



Methods and Frameworks in Sustainable Product Design and Development: A Narrative Literature Review

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ABSTRACT

This literature review examines the application of methods such as Life Cycle Assessment (LCA), Design for Environment (DfE), Cradle to Cradle (C2C), Biomimicry, Circular Economy, and Sustainable Material Selection (SMS) in Sustainable Product Design & Development (SPDD). This study aims to synthesize existing research on the benefits, challenges, and integration of methods for environmentally sustainable product design through a narrative literature review of academic sources from 2008 to 2025, including textbooks and journals such as the *Journal of Cleaner Production*. The findings highlight that these methods collectively reduce environmental impacts by up to 70%, enhance resource efficiency, and foster innovation. However, challenges such as high implementation costs, data scarcity, and scalability issues persist. This review argues that an integrated framework combining LCA, DfE, and Circular Economy effectively mitigates these barriers by streamlining data requirements and optimizing long term cost efficiency through proactive design. Consequently, this integrated approach offers optimal outcomes for sustainable product development while supporting global regulations. Future research should prioritize empirical studies and interdisciplinary collaboration to further bridge the gap between theoretical frameworks and practical application.

Keywords: *Sustainable Product Design & Development, Life Cycle Assessment, Design for Environment*

ABSTRAK

Tinjauan pustaka ini mengkaji penerapan berbagai metodologi utama seperti *Life Cycle Assessment (LCA)*, *Design for Environment (DfE)*, *Cradle to Cradle (C2C)*, *Biomimikri*, *Circular Economy*, serta *Sustainable Material Selection (SMS)* dalam lingkup *Sustainable Product Design & Development (SPDD)*. Melalui tinjauan literatur naratif terhadap sumber akademik periode 2008–2025 termasuk buku teks dan jurnal bereputasi seperti *Journal of Cleaner Production*. Studi ini menyintesis riset mengenai manfaat, tantangan, serta integrasi metode desain produk berkelanjutan. Temuan menunjukkan bahwa penggunaan metode tersebut secara kolektif mampu mereduksi dampak lingkungan hingga 70%, meningkatkan efisiensi sumber daya, dan meningkatkan inovasi. Namun, hambatan seperti tingginya biaya implementasi, kelangkaan data, serta persoalan skalabilitas masih menjadi tantangan. Tinjauan ini menegaskan bahwa kerangka kerja terpadu yang mengintegrasikan LCA, DfE, dan *Circular Economy* secara efektif memitigasi hambatan tersebut melalui penyederhanaan kebutuhan data dan optimalisasi efisiensi biaya jangka panjang berbasis desain proaktif. Konsekuensinya, pendekatan ini menawarkan hasil optimal bagi pengembangan produk sekaligus mendukung regulasi global. Penelitian mendatang perlu memprioritaskan studi empiris dan kolaborasi interdisipliner guna menjembatani kesenjangan teoretis dan aplikasi praktis.

Keyword: *Sustainable Product Design & Development, Life Cycle Assessment, Design for Environment*



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1. Introduction

Sustainable Product Design & Development (SPDD), or sustainable product design and development, emerged in response to the global environmental crisis of the late 20th century, emphasizing the need to integrate ecological principles into industrial practices. This approach is a holistic methodology aimed at creating products that minimize negative impacts on the environment, society, and the economy throughout their life cycle, from raw material extraction to final disposal. This concept is based on principles such as the use of eco-friendly materials, energy efficiency, recycling, and modular design that allows for product repair or quality improvement, thereby reducing waste and extending product lifespan [1].

The importance of Sustainable in product design lies in its ability to strike a balance between business innovation and social responsibility. Companies have implemented SPDD practices with a focus on recycled materials and transparent supply chains, which not only reduce carbon emissions but also enhance customer loyalty and long-term cost efficiency [2]. With the ISO 14001 standard in place, sustainable design has become an industry standard, fostering collaboration among engineers, designers, and stakeholders to create innovative and sustainable solutions. Several approaches to addressing challenges in Sustainable Product Design & Development include Life Cycle Assessment, Design for Environment, Cradle to Cradle, Biomimicry, Circular Economy Design Principles, and Sustainable Material Selection and Assessment [3].

