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Life Cycle Assessment for sustainable business management

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Abstract

This study explores the strategic role of Life Cycle Assessment (LCA) as a decision-support tool for enhancing sustainability in business management. LCA provides a comprehensive and science-based framework to evaluate the environmental impacts of products, services, and systems across their life cycle stages. A key contribution of this work is the classification of LCA uses into internal and external functions, ranging from product development, procurement, and operations to marketing, education, and policy engagement. Moreover, the paper distinguishes between retrospective and prospective applications of LCA, highlighting the former's use in benchmarking and compliance, and the latter's relevance in guiding sustainable innovation and early-stage decision-making. By promoting methodological innovation and expanding practical applications, LCA can evolve from a technical assessment tool into a strategic asset for sustainable business transformation.

Keywords. Life Cycle Assessment (LCA), business management, sustainable business, sustainability goals

1. Introduction

Sustainability, represented by the triad model, integrates the economic, social and environmental dimensions, emphasising their interdependence and the need for a balanced approach to long-term development [1]. Sustainability has become a key aspect to integrate into modern business practices, shaping the strategies and operations of industries worldwide [2, 3]. Companies are increasingly recognising the need to integrate sustainable practices into their business models as global environmental issues such as climate change, resource depletion and environmental degradation continue to intensify [4]. Sustainable business strategies firstly contribute to the preservation of natural ecosystems, and improve long-term profitability, brand reputation, stakeholder relationships and regulatory compliance [5].

Among the various tools developed to support sustainable decision-making, Life Cycle Assessment (LCA) has emerged as one of the most comprehensive and widely adopted methodologies assessing the environmental impact of a product, service or process throughout its life cycle, as the starting point to find the improvements that can be made [6, 7, 8]. The International Organization for Standardization (ISO) has established guidelines for LCA, ensuring reliability and transparency in sustainability assessments, through ISO 14040, which outline its standardized four key steps, as shown in fig. 1. Goal and scope definition is the phase where the purpose, boundaries, and focus of the study are set, and so creates the essential basis for the next phases. The inventory analysis is guided by the methodological choices made in the previous phase of goal and scope definition and is acknowledged worldwide to be the most-time consuming part of LCA [9]. Following the definition of the system and related boundaries and the creation of flow charts, the LCI has the main task of gathering, calculating and reporting data, and of conducting allocation if co-products exist in the system. The analysis is completed by scaling all inputs and outputs to the functional unit of the study, which is still standard practice in LCA [10].

The data inventoried are processed into potential environmental effects that are evaluated in the next phase of life cycle impact assessment. Results from this phase are then analysed to draw meaningful conclusions and support informed decision-making [11, 12, 13].

The outcomes of an LCA can then be used in direct applications, such as improving product design, guiding policy decisions, supporting marketing strategies, or enhancing environmental performance [14].

