Emerging digital product passport initiatives require improved data structuring to support life cycle assessment

Liang, Y.; Mogollón, J.M.; Cunha, S.; Donati, F.; Li, C.; Mintjes, B.A.; ... ; Istrate, I.R.

Journal of Industrial Ecology
https://doi.org/10.1007/s44498-026-00144-7

RESEARCH

Emerging digital product passport initiatives require improved data structuring to support life cycle assessment

Yanan Liang[1] · José M. Mogollón[1] · Sónia Cunha[1] · Franco Donati[1] · Chen Li[1,2] · Berend Mintjes[1] · René Kleijn[1] · Daniel Monfort Climent[3] · Ranran Wang[1,4,5] · Stéphanie Muller[3] · Aina Mas-Fons[3] · Brenda Miranda Xicotencatl[1] · Robert Istrate[1]

Received: 19 December 2025 / Accepted: 26 June 2026

Abstract
Persistent data gaps limit the quality of life cycle assessments (LCAs), which frequently rely on incomplete, outdated, or non-comparable process data. Digital product passports (DPPs), initially developed for supply chain traceability, regulatory compliance, and circular economy objectives, also hold potential to address long-standing data challenges in LCA. Based on 20 selected, publicly documented DPP initiatives assessed as of April 2025, this Comment examines how emerging DPP practices structure information relevant to LCA. These initiatives indicate that core attributes, including material composition, recycled content, hazardous substances, and product carbon footprints, are now common and could provide a basis for improved LCA practice. However, contextual quantitative and qualitative data needed for representative life cycle inventories (LCIs) and methodologically consistent LCAs remain limited, particularly for production characteristics, energy use, end-of-life (EoL) parameters, and data-quality metadata. To enhance the utility of DPPs for LCA, future developments should prioritise the inclusion of disaggregated LCI data and the integration of EoL information as scenario input. Embedding established LCA principles in DPP architectures would support consistency, scalability, and transparency, helping transform DPPs from static compliance tools into dynamic infrastructures for actionable sustainability assessment.

Keywords Industrial ecology · Digital product passport · Life cycle assessment · Life cycle inventory · Product carbon footprint · End-of-life modelling · Circular economy

1 Introduction

The European Union (EU) promotes digitalisation and the circular economy through the European Green Deal (European Commission 2019), the Circular Economy Action Plan (European Commission 2020b), and the Digital Strategy (European Commission 2020a). Formalised under the ecodesign for sustainable products regulation (ESPR), digital product passports (DPPs) are central to this vision (European Commission, 2024), aiming to provide standardised, machine-readable information on environmental impacts, circularity, and material sourcing across value chains (Chawla et al., 2026).

DPP-related efforts are not limited to Europe. In 2025, the United Nations Economic Commission for Europe (UNECE) and the International Organisation for Standardisation (ISO) launched a joint initiative to develop international DPP standards (UNECE, 2025a), building on earlier industry-led pilots such as the Global Battery Alliance (2023). Across sectors, DPPs are expected to embed structured information on material composition, origin, recycled content, and product carbon footprints (PCFs), among others, thereby supporting regulatory compliance and circular-economy objectives (European Commission, 2024). Parallel academic work has

✉ Yanan Liang
y.liang@cml.leidenuniv.nl

1 Institute of Environmental Sciences (CML), Leiden University, 2333 CC Leiden, The Netherlands

2 Department Circularity and Sustainability Impact, Netherlands Organisation for Applied Scientific Research TNO, 3508 TA Utrecht, The Netherlands

3 BRGM, 45060 Orléans, France

4 State Key Laboratory of Water Pollution Control and Green Resource Recycling, School of the Environment, Nanjing University, Nanjing 210023, China

5 Institute for the Environment and Health, Nanjing University Suzhou Campus, Suzhou 215163, China

Published online: 11 July 2026

begun to specify the data attributes required for DPPs to fulfil these ambitions (Berger et al., 2022; Haupt et al., 2024; Jensen et al., 2023).