Despite the extensive exploration of individual SPDD methodologies, a critical research gap persists in the lack of a cohesive synthesis that integrates these six specific frameworks (LCA, DfE, C2C, Biomimicry, Circular Economy, and SMS) into a unified strategic model [4]. Current literature remains largely fragmented, often addressing these methods in isolation or relying on data that fails to reflect the rapid regulatory and technological shifts occurring up to 2025. Therefore, this study addresses this void by evaluating how the synergistic integration of these frameworks can effectively mitigate persistent implementation barriers, such as data scarcity and high costs, to foster industrial innovation [5]. This research aims to provide a comprehensive roadmap for developing products that are not only environmentally viable but also compliant with evolving global standards.

2. Theoretical Framework

2.1. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a systematic analytical method used to evaluate the environmental impacts of a product, process, or system throughout its entire life cycle, from raw material extraction to final disposal [6]. In the context of Sustainable Product Design & Development, LCA serves as a theoretical and practical tool for identifying, measuring, and minimizing negative environmental impacts, thereby supporting more sustainable product design [7]. This theory is based on the principles of industrial ecology and systems analysis, which emphasize a holistic approach to understanding the interactions between products and the environment [8].

This method analyzes a product's environmental impact from raw material extraction through final disposal, including energy use, emissions, and waste [9]. LCA helps identify critical areas for improvement, such as substituting materials with more environmentally friendly alternatives [10].

LCA is structured around four main phases, in accordance with the international standard framework [11]:

- a. **Goal and Scope Definition:** Defining the analysis objectives, system boundaries, and functional units. This ensures the analysis remains focused and relevant.
- b. **Life Cycle Inventory (LCI):** Collecting data on inputs (such as materials, energy) and outputs (such as emissions, waste) at every stage of the life cycle, including extraction, production, distribution, use, and end-of-life.
- c. **Life Cycle Impact Assessment (LCIA):** Categorizing and evaluating potential impacts, such as climate change (CO₂ emissions), eutrophication (water pollution), and human toxicity. These impacts are quantified using methods such as midpoint or endpoint indicators.
- d. **Interpretation:** Analyzing the results to identify areas for improvement, such as replacing materials or adopting more efficient processes, and providing recommendations for sustainable design.

For example, in the analysis using a hybrid LCA framework, a two-step methodology that integrates process based LCA and environmentally extended input-output (EEIO) frameworks [12], this approach was adopted. In the hybrid framework, the process-based LCA is used to evaluate individual supply chain inputs within a defined system boundary, and the EEIO evaluates indirect environmental impacts [13]. This ensures a more comprehensive system boundary for environmental assessment [14]. The impacts of each supply chain input are calculated using:

$$\text{LCA Process} = \sum_{i=1}^n S_p(i) \times E_p(i) \tag{1}$$

Where $S_p(i)$ represents input (i) into the production process within the supply chain, N represents total number of inputs for process i in the supply chain, and $E_p(i)$ represents emission intensity of process i across selected environmental indicators.

The calculation formula in LCA is used to measure and analyze environmental impacts, such as greenhouse gas emissions or energy consumption. These formulas are not uniform but vary depending on impact categories such as Global Warming Potential (GWP) or Acidification Potential (AP). The conceptual framework regarding the use of LCA is shown in Figure 1.