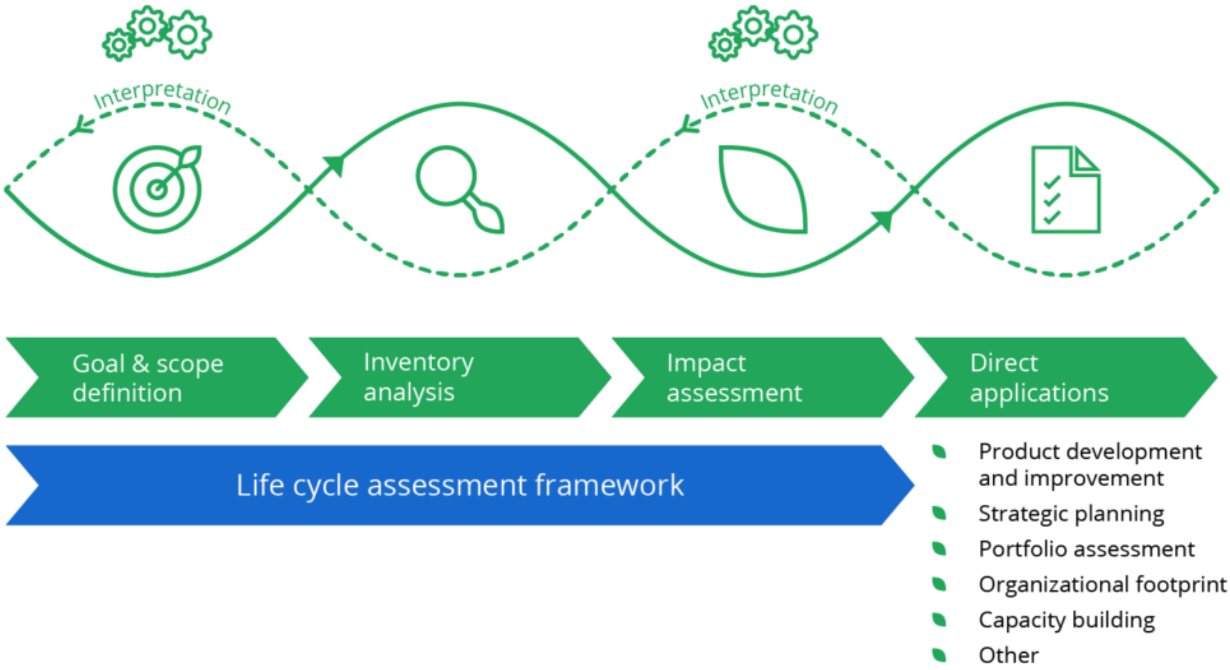

Fig. 1. The four fundamental steps of LCA [14].

By providing a comprehensive analysis of energy consumption, greenhouse gas emissions, waste generation, and resource utilization, LCA enables businesses to identify critical impact areas and make data-driven decisions, implementing more sustainable practices in product design and operations [8, 15]. Thus, LCA can contribute to business improvement and transformation, by highlighting inefficiencies, guiding eco-design strategies, achieving a better reputation and gaining a competitive advantage, and supporting compliance with sustainability regulations and reporting frameworks [16, 17, 18].

The integration of LCA into business strategies plays a key role in advancing the United Nations Sustainable Development Goals (SDGs), providing a science-based framework to assess and reduce environmental impacts. LCA directly supports SDG 12 (Responsible consumption and production) by promoting resource efficiency, circularity, and the reduction of waste across the entire life cycle of products and services [19, 20]. Its application also contributes to SDG 13 (Climate action) by identifying emissions hotspots and enabling mitigation strategies aligned with corporate climate targets [21]. Moreover, when used to guide innovation in product development and industrial processes, LCA contributes to SDG 9 (Industry, innovation and infrastructure) [22]. Depending on the sector of application, LCA can also generate valuable insights for SDG 6 (Clean water and sanitation), SDG 7 (Affordable and clean energy), and SDG 15 (Life on land) [23]. As such, the adoption of LCA fosters not only internal sustainability performance but also measurable contributions to global sustainability commitments, positioning businesses as active agents in the achievement of the 2030 Agenda [24].

In this context, Environmental Product Declarations (EPDs) are standardized LCA-based documents that communicate the environmental impacts of a product throughout its life cycle [25, 26]. Developed in accordance with international standards such as ISO 14025 and EN 15804 (for construction products), EPDs are grounded in comprehensive LCA studies and follow specific Product Category Rules (PCRs) to ensure consistency and comparability among similar products [25, 27]. By quantifying key environmental indicators – such as global warming potential, resource consumption, and pollutant emissions – across the entire product life cycle, EPDs offer objective data to support sustainable decision-making in procurement, design, and regulatory compliance [28]. EPDs translate complex LCA results into accessible formats that are easily interpreted by stakeholders, including customers, policymakers, and certification bodies. As such, EPDs are increasingly used to support green public procurement policies, sustainability certification schemes (e.g., LEED, BREEAM), and corporate environmental reporting [29]. Their growing importance reflects a broader shift towards data-driven and transparent sustainability communication, in which LCA plays a foundational role.

This discussion paper contributes to the literature by providing a structured and comprehensive classification of LCA applications in business management, distinguishing between internal and external functions and mapping them across retrospective and prospective dimensions. Despite the growing volume of research linking LCA to business decision-making, its potential as a strategic management tool is still underexploited [22]. There is a pressing need to develop integrated frameworks that bridge environmental assessment with business-oriented tools. These would enable companies to systematically incorporate life cycle thinking into long-term decision-making, thereby aligning environmental sustainability with competitive advantage [30]. By illustrating how LCA supports both operational and strategic decision-making, this study offers a novel perspective that bridges methodological rigour with managerial relevance. Furthermore, the paper advances the discussion on prospective LCA, highlighting its underutilised role in fostering innovation, guiding early-stage decisions, and anticipating sustainability-driven policy and market transformations. These insights lead to concrete policy recommendations for integrating LCA into corporate strategy, procurement practices, and regulatory dialogues, contributing to more adaptive and sustainability-oriented business models.