Currently, life cycle assessment (LCA), the primary method for quantifying the potential environmental impacts of products and services over their life cycle, remains constrained by limited access to primary data, defined here as company-specific, measurement-based information. Many LCAs rely on secondary life-cycle inventory (LCI) datasets that lack geographical, temporal, and technological representativeness (Crenna et al., 2019; Heijungs, 1996; Hellweg & Milà i Canals, 2014; Istrate et al., 2024; Wernet et al., 2016). For instance, Eltohamy et al. (2024) found that LCAs of electric mobility are hindered by scarce primary data for battery raw material supply chains, while Xu et al. (2025) identified persistent challenges in traceability and interoperability across LCI databases. Overall, the field recurrently highlights the need for improved access to primary data, along with standardised metadata on aspects such as temporal representativeness, location, technology specifications, and energy sources.

Although DPPs were originally designed to support traceability and compliance, they may also help address several of these LCA data challenges. By embedding harmonised, machine-readable, product-level information on material composition, product characteristics, and environmental indicators, DPPs could reduce reliance on outdated secondary datasets and improve the granularity and traceability of LCI data (Adisorn et al., 2021; Berger et al., 2022; Çetin et al., 2023). Conversely, LCA provides a science-based, standardised methodological framework for structuring and interpreting environmental information, including principles for defining system boundaries or assessing data quality (ISO, 2006a). This bidirectional relationship, where DPPs improve access to verifiable product-level data and LCA provides the methodological backbone, positions both as potentially complementary components of a shared sustainability data ecosystem. Recent work has explored this interface. For example, Haupt et al. (2024) compiled 32 LCA data requirements for DPPs, covering aspects from goal and scope definition to results verification and validation, while Panza et al. (2023) suggested extending DPPs to social impact and planetary boundaries-based indicators. Besides, Gieß and Möller (2025) conceptualise DPPs as boundary objects for data exchange.

However, existing studies have primarily focused on defining data requirements for DPPs or conceptualising their role in sustainability assessment. Less attention has been paid to how emerging DPP initiatives perform in practice, particularly in terms of the types of data they provide and their usability for LCA. This Comment addresses this gap by examining 20 publicly documented DPP initiatives, assessed up to April 2025, to evaluate how their data attributes can support LCA and to identify key data and methodological limitations that constrain their integration into the LCA workflow. By shifting the focus from conceptual requirements to proposed data structures, the analysis provides a practice-based perspective on how emerging DPP systems align with, or diverge from, the needs of LCA practice.

2 Coverage of LCA-relevant data in selected DPP initiatives

We selected 20 DPP initiatives to illustrate the coverage of LCA-relevant data in emerging DPP practices. The sample was assembled purposively from publicly documented initiatives across different DPP-relevant sectors and implementation contexts. It therefore provides a cross-sectoral overview rather than a systematic, representative, or exhaustive inventory of the DPP landscape. The term "initiative" is used here as a pragmatic umbrella to capture diverse forms of DPP-related developments, including research projects, policy platforms, industrial implementations, and standardisation efforts, which often overlap in practice. Initiatives were identified through a targeted review of publicly available sources, including policy documents, industry reports, and project documentation available as of April 2025. Selection was guided by two topical criteria: (i) explicit engagement with DPP-related data structures or data exchange, and (ii) inclusion of information relevant to sustainability assessment or circularity (e.g., material composition, environmental indicators, or end-of-life (EoL) considerations). The final sample covers batteries, electronics, construction products, textiles, and other material-intensive sectors. Further details on the initiative selection process are provided in **Supplementary Information SI1 Table S2**, which documents the analysed initiatives, sectors, data focus, and public sources, thereby supporting the traceability of the evidence base. Across these initiatives, LCA-relevant data attributes were grouped into four categories: assessment results and product, production, and EoL characteristics. These categories are used to facilitate comparison across initiatives, not as a formal taxonomy.

Figure 1 summarises attribute coverage across the analysed initiatives and maps the documented DPP content to environmental LCA. Several initiatives focus on the exchange of data across value chains to support PCFs. Examples include the Pathfinder/PACT framework from the World Business Council for Sustainable Development, which defines a cross-sector methodology and data-exchange protocol for PCFs, sectoral standards such as Together for Sustainability in the chemical industry (Together for Sustainability, 2025; World Business Council for Sustainable Development, 2023), and DPP-oriented data spaces such as Catena-X in the automotive sector (Catena-X Automotive