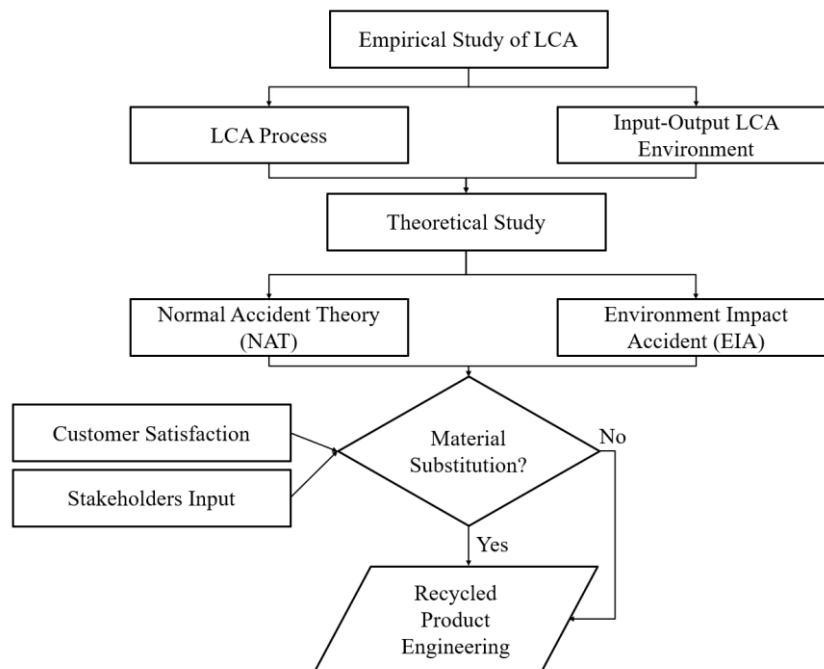


Figure 1. Conceptual Framework of the LCA Method

2.2. Design for Environment (DfE) or Eco-Design

This approach takes environmental impacts into account from the earliest stages of design, such as selecting recycled materials, optimizing energy use, and designing products that are easy to recycle. DfE encourages designers to minimize resource consumption and waste [15].

Design for Environment (DfE) is based on life-cycle thinking and involves design procedures that minimize material and energy consumption while maximizing opportunities for reuse and recycling. DfE is a systematic consideration of design performance in relation to environmental, health, and safety objectives throughout the entire life cycle of products and processes [16]. This process is carried out early in the design or product improvement phase to ensure that the environmental consequences of the product’s life cycle are understood before final decisions regarding the manufacturing process are made [14]. DfE requires the coordination of several design and data-based activities, such as environmental impact assessments, data collection and management, design optimization, and others.

A product’s environmental impact can be reduced through various strategies [13]. Selecting materials with a low environmental impact, such as recycled or bio based materials, to reduce the extraction of new resources; designing energy efficient production processes that generate minimal waste, such as using green technology or lean manufacturing; ensuring products are easily recyclable or naturally biodegradable by minimizing the use of toxic materials and facilitating component separation, assessing the impact from extraction through the product’s end of life, and iterating the design based on findings, as well as involving stakeholders such as suppliers and consumers in the design process, and fostering innovation through research into new materials [3]. A series of DfE strategies for optimizing each stage of the life cycle, along with their specific strategies, are presented in Table 1 [17].

Table 1. Design for Environment (DfE) Strategy

Recycle Steps	Strategy of DfE	Specific Strategy
Raw materials	Optimizing material usage	Design for resource conservation Reducing material use Using renewable materials Using recyclable materials Design for low impact material Avoiding hazardous and toxic substances Using low-energy materials
Manufacturing	Clean manufacturing	Design for cleaner production Minimizing material variation Avoiding material waste Selecting processes and auxiliary materials with a low environmental impact
Distribution	Distribution efficiency	Design for efficient distribution Reducing product weight Reducing product packaging weight Ensuring that packaging materials are reusable and recyclable Ensuring distribution efficiency
Product usage	Clean use/ operation	Design for energy efficiency Design for material conservation Design for minimal consumption Reducing waste Design for low impact use/ operation Design for durability
End of life	End of life optimization	Design for reuse Design for remanufacturing Design for disassembly Design for recycling Design for safe disposal

DfE also serves as an extension of LCA, in which product design is optimized to reduce greenhouse gas emissions, water use, and pollution. They emphasize that DfE is not only about efficiency but also about innovation to achieve long-term Sustainable [11].

