%, while re-use had potential of minimising the Climate Change Impact by 17%.

Sensitivity Analyses

The analysis shows that end-of-life treatment techniques have the greatest impact on Climate Change impact out of the twenty design characteristics that were assessed. The first-order Sobol index for end-of-life is approximately 0.165, and the total-order index is about 0.175. In both S1 and ST results, other characteristics including transportation distance, insulation U-value, wall and floor coverings, and others exhibit little sensitivity. Further proof of the robustness of the sensitivity analysis may be found in the convergence graphs for S1 and ST values across increasing sample sizes. This comprehensive sensitivity analysis reinforces the idea that in LCA of RMB. The decisions on materials used for structural members and end-of-life strategies have a greater bearing on environmental outcomes than other choices across the life cycle of the building.

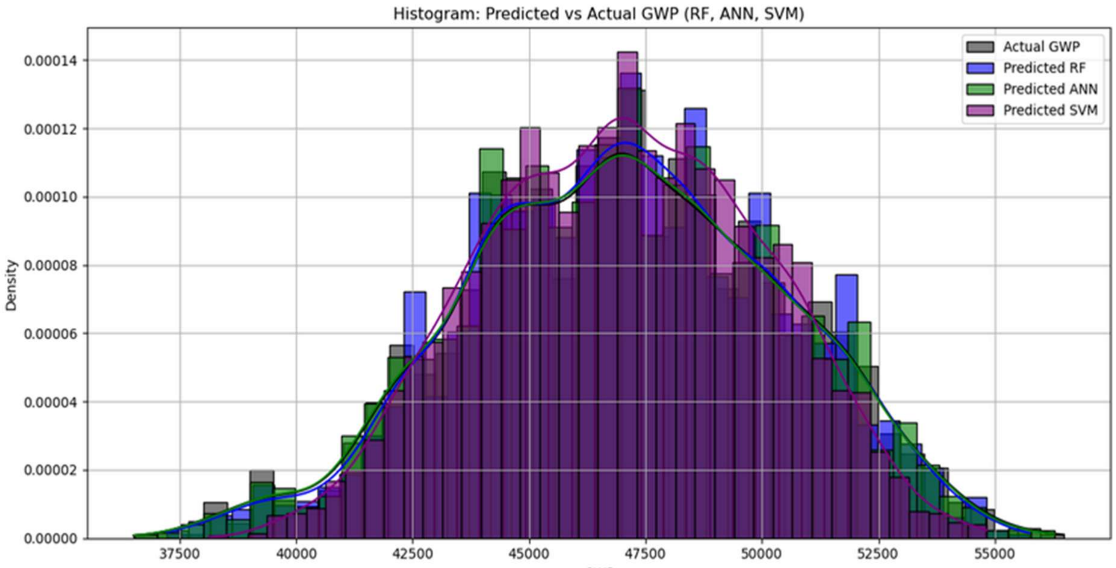


Figure 3. Predicted vs Actual Climate Change Impact according to ML Algorithms

ML prediction

The results show that ANN achieved the highest predictive accuracy, with the lowest MAE (157.18), RMSE (194.94), and MAPE (0.247%) along with the highest R^2 (0.9980), indicating its strong ability to capture complex non-linear relationships in the data. RF performed well (R^2 = 0.9862) but showed higher errors than ANN, likely due to its limitations in modelling subtle non-linearities. SVM had the lowest performance (R^2 = 0.9779) and the highest errors, which may be due to challenges in parameter tuning for high-dimensional data. These results are supported by the fact that SVM's performance can deteriorate when dealing with complex, non-linear, and high-dimensional datasets (Duprez et al., 2018) ANN's multi-layered architecture facilitates efficient learning of complex parameter interactions, and RF gains from ensemble averaging but may smooth out fine patterns. All things considered, ANN turned out to be the best model for precise and effective Climate Change impact prediction.

Discussion

This study has utilised ML techniques in appraising uncertainties in the LCA of RMB. Based on our findings, the end-of-life strategy has significant uncertainties with regards to environmental performance. Equally, the use of ML has revealed that improvements in the conduct of LCA can be accomplished using our integrated approach. The results are consistent with Duprez et al. (2018), where integrating LCA with advanced modelling identified a small set of dominant parameters influencing environmental outcomes. Consistent with previous work findings, this study highlighted end-of-life treatment as the most significant factor affecting Climate Change impact prediction reinforcing the importance of recycling and disposal strategies in RMB design. These results suggest that early design decisions should prioritise high-sensitivity parameters to achieve meaningful Climate Change impact reductions.

The strong predictive performance of the ANN model further demonstrates its potential to provide rapid Climate Change impact prediction estimates, reducing the need for repeated full-scale LCA runs and enabling faster, data-driven decision-making. However, the validity of these outcomes depends on the dataset and regional context, as the models were trained on Australian construction and supply chain data; application to other regions would require retraining with localised inputs. Future research should explore advanced models such as XGBoost, apply multi-objective optimisation methods like NSGA-II, and integrate real-time ML predictions into BIM workflows to enable instantaneous sustainability feedback during the design process.