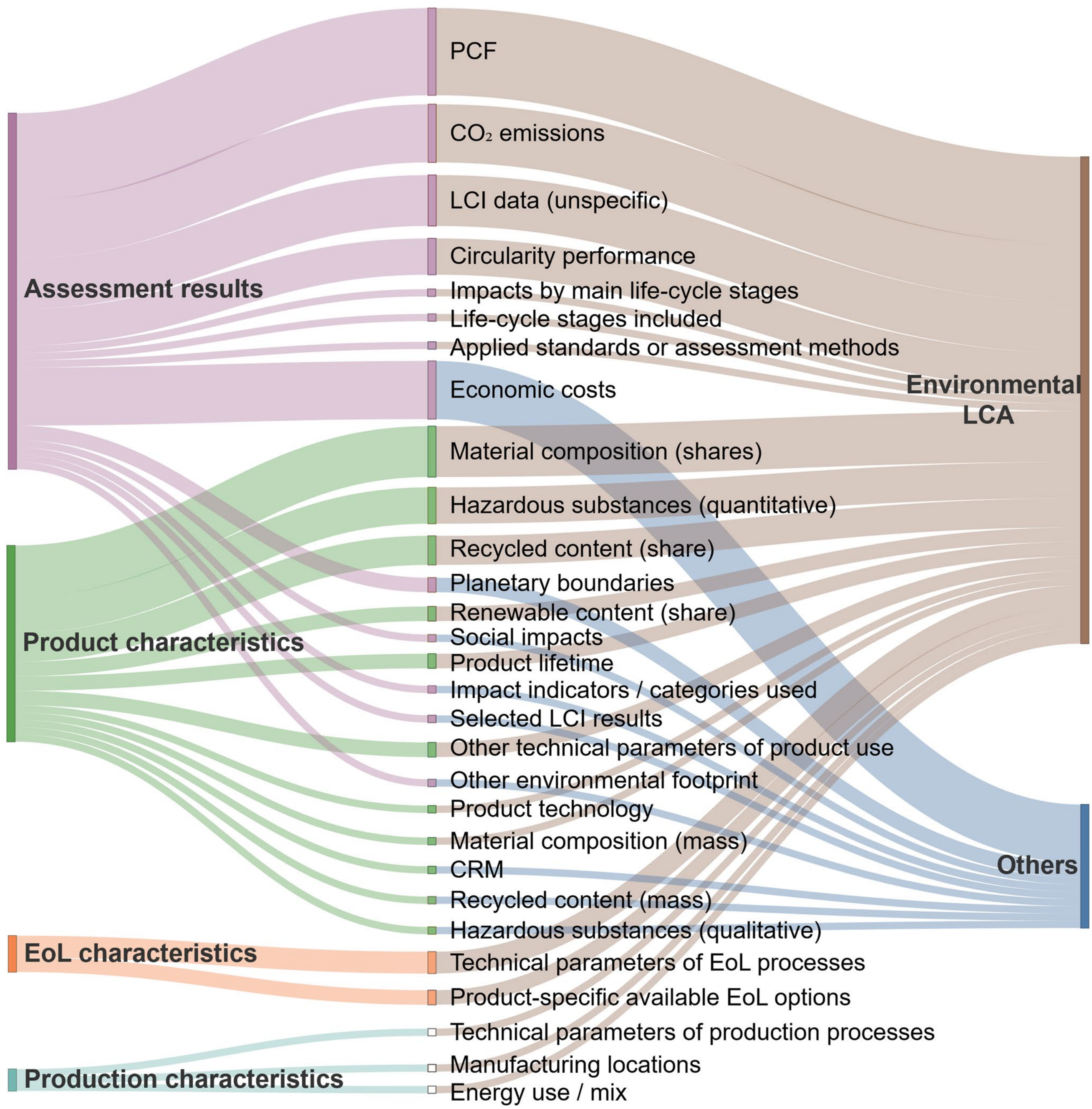

Fig. 1 Mapping data attributes from 20 DPP initiatives to environmental LCA. The left nodes represent content categories (product, production or EoL characteristics, and Assessment results). Middle nodes denote specific reporting requirements, and the right nodes indicate assessment methods. Link thickness reflects the number of initiatives that include each requirement (n = 20). *Source*: Authors' compilation based on the initiative-by-attribute mapping provided in **Supplementary Information SI2**

Network e.V. 2025). Across initiatives, a common logic is that each supply chain actor calculates a cradle-to-gate PCF based on its own processes and passes the aggregated result downstream. The downstream user then multiplies the received PCF by the quantity of the input product to derive their own PCF, forming an inheritance-based calculation model (Holzapfel et al., 2024).