The basic principles of DfE include life cycle thinking, waste reduction, and increased recycling [15]. Design for Environment: Creating Eco-Efficient Products and Processes outlines four main pillars, namely:

- a. Minimizing the use of materials and energy
- b. Selecting recyclable materials

- c. Designing for ease of assembly and repair
- d. Integrating green technology

The concept of life cycle design serves as the foundation of Design for the Environment (DfE), which involves analyzing trade-offs between cost, performance, and environmental impact. They recommend strategies such as designing for durability (extending a product's lifespan) and using bio-based materials to reduce reliance on fossil resources [18].

The article “Ecodesign: A Promising Approach to Sustainable Production and Consumption” classifies DfE strategies into three categories, namely:

- a. Reducing production impacts, such as optimizing manufacturing processes.
- b. Improving usage efficiency, such as energy-efficient product design.
- c. Improving end-of-life management, such as designing for recycling or composting.

It provides case studies from the automotive and electronics industries showing how DfE can reduce emissions by up to 20–30% [1].

While Life Cycle Assessment (LCA) provides a robust quantitative diagnostic of environmental burdens, it is inherently retrospective and lacks the prescriptive capacity to offer direct design solutions. Design for Environment (DfE) effectively bridges this gap by extending LCA findings into the early stages of product development through proactive decision making [19]. Specifically, DfE translates the environmental impact data generated by LCA into actionable engineering parameters, allowing designers to mitigate identified hotspots before they are locked into the product's architecture. By integrating DfE, the analytical rigor of LCA is transformed from a mere evaluative tool into a strategic driver for sustainable innovation, ensuring that resource efficiency and circularity are optimized during the conceptual phase [20].

2.3. Cradle to Cradle (C2C)

This method emphasizes the design of products that can be biologically or technically recycled without losing value, thereby promoting the regeneration of natural resources. Products are designed to serve as nutrients for other systems, rather than as waste [21]. A schematic diagram of the cradle-to-cradle method is shown in Figure 2.

C2C is based on three main principles:

- a. Waste equals food, where all product outputs become inputs for other systems.
- b. 100% use of renewable energy.
- c. Respect for biodiversity. This approach distinguishes between biological cycles (for naturally degradable materials) and technical cycles (for synthetic materials that are recycled without degradation) [21].

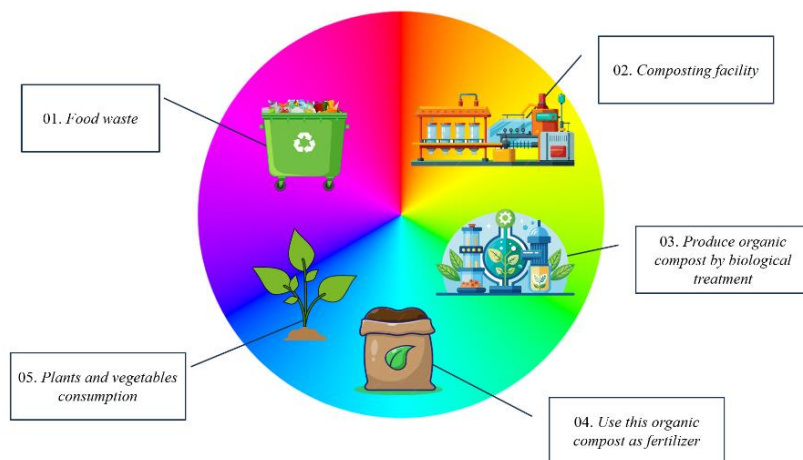


Figure 2. Schematic Diagram of the Cradle to Cradle Process [22]

The biological cycle involves products designed to return to nature as nutrients, using safe, compostable organic materials. The technical cycle involves products made from synthetic materials that can be continuously recycled, such as plastics or metals, without losing their intrinsic value [23]. C2C is implemented

through a framework involving certification, design tools, and stakeholder collaboration. C2C requires material analysis to ensure materials are safe and recyclable, as well as designs that separate biological and technical components to facilitate recovery [24].

2.4. *Biomimicry*

Biomimicry is an interdisciplinary approach that brings together biologists, designers, engineers, and others to study and apply principles or mechanisms from nature to solve design challenges [25]. This technique mimics natural processes, structures, and systems to create efficient and sustainable products, such as designs that reduce energy or material use [26]. Sustainable framework of Biomimicry is shown in Figure 3.