This discussion paper argues that the integration of LCA into corporate decision-making processes is essential for sustainable business management, while also examining its benefits and limitations.

2. Research development needs

This study adopts a qualitative, literature-based approach, commonly used in discussion papers. The aim of this work is to highlight the pivotal role of LCA as a decision-making tool in enhancing business sustainability with a smart and reader-friendly approach. To ensure alignment between the literature analysed and the scope of the study, the authors identified a set of relevant keywords that reflect the core thematic dimensions explored: “life cycle assessment”, “business management”, and “sustainable business”. These keywords were searched within the title, abstract, and keyword fields of the Scopus database, which was chosen for its global recognition and comprehensive coverage of peer-reviewed scientific literature across a wide range of disciplines [31]. Scopus’s breadth and quality make it particularly suited for capturing interdisciplinary studies at the intersection of sustainability, management, and LCA methodology. To ensure relevance and academic rigor, inclusion and exclusion criteria were applied. Inclusion criteria comprised peer-reviewed articles published in English, with a clear methodological application or discussion of LCA in the context of business or sustainability management. Conversely, exclusion criteria involved publications focused solely on technical or engineering-specific LCA applications (e.g., in materials science or chemical processes) without managerial or strategic implications. Each selected article was then screened based on its stated objectives and contributions to the intersection of sustainability assessment, strategic business planning, and business management. The final sample was analysed to extract recurring patterns of LCA application, which were then classified into internal or external and retrospective or prospective uses. The methodological contribution of this paper lies in offering a new conceptual framework that enhances the understanding of how LCA supports sustainable business practices. This framework is summarised in Tables 1 and 2, which provide a visual synthesis of the findings.

3. LCA as a tool in business management

LCA can be applied in various ways within companies, serving both internal and external purposes [32]. Internally, LCA results can support strategic decision-making across multiple departments, including product design, procurement, operations, and sustainability management [33]. These insights help optimize resource use, reduce environmental impacts, and align practices with corporate sustainability goals. Externally, LCA findings can be communicated to stakeholders such as customers, investors, regulatory bodies, and certification agencies. In this context, LCA serves as a transparency and accountability tool, enhancing corporate reputation, meeting regulatory requirements, and supporting environmental labelling or sustainability reporting initiatives.

Moreover, the applications of LCA can be broadly categorized into retrospective and prospective uses [32]. Retrospective LCA focuses on analysing existing products, processes, or systems to provide a detailed picture of their current environmental impacts. This approach is valuable for benchmarking, performance evaluation, and identifying areas for improvement. In contrast, prospective LCA is forward-looking and used during the early stages of product or process development. It plays a crucial role in guiding innovation by assessing the potential environmental consequences of design choices, emerging technologies, or future scenarios. This proactive use of LCA supports more sustainable innovation and helps companies anticipate regulatory trends and market expectations.

3.1 Internal and External uses of LCA

LCA can be implemented within companies to serve both internal and external functions, offering strategic value across various levels of business activity.

3.1.1 Internal uses

- Design, and Research and development (R&D).

One of the most common internal applications of LCA is the identification of environmental critical point along the product life cycle [33]. Another key use is the comparison of existing products with planned or existing alternatives, supporting evidence-based decision-making. In the context of R&D, LCA serves as a strategic decision-support tool that drives product innovation and improvement. By identifying potential environmental impacts issues at the early stages of development process - whether concerning a product, process, or service - LCA facilitates the creation and market introduction of more environmentally sustainable solutions. This proactive approach supports the integration of sustainability principles from the very outset of innovation efforts [32, 34].

- Procurement decision-making

LCA is a valuable tool for procurement decision-making, as it enables organizations to evaluate and compare the environmental impacts of products and services across their entire life cycle. By incorporating LCA into procurement processes, decision-makers can identify more sustainable suppliers and materials, optimize supply chain practices, and reduce environmental risks and costs [35, 36]. This life-cycle perspective supports more informed and responsible purchasing choices, aligning procurement strategies with environmental performance goals and broader sustainability commitments [37].