Exchanging aggregated PCFs reduces the reporting burden but creates comparability challenges. Consistent use of PCFs requires alignment in methodological and modelling choices (e.g., system boundaries and background LCI datasets), which is difficult to guarantee in heterogeneous supply chains. Several sectoral initiatives provide PCF harmonisation guidelines, such as the Catena-X PCF

Rulebook (2025), the Global Battery Alliance (2023) calculation framework, and CarbonBlock (2026)'s built-in methodological documentation. Nevertheless, full alignment across the entire supply chain remains challenging, as companies may rely on different background datasets or make divergent modelling choices. As data exchange systems, the analysed initiatives prioritise technical interoperability, data exchange formats, and governance structures rather than full end-to-end methodological harmonisation.

Beyond PCFs, several initiatives report attributes that are directly useful as LCI inputs, including material composition, sometimes with absolute masses (Berger et al., 2022, 2023; EPEA GmbH, 2021; Jensen et al., 2023; KEEP, 2025; Spherity GmbH, 2025a), and hazardous substances information, which is quantitative in some initiatives (Battery Pass consortium, 2023; Spherity GmbH, 2025b). These attributes often require limited incremental effort because they are already collected for regulatory compliance, for example, under the restriction of hazardous substances directive (RoHS), the Ecodesign framework, and the registration, evaluation, authorisation and restriction of chemicals regulation (REACH) (European Commission, 2025; European Parliament & Council of the European Union, 2006).

In contrast, production characteristics (e.g., factory energy use and sources, geographical and temporal metadata) and EoL characteristics appear far less frequently in the analysed initiatives. Examples include Spherity's initiative and the Battery Pass, which have incorporated the separate EoL disposal guidelines into their DPPs (Battery Pass consortium, 2023; Spherity GmbH, 2025a). The initiatives reviewed here therefore predominantly capture upstream and mid-stream product attributes, while providing limited coverage of production conditions, use-stage performance, and EoL outcomes.

This asymmetry is not simply a design gap but reflects structural differences in data controllability across life-cycle stages. Upstream and mid-stream data are typically closer to the manufacturer's sphere of influence and are often already collected for procurement, compliance, traceability, or quality control purposes. In contrast, use and EoL outcomes depend on factors beyond direct producer control, including user behaviour, product use patterns, local infrastructure, and downstream waste management systems.

As a result, manufacturers and suppliers can more readily report information on product composition and production-related attributes than on actual downstream performance. In the selected initiatives, downstream information therefore mainly reflects intended use conditions, repair guidance, or recyclability claims, rather than measured outcomes. This indicates a structural boundary to the types of life-cycle information DPPs can realistically provide at the point of product placement.

3 Data gaps and needs for enhancing LCAs

Therefore, limited data granularity remains the principal constraint limiting the usefulness of DPPs for LCA research. Aggregated PCFs facilitate exchange but mask the processes, technological parameters, geographical conditions, and operational behaviours driving these impacts. For most LCA-based decisions, such aggregation is overly simplified. Researchers require process-specific data to identify impact hotspots across a product life cycle, assess burden shifting, or design mitigation strategies (an overview of potential process-specific data gaps is provided in Table 1).

From an LCA perspective, process-specific inventory data are more analytically valuable because it preserves the detail required for robust modelling and interpretation. However, generating and sharing such data is challenging in practice. It increases reporting burden, requires frequent updates, and may expose commercially sensitive information, such as production efficiencies and technology choices. The trade-off is therefore not only technical but also organisational and governance-related: the data that is most informative for LCA is often also the least shareable within supply chains.

As a result, the value of DPP data for LCA is inherently dependent on the level of access and intended use. While more detailed data would improve assessment capabilities, practical implementation often requires balancing transparency with confidentiality and feasibility. Such limitations may reflect deliberate design choices to reduce reporting burden, protect sensitive information, and support industry uptake. Some DPP architectures already include tiered access rights to manage this trade-off (Catena-X Automotive Network e.V. 2025; CIRPASS Consortium, 2024; CIRPASS-2 Consortium, 2025; Global Battery Alliance, 2023). If detailed LCI data were included, access would likely be restricted to accredited actors, such as regulators or auditors. While such arrangements can strengthen verification and security, they may also limit accessibility for a broader audience and, consequently, the analytical use of DPPs.