Conclusion

This study developed and demonstrated an integrated framework combining Life Cycle Assessment (LCA), and machine learning (ML) to evaluate and predict the Climate Change impact of relocatable modular buildings (RMBs). The LCA revealed that the Use phase (B4 & B6) was the most significant life cycle stage accounting for 45% of Climate Change impact. The comprehensive sensitivity analysis, on the other hand, reinforces the idea that material choices of structural components and end-of-life strategies have a greater bearing on environmental outcomes than superficial or operational choices.

Finally, amongst the ML models considered, the ANN achieved the highest predictive accuracy, with the lowest MAE (157.18), RMSE (194.94), and MAPE (0.247%) along with the highest R^2 (0.9980), indicating its strong ability to capture complex non-linear relationships in the data. Lastly, all the three models (Random Forest, ANN, SVM) agreed on the ranking of top parameters, indicating strong model consensus and robustness of the results. The methodology can be adapted to different geographical contexts by retraining with region-specific data, ensuring its relevance beyond the current case study. The novelty of the study lies in its focus on uncertainties that can be ignored or undermined using standard LCA techniques. Options for improving the re-use potential in buildings will need to be considered in future iterations. The decarbonisation of electricity will be vital in enhancing the circularity potential of RMBs along with enhanced re-use for the structural steel.

The study has some limitations. Firstly, the study has examined building design parameters that are relevant in the context of Australia. Secondly, only one relocatable modular building has been tested, and the focus is on just three ML models. Nevertheless, the underlying methods are likely quite adaptable and versatile enough to be applicable to a broader set of research questions and studies. Lastly, focus on Climate change impact has been examined but there is scope to extend the studies to other LCIA indicators.

References

- Bakker, C.A., Mugge, R., Boks, C. and Oguchi, M., 2021. Understanding and managing product lifetimes in support of a circular economy. J Cleaner Prod. https://doi.org/10.1016/j.jclepro.2020.123764
- Dragonetti, L., Papadaki, D., Mazzoli, C., Monacelli, A., Assimakopoulos, M.N. and Ferrante, A., 2025. Circular deep renovation versus demolition with reconstruction: Environmental and financial evaluation to support decision making in the construction sector. Energy and Buildings, https://doi.org/10.1016/j.enbuild.2025.115610
- Duprez, S., Fouquet, M., Herreros, Q. and Jusselme, T., 2019. Improving life cycle-based exploration methods by coupling sensitivity analysis and metamodels. *Sustainable Cities and Society*, *44*, pp.70-84. https://doi.org/10.1016/j.scs.2018.09.032
- Feng, K., Chen, S. and Lu, W., 2018, December. Machine learning based construction simulation and optimization. WSC Conference. https://doi.org/10.1109/WSC.2018.8632290
- Gallo, P., Romano, R. Belardi, E., 2021. Smart green prefabrication: Sustainability performances of industrialized building technologies. Sust. https://doi.org/10.3390/su13094701

- Hansen, R.N., Eliassen, J.L., Schmidt, J., Andersen, C.E., Weidema, B.P., Birgisdóttir, H. and Hoxha, E., 2024. Environmental consequences of shifting to timber construction: The case of Denmark. Sus Prod Con. https://doi.org/10.1016/j.spc.2024.02.014
- Hao, J.L., Cheng, B., Lu, W., Xu, J., Wang, J., Bu, W. Guo, Z., 2020. Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. Sci Total Env. https://doi.org/10.1016/j.scitotenv.2020.137870
- Kyrö, R., Jylhä, T., Peltokorpi, A., 2019. Embodying circularity through usable relocatable modular buildings. Facilities. https://doi.org/10.1108/F-12-2017-0129
- Liu, Y., Wu, Y. Zhang, M., 2024. Specialized, diversified agglomeration and CO2 emissions—An empirical study based on panel data of Chinese cities. J Clean Prod. https://doi.org/10.1016/j.jclepro.2024.142892
- Martínez-Rocamora, A., Rivera-Gómez, C., Galán-Marín, C. and Marrero, M., 2021. Environmental benchmarking of building typologies through BIM-based combinatorial case studies. Automation in Construction. https://doi.org/10.1016/j.autcon.2021.103980v
- Minunno, R., O'Grady, T., Morrison, G.M. and Gruner, R.L., 2020. Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2020.104855
- Modular Building Institute. 2023 Commercial Modular Construction Relocatable Buildings
- Schneider-Marin, P. and Lang, W., 2020. Environmental costs of buildings: monetary valuation of ecological indicators for the building industry. Int J Life Cycle Assessment. https://doi.org/10.1007/s11367-020-01784-y
- Trigaux, D., Allacker, K. and Debacker, W., 2021. Environmental benchmarks for buildings: a critical literature review. Int J Life Cycle Assessment. https://doi.org/10.1007/s11367-020-01840-7
- Yao, J., 2020. Building cooling energy uncertainty and life cycle economic performance: A stochastic air conditioning behaviour model based comparative analysis. J Clean Prod, https://doi.org/10.1016/j.jclepro.2020.121910

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