- Production

LCA plays a crucial role in supporting production-related decision-making by identifying environmental hotspots within manufacturing processes and guiding improvements in resource efficiency, energy use, and waste management. By systematically assessing inputs and outputs across each stage of production, LCA helps organizations optimize process design, select lower-impact materials, and implement cleaner technologies [21, 38]. LCA is also suitable to support long-term strategic decisions; this tool is often integrated into the product development process, as it can significantly reduce costs by avoiding later-stage design flaws and ensuring compliance with environmental regulations [39]. Through these insights, LCA fosters more sustainable production systems, contributing to both operational efficiency and environmental performance.

- Marketing

LCA is increasingly used as a strategic tool in marketing to substantiate environmental claims, enhance product transparency, and strengthen brand reputation. By providing scientifically grounded data on the environmental performance of products and services, LCA enables companies to communicate credible sustainability attributes to consumers and stakeholders [29, 40]. This is particularly valuable in green marketing, where consumer trust depends on the verifiability of claims such as “carbon neutral”, “eco-friendly”, or “low environmental impact”. LCA also supports benchmarking against environmental standards and eco-labelling criteria, such as the EU Ecolabel or Environmental Product Declarations (EPDs), thereby facilitating the attainment of recognized certifications that strengthen market positioning and open access to green procurement channels [25]. Moreover, LCA enables companies to compare their products with those of competitors, helping to demonstrate superior environmental performance and positioning their offerings as market leaders [33]. It also provides a robust method for evaluating compliance with established eco-label schemes or regulatory requirements, offering a reliable basis for achieving certifications like the EU Ecolabel [27, 28]. By integrating LCA into marketing strategies, companies can ensure that their sustainability communication is aligned with corporate goals, enhance brand differentiation, and reduce the risk of greenwashing through transparent and data-driven communication.

- Information and education

LCA serves as a powerful educational and informational tool by providing a structured and quantitative framework to understand the environmental consequences of human activities, products, and systems. It helps students, professionals, policymakers, and consumers gain awareness of the full life cycle impacts – such as resource depletion, greenhouse gas emissions, and waste generation – associated with production and consumption choices [22, 40]. LCA also supports the education and training of employees, helping companies build internal capacity for sustainability-oriented decision-making. By integrating LCA into employee training programs, organizations can improve understanding of environmental performance metrics, foster cross-departmental collaboration, and promote continuous improvement across operations [41]. Additionally, LCA facilitates clear communication of environmental information in both academic and corporate settings, reinforcing a culture of sustainability and responsible innovation.

- Strategic decision-making

LCA is increasingly recognized as a strategic tool that supports high-level decision-making in businesses aiming to integrate sustainability into their core strategy [33]. By providing comprehensive insights into environmental impacts across the product life cycle, LCA informs strategic portfolio optimization, enabling firms to prioritize low-impact products, redesign or eliminate environmentally burdensome offerings, and align their portfolios with sustainability goals and stakeholder expectations [42]. LCA also supports radical innovation, such as redesigning entire product systems or extending product life cycles through reuse, remanufacturing, or modular design [30, 33]. Moreover, it facilitates transitions from product-based models to service-based models (e.g., product-as-a-service), by identifying environmental advantages of shared-use or performance-based approaches [43]. LCA insights can also guide entry into new green markets, where environmental performance becomes a competitive differentiator, and help companies anticipate or exceed evolving environmental regulations, reducing compliance risks and fostering long-term resilience [22]. As such, LCA enables businesses to make proactive, sustainability-oriented strategic decisions grounded in robust data.

3.1.2 External uses

- Marketing

LCA plays a key role in supporting external marketing activities by providing scientifically grounded evidence for environmental claims used in advertising, product labelling, and sustainability communication. Companies increasingly rely on LCA to back eco-friendly claims, differentiate their offerings in competitive markets, and join recognized eco-labelling [25, 28]. LCA-based EPDs and certifications build trust with environmentally conscious consumers, helping firms position themselves as leaders in sustainability and access green markets [29]. However, a key challenge for the credibility of LCA in marketing contexts lies in the transparency and consistency of its underlying assumptions (system boundaries, allocation rules, energy mix, etc) and data. The results of an LCA study can vary significantly depending on choices such as system boundaries, allocation rules, impact assessment methods, and data quality. As noted by [40], “the most crucial point has usually been the availability and quality of data”, which can undermine stakeholder confidence if not managed transparently. To ensure credibility in external communication, it is essential that LCA results are thoroughly documented, verified, and aligned with international standards such as ISO 14040 and ISO 14025. When applied rigorously, LCA enables companies to engage in responsible marketing and demonstrate measurable environmental performance.