A further limitation concerns EoL information. In the analysed initiatives, manufacturers can at best report intended treatment routes or recyclability potential, rather than observed outcomes. In LCA, EoL modelling combines factual data (e.g., recycling or landfilling rates) with scenario assumptions. If EoL impacts are embedded with an aggregated PCF, they must be sufficiently disaggregated to separate assumed downstream scenarios from upstream processes. However, dynamic, product-specific EoL performance data is rarely available in a verifiable form and generally falls outside the practical scope of DPP systems.

Table 1 Data gaps to enhance the value of DPPs for LCA research (non-comprehensive overview) (European Commission 2023, 2025; European Parliament and Council of the European Union, 2023)

	Possible data attributes	Barriers to inclusion in DPP	Why needed	Current LCA practice	Potential implementation pathways in DPPs
Foreground system characteristics	• Process energy use and energy sources (by site, period, etc.) • Materials intensity, including critical raw materials (CRMs) • Hazardous substances content in the product (quantitative)	• High metering cost; supplier confidentiality; frequent updates • Trade and security sensitivity • Competitive concerns; inconsistent reporting rules	• Drives LCA results (ensure geographic, technology, and temporal representativeness) • Drives LCA results; CRM Act alignment • Drives LCA results, particularly toxicity impacts; compliance checks are mandatory under RoHS	• Usually replaced with generic consumption and supply mix "averages" • Often outdated material intensities that are not representative of evolving technologies (e.g., electronics) • Partial or qualitative lists; poor comparability	• Tiered reporting, including e.g., aggregated values for public disclosure; Internet of Things (IoT) systems to automate updates • Tiered data access • Harmonised reporting templates, threshold-based disclosure
Use stage	• Technical lifetime, energy efficiency, etc. (measured)	• High variability across users and contexts; costly test design; frequent updates; highly user behaviour dependent	• Crucial where the use stage dominates impacts (e.g., household appliances)	• Direct metered data is rarely available, and few standardised tests exist	• Combine standardised test protocols with optional real-world performance data
EoL characteristics	• EoL parameters (technology used, recovery rate, geography, etc.)	• Data dispersed across recyclers and operators; multi-actor chains	• Determines materials and energy recovery potential and recycled input rate	• EoL modelled with generic background LCIs	• Chain-of-custody (CoC) integration: link DPPs with waste operator reporting systems
Cross-cutting	• Data-quality and provenance (market coverage, representativeness, verification)	• Extra reporting burden; lack of harmonization	• Allow users to assess reliability	• Data Quality Indicators (DQI) fields are absent, and provenance information is mostly missing	• Mandatory DQI metadata fields; machine-readable provenance tags

Downstream actors are unlikely to feed operational data into individual passports, and many EoL outcomes are inherently modelled rather than measured. Expecting DPPs to resolve these limitations risks conflating product-level information systems with broader waste-system monitoring infrastructures.

4 Integrating the LCA framework into DPPs

A major strength of LCA lies in its standardised principles and reporting requirements, which enable assessments that can be audited for transparency and reproducibility (ISO, 2006b, 2006c). DPPs can align with established LCA conventions by integrating key aspects such as system boundaries, functional units, provenance rules, and DQI into their data models. This would ensure that DPP information remains interpretable and comparable across supply chains, while complementing compliance functions.

In practice, however, transparency in LCAs remains uneven. Many datasets in widely used LCI databases lack accessible documentation, consistent metadata, or traceable sources (Guo et al., 2025; Xu et al., 2025). DPPs could help by requiring product-level data to be reported in machine-readable, interoperable formats with explicit provenance and methodological metadata, allowing users to trace, compare, and reconcile differences across datasets. Here, "verified" product-level information should be understood in a differentiated sense, ranging from self-declared and documented data to audited or measured values, depending on data type, governance arrangements, and available verification mechanisms. DPPs do not ensure uniform verification across all fields, but can make verification status and data provenance more explicit. Where supplier-specific data are unavailable, DPPs could include clearly labelled proxy data that can be replaced when verified primary information becomes available. This would help users distinguish modelled assumptions from verified observations, improving both interpretability and verification. While DPPs cannot eliminate diversity in LCA practice, they can make this diversity visible and auditable, turning opaque uncertainty into an attribute that can be examined and managed. In practice, limited documentation and inconsistent metadata in existing LCI databases reduce reproducibility and complicate systematic linkage with DPP-based data.