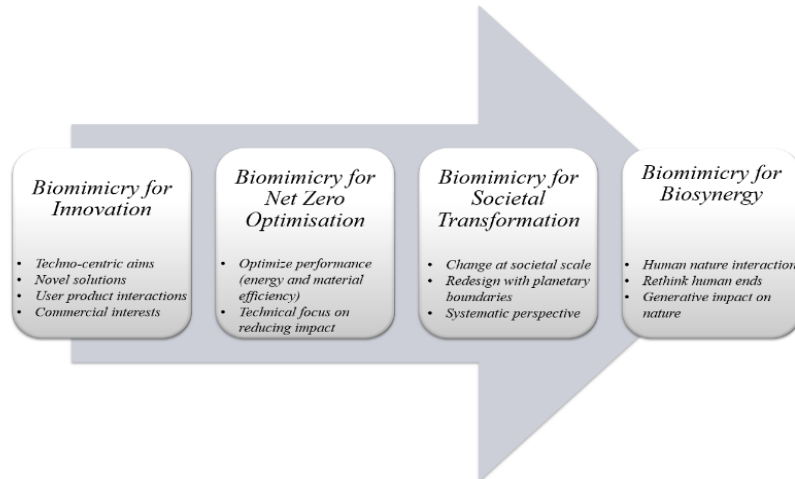


Figure 3. The Biomimicry for Sustainable Framework [25]

Biomimicry is applied through methods such as observing nature, functional analysis, and prototyping. Designers use tools like biomimicry databases to find natural analogies. The process involves identifying problems, searching for natural solutions, and adapting them to human contexts [27]. Biomimicry has produced innovative products across various fields. A classic example is Velcro, inspired by the burdock fruit that sticks to dog fur. In Sustainable, biomimicry is used for building design, transportation, and materials [28].

2.5. *Circular Economy Design Principles*

Focus on product designs that support the circular economy such as reuse, repair, remanufacture, and recycling to minimize waste and extend product lifecycles. This involves modularity and separable materials [29]. The phases of the circular economy approach are illustrated in Figure 4.



Figure 4. Circular Economy Phase Diagram [30]

Circular economy design principles are typically classified into three main categories, namely:

- a. Design for regeneration (using renewable materials and restoring natural systems)
- b. Design for sharing
- c. Design for optimization (focusing on maintenance, recycling, and value recovery)
- d. These principles promote products that are modular, durable, and easy to repair or recycle [31].

2.6. Sustainable Material Selection

Sustainable Material Selection (SMS) is a systematic process for selecting and evaluating materials in product design that prioritizes Sustainable, taking into account environmental, social, and economic impacts throughout the material’s life cycle. This method involves evaluating materials based on criteria such as Sustainable, toxicity, and availability, often using tools like Material Flow Analysis (MFA) to select environmentally friendly materials [32]. The implementation framework is shown in Figure 5.