- Information and education

LCA is a valuable tool for external communication, education, and engagement with stakeholders, customers, and regulatory authorities. By offering a transparent and science-based assessment of a product's environmental performance, LCA helps companies convey credible sustainability information and foster trust across their value chain [40]. One widely adopted mechanism for sharing LCA results is the EPD, a standardized and verified document that communicates a product's environmental impacts throughout its life cycle in an objective and comparable format [27, 28]. Companies are increasingly exploring such tools to inform and influence suppliers, clients, and institutional stakeholders, gaining market benefits while ensuring regulatory compliance and alignment with sustainability expectations. Furthermore, LCA-based communication enhances public understanding of environmental trade-offs and supports constructive dialogue with authorities in areas such as product design regulations, ecolabel eligibility, and sustainability reporting [25]. When used consistently and transparently, LCA can contribute to a broader culture of environmental responsibility and informed decision-making among both businesses and the public.

- Strategic decision-making

LCA plays a crucial role in strategic decision-making for external purposes by providing robust, science-based evidence that supports companies in policy dialogue and the negotiation of long-term environmental legislation. Through its comprehensive and systematic analysis of environmental impacts across the entire life cycle of products and systems, LCA enables firms to anticipate regulatory trends, demonstrate proactive environmental responsibility, and engage constructively with policymakers [22, 44]. LCA results can be used to inform and influence legislative discussions on issues such as carbon taxation, extended producer responsibility (EPR), eco-design requirements, and green public procurement [45]. By sharing transparent and standardized LCA data – often in the form of EPDs or policy briefs – companies can substantiate their sustainability claims and advocate for feasible, evidence-based regulations that reflect the real environmental burdens of products and services. In this way, LCA becomes not only a technical tool but a strategic asset for long-term positioning in an increasingly regulated global market.

3.2 The retrospective and prospective uses of LCA

The uses of LCA can be classified as retrospective or prospective, the former refers to the picture of the existing situation, the latter leads to innovation [32].

Building upon this distinction, retrospective LCA is typically applied to mature technologies and established production systems, offering insights into the actual environmental burdens associated with current operations. This type of assessment is often used for compliance reporting, product environmental footprint, and sustainability benchmarking across industries [21]. It helps identify inefficiencies and hotspots, enabling continuous improvement and supporting eco-efficiency strategies.

On the other hand, prospective LCA is increasingly employed in the context of eco-design, R&D, and strategic foresight, especially when evaluating emerging technologies such as hydrogen fuels, carbon capture, or bioplastics [46]. By modelling possible future scenarios, prospective LCA enables companies and policymakers to assess the environmental implications of early-stage decisions, even when complete data are not yet available [47]. This forward-looking approach aligns with sustainability-driven innovation and is crucial for anticipating environmental legislation, de-risking investment, and entering new green markets. Moreover, the integration of prospective LCA with tools such as scenario analysis, dynamic modelling, or life cycle sustainability assessment (LCSA) further enhances its potential to address system-level transformations and long-term impacts [48].

While challenges remain – especially regarding uncertainty and data availability – both retrospective and prospective LCA approaches are essential for advancing corporate and policy-level sustainability goals in a complementary manner. However, the application of prospective LCA, especially for guiding innovation and early-stage decision-making, is an unexplored area. Most current LCAs are retrospective, focusing on existing products or processes, which limits their utility in future-oriented decision-making under uncertainty [46, 47]. Integrating LCA with scenario analysis, system dynamics, and foresight methodologies could enhance its value in anticipating regulatory trends, consumer preferences, and emerging technologies, thus supporting more resilient and adaptive business models [48]. Addressing these challenges through targeted research and methodological innovation will lead to more actionable, accessible, and context-sensitive LCA applications, allowing businesses to better align environmental performance with long-term value creation and sustainability goals.