To be effective for LCA, DPPs should integrate the priority data attributes (Table 1), including energy use, EoL parameters, CRM intensity, and hazardous substances, accompanied by provenance information, verification status, and DQI. DPPs can include dynamic update mechanisms, such as change logs and timestamps, that allow information to be updated over time, helping passports function as living datasets rather than static records (UNECE, 2025b). This is particularly relevant where composition and CRM content shift rapidly with regulation and technology (European Commission, 2023).

5 Moving forward

DPPs and LCA can be mutually reinforcing. DPPs offer a pathway to improve access to structured, product-level information, while LCA offers a methodological framework for interpreting and using such data. Realising this complementarity requires deliberate shifts in DPP design and governance.

Moving beyond aggregated indicators towards disaggregated LCI data is essential to enhance analytical value. While aggregated indicators (e.g., PCFs) offer a pragmatic starting point by lowering reporting burdens and enabling data exchange, they can provide limited informational value. Greater benefits may arise once DPPs capture disaggregated LCIs, such as energy use and sources, EoL parameters, CRM intensity, and provenance metadata. At the same time, DPPs should not be treated as LCI databases, as they do not model full supply chains, but they provide structured product-level data that can complement, rather than replace, existing LCIs.

Framing EoL information as scenario input, not factual reporting. Given the limited control of manufacturers over downstream processes, DPPs are unlikely to provide measured EoL outcomes. Instead, they can support LCA by providing structured information that informs scenario-based modelling. Clear guidance on plausible product-specific EoL pathways would support more consistent downstream assumptions without exceeding the industry's reporting capacity or undermining data credibility.

Harmonisation of methodological choices is necessary for meaningful reuse of DPP data. The potential reuse of DPP data depends on aligned definitions of functional units, reference flows, and system boundaries. Without such alignment, interoperability across components and assemblies remains limited in practice. Clear, machine-readable metadata, supported by the LCA community guidance tailored to product groups, will be essential for comparing, aggregating, and reusing DPP data. Embedding harmonised reporting conventions aligned with ISO and ProductEnvironmental Footprint (PEF) principles would make LCAs more representative, transparent, and reproducible. This will allow DPPs to function as more effective infrastructures for environmental assessments.

The value of DPP data is shaped by governance frameworks that balance transparency, confidentiality, and feasibility. While detailed data may remain restricted to authorised actors, aggregated or anonymised datasets can still improve representativeness and reduce reliance on generic assumptions. In this way, DPPs can evolve into data infrastructures that support both regulatory compliance and environmental assessment.

While this Comment focused on LCA, the broader potential of DPP lies in how Industrial Ecology methods can shape their design and amplify their usefulness across stakeholders. Beyond supporting environmental assessment, DPPs should also provide accessible information to end-users, repairers, and recyclers, for example, on product composition, durability, repairability, and recyclability. Where such information is structured and verifiable, it can also support improved modelling of use-phase and EoL processes in LCA. Embedding these principles can help DPPs evolve into coherent data infrastructures linking product information with material, environmental, and socio-economic flows.

6 Conclusion

Here we examined how a selected set of publicly documented DPP initiatives can support LCA, and conversely, how LCA can inform DPP design. The analysed initiatives increasingly include selected product-level attributes and environmental indicators, but key elements required for representative LCIs, particularly production characteristics, EoL parameters, and data-quality metadata, remain limited. Strengthening the integration of LCA principles into DPP data models could improve the transparency and reproducibility of environmental assessments based on DPP data. This assessment is intended as an illustrative overview of selected emerging practices rather than a comprehensive evaluation. In addition, no systematic comparison of DPP maturity or coverage is conducted, as comparable indicators and standardised information are not consistently available across initiatives, many of which remain at pilot or early stages.

7 Summaries

Supplementary Information SI1: This supporting information provides the abbreviation list and details of the selection and categorisation of the digital product passport initiatives analysed in the manuscript. It includes Table S1, listing abbreviations used in the manuscript, and Table S2, documenting the analysed initiatives and supporting public sources.

Supplementary Information SI2: This supporting information provides the qualitative assessment underlying Figure 1 of the main text.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44498-026-00144-7.