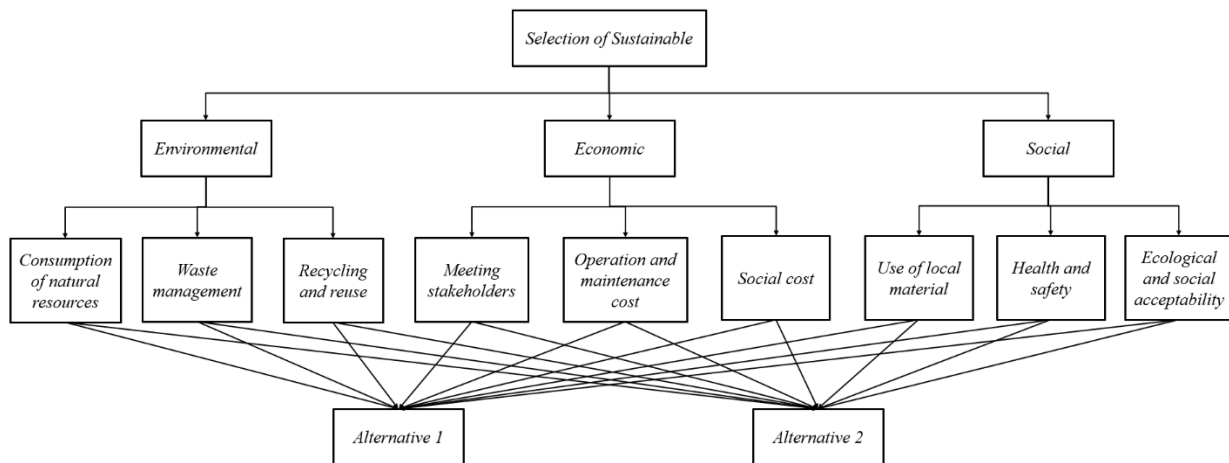


Figure 5. Framework for Implementing Sustainable Material Selection [7]

Its implementation involves tools such as green material databases, for example Ecoinvent or CES Selector and methodologies such as the Analytic Hierarchy Process (AHP) for comparing materials. Designers begin by defining product requirements, then evaluate material alternatives through simulation and testing.

3. Research Method

The research method used is the narrative literature review method, which is a type of literature review that involves compiling and presenting the results of previous research in the form of a narrative or story [33]. In this method, no statistics are involved, and no formal analysis is performed on the data; in other words, findings are expressed in a narrative or descriptive form, which provides a clearer and more holistic picture of the topic under study [34].

The literature search was systematically conducted using Google Scholar as the primary search engine to identify a broad range of relevant articles, books, and academic literature. To ensure the retrieval of high-quality, peer-reviewed content, the search was further extended to specialized academic databases, including ScienceDirect (Elsevier), Taylor & Francis Online, IEEE Xplore, SpringerLink, and other Scopus-indexed journals. The search strategy employed a combination of Boolean operators with keywords such as “Sustainable Product Design & Development” AND “Life Cycle Assessment,” “Design for Environment,” “Cradle to Cradle,” “Biomimicry,” “Circular Economy,” and “Sustainable Material Selection.” Literature was purposively selected based on its thematic relevance to the research questions, the significance of its scholarly contributions, and the rigor of the methodologies employed in the studies.

To ensure a comprehensive and contemporary synthesis of the literature, this study established specific inclusion criteria for the search process. A primary criterion was the temporal scope, which was restricted to academic sources published between 2008 and 2025. A literature review is also used to identify issues to be addressed as research topics and to contextualize these issues within a broader framework. The theoretical framework established in the literature review provides the foundation for the research [35].

4. Result and Discussion

A literature review on the use of methods in Sustainable Product Design & Development (SPDD) indicates that methods such as Life Cycle Assessment (LCA), Design for Environment (DfE), Cradle to Cradle (C2C), Biomimicry, Circular Economy, and Sustainable Material Selection (SMS) have become key tools for integrating Sustainable from the design stage onward. Following a preliminary screening of titles and abstracts, 12 sources were identified as potentially relevant. Research focuses on benefits such as reduced environmental impact, resource efficiency, and product innovation, but also on challenges such as implementation complexity and data limitations. The following is a summary of the discussion based on the latest literature review (2008–2025), with a focus on key findings, benefits, challenges, and case studies, as shown in Table 2.