Tables 1 and 2 summarise information on the various internal and external uses of LCA, organised by retrospective and prospective applications, providing a useful framework to visualise how LCA supports business decisions in different life cycle phases and operational contexts.

Table 1. Internal uses of LCA: retrospective and prospective applications and benefits.

LCA internal uses	Retrospective	Prospective
Design, R&D	• Analysis of environmental impacts of existing products • Benchmarking and performance evaluation	• Identification of environmental hotspots in early development stages • Sustainable innovation in design
Procurement decision-making	• Assessment of environmental impacts of current suppliers • Optimization of sourcing practices	• Selection of more sustainable suppliers • Resource optimization along the supply chain
Production	• Optimization of existing manufacturing processes • Waste management and resource efficiency	• Long-term strategic support to reduce costs and improve sustainability • Eco-efficient process design
Marketing	• Verification and certification of current environmental performance • Communication of current sustainability attributes	• Competitive positioning through credible environmental claims • Compliance with eco-label standards
Information and education	• Awareness-raising on the environmental impacts of current operations • Optimization of internal processes	• Educating consumers and stakeholders on future sustainable choices • Employee training and development
Strategic decision-making	• Monitoring current environmental performance for portfolio optimization • Continuous improvement	• Strategic planning for radical innovation • Supporting transitions from product-to service-based models

Table 2. External uses of LCA: retrospective and prospective applications and benefits.

LCA external uses	Retrospective	Prospective
Marketing	• Environmental communication based on factual data • Environmental reports and compliance with existing standards	• Branding strategy to position products as sustainable • Eco-labelling and Environmental Product Declarations (EPDs)
Information and education	• Communication with authorities and stakeholders for compliance • Public reports based on LCA	• Raising awareness on long-term benefits of sustainable choices • Proactive dialogue with consumers and institutions
Strategic decision-making	• Analysis of compliance with current environmental regulations • Evaluation of impact of past policies	• Engagement in policy dialogue and regulatory foresight • Anticipating trends and aligning with future legislation

The authors classified LCA applications into internal/external and retrospective/prospective using results from a conceptual synthesis of the reviewed literature, thereby creating a framework that identifies recurring patterns in how LCA is applied across different functional areas (e.g., design, procurement, and marketing) and temporal orientations. These “variables” were selected to capture both the strategic and operational dimensions of LCA in business contexts, as widely discussed in key studies (e.g., [22], [30], [32], [33], [46]). This structured typology aims at helping practitioners and scholars to best interpret the multidimensional role of LCA.

While this discussion paper does not focus on a specific territorial case study, the proposed conceptual framework has broad applicability across different geographic and socio-economic contexts. In particular, the dual internal/external and retrospective/prospective classification of LCA uses can support companies operating in urban areas, where sustainability challenges are particularly acute due to higher population density, resource consumption, and regulatory pressures. Urban industrial ecosystems – such as metropolitan manufacturing districts or service hubs – can particularly benefit from the integration of LCA into local sustainability strategies, circular economy initiatives, and innovation policies.

Moreover, findings from this study can be relevant for regional and national policy frameworks aiming to support sustainable transitions in urban contexts. The alignment of LCA-based practices with broader urban dynamics (such as smart city planning, clean mobility, and local green procurement) can enhance the systemic integration of environmental performance into local economic development. Future research could explore how the proposed framework performs when applied to real-world urban business clusters or local government programs aimed at fostering eco-innovation.

4. Policy implications

The proposed framework can offer a set of actionable recommendations that can inform policy measures supporting the wider adoption of LCA in sustainable business strategies. First, to promote the integration of LCA in early-stage innovation, policymakers should incentivise the adoption of prospective LCA tools in research and development activities. This approach is essential for evaluating environmental trade-offs under uncertainty and aligning innovation trajectories with sustainability goals. Recent studies highlight the growing relevance of forward-looking LCA and call for dedicated policy instruments to enhance its application in R&D contexts, such as funding open-source tools and dynamic databases [49, 50].

Second, public procurement can act as a key driver of sustainability through the mandatory or incentivised use of LCA-based Environmental Product Declarations (EPDs). Empirical evidence shows that incorporating LCA criteria into green public procurement (GPP) leads to more circular and resource-efficient outcomes [51], while also encouraging transparency and innovation in supply chains [52]. The positive role of prior GPP experience in facilitating systematic LCA integration is also well documented [53].