Acknowledgements This research was conducted under the MaDiTraCe, CE-RISE, and Lasers4MaaS projects, funded by the European Union's Horizon Europe research and innovation programme under grant agreements No. 101091502, No. 101092281, and No. 101178719, respectively.

Author contribution Conceptualization: B.M., C.L., R.I., S.C., Y.L.; Writing—original draft: Y.L.; Data curation: S.C., B.M., C.L., Y.L., and R.I.; Writing—review and editing- J.M.M., F.D., D.M.C., A.M.-F., S.M., B.M.X., C.L., R.W., R.K., S.C., and R.I.; Visualization: Y.L. and R.I.; Funding acquisition: R.K. and J.M.M.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a digital product passport fit for contributing to a circular economy. *Energies, 14*(8), Article 2289.

Battery Pass consortium. (2023). *Battery passport content guidance: Achieving compliance with the EU battery regulation. Guidance document*. Battery pass consortium (co-funded by German Federal Ministry for Economic Affairs and Climate Action), April. https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Content_Guidance.pdf.

Berger, K., Baumgartner, R. J., Weinzerl, M., Bachler, J., & Schöggl, J.-P. (2023). Factors of digital product passport adoption to enable circular information flows along the battery value chain. *Procedia CIRP, 116*, 528–533. 30th CIRP Life Cycle Engineering Conference.

Berger, K., Schöggl, J.-P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production, 353*, Article 131492.

Catena-X Automotive Network. (2025). Catena-X Product *Carbon Footprint Rulebook: CX-PCF Rules*. Version 4. Catena-X Automotive Network

Catena-X Automotive Network e.V. (2025). Catena-X Standardisation. *Catena-X: Standardisation (Web Page)*. December 4. https://catena-x.net/association/standardization/.

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Production and Consumption, 40*, 422–437.

Chawla, K., Chirvasuta, T., Wolf, M.-A., Wolf, K., & Rongen, S. (2026). *Methodology for defining data requirements for the digital product passport under the ESPR framework*. Publications Office of the European Union.

CircularTree. (2026). CarbonBlock. *CircularTree Platform*. CircularTree. https://circulartree.com/carbonblock/.

CIRPASS Consortium. (2024). *CIRPASS: Digital product passport — cross-sector and sector-specific roadmaps and data-model proposal*. CIRPASS Project Documentation. March 1. https://cirpassproject.eu/.

CIRPASS-2 Consortium. (2025). *CIRPASS-2: Digital product passports enabling at-scale and real-life circular economy use cases*. CIRPASS-2 Project Documentation. December 4. https://cirpass2.eu/.

Crenna, E., Secchi, M., Benini, L., & Sala, S. (2019). Global environmental impacts: Data sources and methodological choices for calculating normalization factors for LCA. *The International Journal of Life Cycle Assessment, 24*(10), 1851–1877.

Eltohamy, H., van Oers, L., Lindholm, J., Raugei, M., Lokesh, K., Baars, J., Husmann, J., Hill, N., Istrate, R., Jose, D. & Tegstedt, F. (2024). Review of current practices of life cycle assessment in electric mobility: A first step towards method harmonization. *Sustainable Production and Consumption, 52*, 299–313.

EPEA GmbH. (2021). *The Cradle to Cradle design principle for buildings*. EPEA GmbH, December 1. https://www.epea.com/en/news/booklet-das-cradle-to-cradle-designprinzip-fur-gebaude.

European Commission. (2019). European Green Deal. European Commission, December 11. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

European Commission. (2020a). *Europe fit for the digital age*. European Commission, February 19. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age_en.

European Commission. (2020b). *Circular economy action plan*. European Commission, March 11. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.

European Commission. (2023). *Critical raw materials act*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en. Accessed May 5, 2025.

European Commission. (2024). *Ecodesign for sustainable products regulation - European Commission*. August 8. https://environment.ec.europa.eu/topics/circular-economy/ecodesign-sustainable-products-regulation_en.

European Commission. (2025). *RoHS directive*. July. https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en.

European Parliament and Council of the European Union. (2006). Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the registration, evaluation, authorisation and restriction of chemicals (REACH). *Official Journal of the European Union L 396*. Brussels, December 18. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006R1907.

European Parliament and Council of the European Union. (2023). Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC. *Official Journal of the European Union*, July 12. https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng.

Gieß, A., & Möller, F. (2025). Exploring the value ecosystem of digital product passports. *Journal of Industrial Ecology, 29*(2), 561–573.