Table 2. Synthesis of Literature Review Findings

No.	Article Name	Writer	Context	Key Findings
1.	Enhancing Life Cycle Product Design Decision-Making Processes: Insights from Normal Accident Theory and the Satisficing Framework	Ibn-Mohammed et al., 2024	General Manufacturing	Introduces a decision-making framework that balances technical complexity with safety and satisficing criteria to prevent design failures
2.	Life Cycle Assessment and Eco-Design in Sustainable New Product Development	Ailyn, 2024	Product Development	Demonstrates that integrating LCA early in the R&D phase significantly reduces carbon footprints compared to end-of-pipe solutions
3.	Exploring the Factors Influencing the Adoption of Design for Environment (DfE) in the Japanese Food Industry	Ueda, 2023	Food & Beverages Industry	Identifies regulatory pressure and consumer demand as primary drivers for DfE adoption in specialized food packaging and processing
4.	A Framework for the Integration of Environmental and Business Aspects Toward Sustainable Product Development	Choi et al., 2008	Industrial Design	Proposes a dual-focus model that aligns environmental goals with economic profitability and market competitiveness
5.	Cradle to Cradle Front-End Innovation: Management of the Design Process	Saari et al., 2023	Design Management	Emphasizes the importance of nutrient cycles in the initial innovation phase to ensure total product recyclability.
6.	Designing Cradle to Cradle Products: A Reality Check	Bakker et al., 2010	Consumer Goods	Critically evaluates the gap between C2C theoretical ideals and the practical limitations of current industrial recycling infrastructures.
7.	Eco-design Design Strategy: Case Study Biomimicry Approach in Design Product Materials	Taieb & Amor, 2023	Product Design	Shows how biological structures can inspire high-performance, low-impact material alternatives in industrial applications.
8.	Biomimicry as a Sustainable Design Methodology Introducing the Biomimicry for Sustainable Framework	Ilieva et. al, 2022	Sustainable Architecture Design	Standardizes biomimetic principles into a formal design methodology to foster radical resource efficiency.

No.	Article Name	Writer	Context	Key Findings
9.	Product Design in a Circular Economy Development of a Typology of Key Concepts and Terms	den Hollander et al., 2017	Circular Economy	Clarifies the terminology and hierarchy of CE concepts, providing a standardized language for circular product architecture.
10.	Business Model Strategies for a Circular Economy	Bocken et. al, 2016	Business Strategy	Maps specific design strategies (slowing vs. closing loops) to corresponding business models for long-term sustainability.
11.	Sustainable-Informed Materials Selection, Design, Discovery, and Development	Schoenung et al., 2025	Materials Engineering	Integrates informatics and environmental data to accelerate the discovery of sustainable materials during the design phase
12.	Sustainable Material Selection Criteria Framework for Environmental Building Enhancement	A. Ahmad et. al, 2022	Construction & Built Environment	Establishes a multi-criteria decision-making framework specifically for low-impact material selection in the building sector

In the context of Sustainable Product Design & Development (SPDD), methods such as Life Cycle Assessment (LCA), Design for Environment (DfE), Cradle to Cradle (C2C), Biomimicry, Circular Economy, and Sustainable Material Selection (SMS) have advantages and disadvantages based on a review of the literature. The advantages generally include reduced environmental impact and increased efficiency, while the disadvantages involve implementation complexity and data limitations [36].

The advantages of the Life Cycle Assessment (LCA) method include providing a comprehensive evaluation of a product’s entire life cycle, helping to identify emission hotspots and areas for improvement, supporting data-driven decision-making, enhancing transparency and regulatory compliance, and reducing the carbon footprint by up to 30–50% through design optimization [10]. The disadvantages of the Life Cycle Assessment (LCA) method are that it requires accurate and complete data, which is often difficult to obtain, especially for global supply chains; the process is time-consuming and costly; it requires technical expertise; and it is susceptible to subjective assumptions that can affect the accuracy of results [37].

The advantages of the Design for Environment (DfE) method include integrating Sustainable aspects from the initial design stage, reducing waste and life-cycle costs by up to 40%, fostering green product innovation and enhancing competitiveness in eco-friendly markets, and facilitating cross-disciplinary collaboration for more efficient design [38]. The disadvantages of the Design for Environment (DfE) method include difficulty in quantitative measurement, resulting in often subjective outcomes; the need for initial investment and organizational cultural change; and reduced effectiveness if not supported by LCA data or other evaluation tools [39].

The advantages of the Cradle to Cradle (C2C) method include promoting product design that is fully recyclable with zero waste, reducing reliance on new resources, fostering material innovation and increasing product value through recycling, and reducing environmental impact by up to 90% in applications such as green buildings [24]. The disadvantages of the Cradle to Cradle (C2C) method include high initial implementation costs and technical challenges in separating biological and technical materials, difficulty in applying it to complex products with long supply chains, and the need for costly certification and external validation [40].