Third, to overcome adoption barriers among small and medium-sized enterprises (SMEs), simplified and sector-specific LCA tools should be developed and promoted. A recent literature review identifies high costs, limited expertise, and data complexity as critical barriers to LCA uptake among SMEs and recommends the development of accessible instruments supported by targeted capacity-building [54]. Capacity building is, in fact, a cross-cutting enabler: training programs targeting both professionals and students are essential to building LCA literacy and supporting long-term organisational change. Integrating LCA into academic curricula and professional development courses is consistently cited as a crucial strategy for enabling broader use of sustainability assessment tools.

Lastly, there is a growing need to integrate life-cycle-based indicators into corporate sustainability and ESG reporting. As regulatory frameworks evolve – notably the EU Corporate Sustainability Reporting Directive (CSRD) – LCA provides robust and science-based data that can improve the transparency and comparability of environmental disclosures. Recent methodological proposals explore how LCA can be aligned with ESG metrics and support more meaningful impact reporting [55].

By addressing these interconnected dimensions through coherent and feasible policy interventions, institutions can help unlock the full potential of LCA as a transformative instrument for sustainable business innovation and decision-making.

To make policy implications more actionable, Table 3 outlines concrete implementation steps for each proposed recommendation. These steps identify key actors who can drive the change process, thus enhancing the potential for real-world uptake of LCA in sustainable business strategies.

Table 3. Policy recommendations and implementation pathways.

Policy Area	Recommendation	Implementation steps	Actors involved
Prospective LCA in R&D	Incentivise prospective LCA integration in innovation projects	Include LCA criteria in public R&D funding calls (e.g., Horizon Europe, national grants); provide training modules	Research agencies, ministries, universities
LCA adoption in SMEs	Support LCA use among SMEs through simplified tools	Develop sector-specific LCA templates; co-fund external LCA consultancy; offer tax relief for certification efforts	Chambers of commerce, local authorities
Public procurement	Promote LCA-based EPDs in GPP	Make EPDs a requirement or scoring criterion in green tenders; publish national LCA databases for key sectors	Public buyers, standard bodies
Education and training	Build capacity on LCA in business and academic curricula	Launch national/regional training programs for professionals; include LCA in university business & engineering degrees	Ministries, academia, industry associations
ESG and sustainability reporting	Integrate LCA into corporate ESG frameworks and standards	Require disclosure of life cycle impacts in ESG reports; align LCA with EU CSRD and taxonomy regulation	EU, stock exchanges, reporting bodies

5. Limitations of the LCA methodology and future perspectives

While LCA is a widely recognized and standardized tool for evaluating the environmental impacts of products, services, and systems, it still presents several limitations that constrain its broader application and strategic potential in business contexts.

One of the main limitations is its static nature, which offers a snapshot of environmental consequences at a specific time, thereby failing to capture temporal dynamics and system evolution over time [13]. This can be problematic in contexts involving emerging technologies or long-term strategic planning, where environmental impacts may shift significantly across different stages of development or in different future scenarios. Furthermore, the retrospective orientation of many LCA applications means that it is more commonly used for evaluating existing products or processes, rather than anticipating future impacts. Prospective LCA methods exist but remain underutilised due to their inherent uncertainty, lack of data, and methodological complexity [46, 47].

Another significant limitation concerns the quality, availability, and transparency of data. LCA heavily relies on accurate and comprehensive life cycle inventory data, yet such data are often incomplete, outdated, or inconsistent, particularly when assessing complex supply chains or new product systems [21, 40]. This affects the reliability of results and makes it challenging to compare studies, particularly when assumptions regarding system boundaries, allocation rules, and impact assessment methods are not clearly documented.

Furthermore, traditional LCA primarily focuses on environmental dimensions, with limited integration of social or economic aspects. Although extensions like Life Cycle Sustainability

Assessment (LCSA) are being developed, most LCA studies still neglect multidimensional trade-offs relevant to broader sustainability goals [41].

Finally, although LCA can inform strategic and operational decision-making, its technical complexity and resource intensity may limit accessibility for non-expert users and small enterprises. This creates a gap between technical assessments and practical implementation. Therefore, there is a need for simplified tools, integrated frameworks, and capacity-building efforts to broaden the effective use of LCA in diverse business contexts [22].