Global Battery Alliance. (2023). *GBA battery passport - proof of concept pilots: Setup. Learning. Next steps*. Global Battery Alliance. https://www.globalbattery.org/media/pilot/documents/gba-bp-pilot-master.pdf. Accessed April 21, 2023.

Guo, J., Li, R., Zhang, R., Qi, J., Li, N., Xu, C., Chiu, A. S. F., Wang, Y., Tanikawa, H., & Xu, M. (2025). Shedding light on the shadows: Transparency challenge in background life cycle inventory data. *Journal of Industrial Ecology, 29*(3), 766–776.

Haupt, J., Cerdas, F. & Herrmann, C. (2024). Derivation of requirements for life cycle assessment-related information to be integrated in digital battery passports. In *Procedia CIRP* 122. *31st CIRP Conference on Life Cycle Engineering* (pp. 300–305).

Heijungs, R. (1996). Identification of key issues for further investigation in improving the reliability of life-cycle assessments. *Journal of Cleaner Production, 4*(3–4), 159–166.

Hellweg, S., & Milà i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science, 344*(6188), 1109–1113.

Holzapfel, P., Bach, V., Jaeger, F. A., & Finkbeiner, M. (2024). The primary data share indicator for supply chain specificity in product carbon footprinting. *Ecological Indicators, 166*, Article 112435.

ISO. (2006a). *ISO 14025:2006—environmental labels and declarations—Type III environmental declarations—principles and procedures*. ISO.

ISO. (2006b). *ISO 14044:2006 Environmental management—life cycle assessment—requirements and guidelines*. International Organization for Standardization. https://www.iso.org/standard/38498.html.

ISO. (2006c). *ISO 14040:2006 environmental management—life cycle assessment—principles and framework*. Standard. International Organization for Standardization. https://www.iso.org/standard/37456.html.

Istrate, R., Mas-Fons, A., Beylot, A., Northey, S., Vaidya, K., Sonnemann, G., Kleijn, R., & Steubing, B. (2024). Decarbonizing lithium-ion battery primary raw materials supply chain. *Joule, 8*(11), 2992–3016.

Jensen, S. F., Kristensen, J. H., Adamsen, S., Christensen, A., & Waehrens, B. V. (2023). Digital product passports for a circular economy: Data needs for product life cycle decision-making. *Sustainable Production and Consumption, 37*, 242–255.

KEEP. (2025). *KEEP innovation project*. https://keepelectronics.com/#/. Accessed December 2, 2025.

Panza, L., Bruno, G., & Lombardi, F. (2023). Integrating absolute sustainability and social sustainability in the digital product passport to promote industry 5.0. *Sustainability, 15*(16), Article 12552.

Spherity GmbH. (2025a). *Spherity*. Spherity GmbH. https://www.spherity.com/.

Spherity GmbH. (2025b). *VERA digital product passport suite: Enabling compliance, trust, and circularity*. *Product Brief / Overview*. Spherity GmbH, March. https://www.spherity.com/digital-product-passport.

Together for sustainability. (2025). Together for sustainability – The chemical initiative for sustainable supply chains. December 5. https://www.tfs-initiative.com/. Accessed December 5, 2025.

UNECE. (2025a). UNECE and ISO launch joint initiative on Digital Product Passport to advance sustainability and circular economy. April 8. https://unece.org/digitalization/news/unece-and-iso-launch-joint-initiative-digital-product-passport-advance. Accessed October 1, 2025.

UNECE. (2025b). *White paper on globally unique identifiers in supply chains*. Geneva, Switzerland: UNECE, June 4. https://unece.

org/trade/documents/2025/06/standards/white-paper-globally-unique-identifiers-supply-chains.

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.

World Business Council for Sustainable Development. (2023). *Pathfinder framework: Guidance for the accounting and exchange of product life cycle emissions*. WBCSD. https://www.wbcsd.org/Programs/Climate-and-Energy/Climate/Pathfinder.

Xu, C., Jia, T., Qi, J., Cai, Z., Zhang, R., Xiong, R., Chang, H., Lu, X., Li, N., Tian, J. & He, K. (2025). Addressing critical challenges towards a robust data system for life cycle assessment. *Nature Reviews Clean Technology*, 1–13. https://doi.org/10.1038/s44359-025-00107-4