Despite its current limitations, LCA holds significant potential for further development in sustainable business management. Methodological advancements are increasingly addressing its static nature; for instance, the adoption of dynamic LCA, consequential LCA, and scenario-based approaches allows for more temporally sensitive and context-aware assessments. At the same time, digital transformation is reshaping the way LCA is conducted. The integration of big data analytics, artificial intelligence, and blockchain technologies offers new opportunities to improve data availability, accuracy, and traceability, thereby enhancing the overall reliability of assessments.

To broaden its usability across different organizational scales, particularly among SMEs, efforts are being made to develop simplified tools and user-friendly platforms. These solutions aim to reduce technical barriers, making LCA more accessible to non-experts and facilitating its integration into routine business practices. In parallel, there is growing momentum towards harmonizing LCA with emerging sustainability frameworks, such as Life Cycle Sustainability Assessment (LCSA) and Environmental, Social, and Governance (ESG) reporting standards. This convergence strengthens the strategic value of LCA by aligning it more closely with broader corporate sustainability goals and regulatory expectations.

Furthermore, LCA is increasingly being explored in combination with strategic foresight tools, including system dynamics, innovation management, and scenario planning. These integrations enhance LCA's capacity to inform long-term decisions, support sustainable innovation, and guide companies in anticipating future regulatory or market developments.

By addressing its current limitations and embracing these developments, LCA can evolve from a technical assessment instrument into a transformative enabler of sustainable business innovation and long-term value creation.

6. Conclusions

LCA is a technical tool for environmental accounting and a strategic instrument that supports sustainability integration across business management. Its dual nature – retrospective and prospective – enables companies not only to evaluate the environmental performance of existing products and processes but also to guide innovation and long-term planning by anticipating future impacts, technologies, and regulatory landscapes. Through a conceptual synthesis, it has proposed a dual framework that classifies LCA applications along internal/external and retrospective/prospective dimensions. This classification highlights the versatility of LCA in supporting a wide range of business functions – from design and procurement to marketing and policy engagement – while also distinguishing between compliance-driven and innovation-oriented uses.

There are many key advantages of conducting LCA for sustainable business management. Firstly, it provides a data-driven approach to impact assessment, enabling companies to make informed decisions based on quantitative analysis rather than relying on assumptions. Additionally, LCA promotes resource efficiency by identifying opportunities to reduce material and energy consumption, which can lead to lower costs and enhanced operational sustainability. Moreover, LCA helps companies improve corporate responsibility and comply with environmental regulations and sustainability standards, ensuring they stay aligned with changing market expectations and policy frameworks. Furthermore, adopting LCA can drive innovation and create a competitive advantage, as businesses that prioritize environmentally responsible practices often experience a stronger market position and an improved brand reputation.

From a managerial perspective, the findings provide actionable insights for companies aiming to embed sustainability into their core decision-making processes. Internally, LCA informs decisions across R&D, procurement, production, marketing, and employee education, fostering eco-efficiency and aligning operations with sustainability objectives. Externally, LCA supports transparent communication with stakeholders through EPDs, strengthens green marketing strategies, and contributes to constructive dialogue with policymakers and regulators.

In terms of policy implications, the paper highlights the need for targeted incentives, simplified tools for SMEs, and greater integration of LCA into public procurement and sustainability reporting frameworks. Policymakers and standardisation bodies can leverage LCA to design evidence-based regulations and support the transition to more resilient and environmentally responsible business models.

However, the effectiveness of LCA depends on the quality and transparency of data, assumptions, and methodologies, which must be addressed to preserve its credibility and impact. As sustainability becomes a core driver of business resilience and competitiveness, LCA offers a powerful framework for integrating environmental responsibility into corporate decision-making and value creation. Future research could expand on this conceptual foundation by testing the framework in real-world settings, such as urban industrial ecosystems or specific sectors where LCA adoption is still limited. Empirical studies could also investigate how firms navigate the challenges of data quality, methodological complexity, and integration of LCA with other sustainability assessment tools. Addressing these dimensions will be key to unlocking the full potential of LCA in driving corporate sustainability transformation.

Conflict of Interest

The authors declare no conflict of interest.

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