A critical synthesis of the reviewed frameworks reveals that while Life Cycle Assessment (LCA) is indispensable for quantifying environmental burdens, it often identifies end of life weaknesses without providing the architectural solutions necessary to rectify them. This is where the Cradle to Cradle (C2C) framework offers a transformative complement. By categorizing materials into distinct biological and technical cycles, C2C addresses the downcycling trap often highlighted in LCA reports [41]. While an LCA might flag the high environmental cost of landfilling or incineration, C2C proactively redesigns the product as a nutrient

for future systems, ensuring that technical materials are perpetually recovered and biological materials are safely returned to the soil [42]. Consequently, integrating C2C's closed-loop principles effectively mitigates the end-of-life impacts quantified by LCA, transitioning the design process from merely 'less bad' to inherently regenerative [43].

The advantages of the Biomimicry method include emulating natural systems for innovative solutions, reducing energy and resource consumption by up to 50%, promoting sustainable and multifunctional design, such as durable structures and opening creative opportunities for new products inspired by nature [28]. The disadvantages of the Biomimicry method include the need for interdisciplinary knowledge (biology, engineering) that is rarely available, difficulty in validating and measuring long-term impacts, potential limitations to specific applications, and the fact that it is not always suitable for mass production [27].

The advantages of the Circular Economy approach include improving resource efficiency through recycling and reuse, reducing raw material extraction by up to 70%, creating long-term economic value and supply chain resilience, and supporting regulatory compliance and sustainable business innovation [44]. The disadvantages of the Circular Economy method include the need for systemic changes across the entire industry, including regulations and infrastructure; scalability challenges in emerging markets; high transition costs; and difficulty in measuring its impact without standardized metrics.

The advantages of the Sustainable Material Selection method include selecting materials based on Sustainable criteria, reducing the carbon footprint by up to 40% and improving product durability, integrating multi-criteria analysis for balanced decision making, and supporting more environmentally friendly product design from the outset [45]. The disadvantages of the Sustainable Material Selection method include limitations due to the availability of LCA data for new materials, frequent trade-off between performance, cost, and Sustainable, and the need for specialized evaluation tools and expertise [46].

The synthesis of the 12 core literature pieces reveals a significant paradigm shift in Sustainable Product Design and Development (SPDD), transitioning from isolated environmental fixes to a holistic, integrated strategic model. Collectively, these studies demonstrate that the synergy between diagnostic tools, such as Life Cycle Assessment (LCA), and prescriptive frameworks, like Cradle to Cradle (C2C) and Biomimicry, can reduce environmental footprints by up to 70% while simultaneously enhancing resource circularity. A critical macro finding is that the integration of these methodologies effectively bridges the gap between theoretical sustainability and industrial feasibility, particularly by aligning environmental imperatives with business model innovation. This foundational overview serves as the basis for a more detailed analysis of the specific strengths and inherent implementation barriers found within the current SPDD landscape.

5. Conclusion

The synthesis of literature spanning from 2008 to 2025 leads to a definitive conclusion in the complex landscape of sustainable manufacturing, no single methodology possesses the comprehensive capacity to resolve all environmental and functional challenges in isolation. While each framework such as LCA, DfE, and Circular Economy offers significant advantages in reducing environmental burdens, their widespread adoption is frequently hindered by inherent complexities and high implementation costs.

The critical analysis presented in this study demonstrates that the strengths of one method consistently address the structural weaknesses of another, making an integrated SPDD strategy the logical and undeniable endpoint for sustainable innovation. For optimal results, these methods should be synergized by utilizing LCA as a diagnostic baseline, DfE as the operational design tool, and the Circular Economy as the overarching strategic framework. To facilitate this transition, the manufacturing industry should initiate small-scale pilot projects, such as integrating DfE into a single product line, while leveraging collaborations with academia and government bodies to secure essential data and funding.

Ultimately, the investment in digitalization (particularly cloud based LCA platforms) and the development of global partnerships will be pivotal in accelerating adoption. These technical and financial challenges should not be viewed as permanent barriers, but rather as strategic opportunities for market differentiation. By adopting this integrated approach, industries can move beyond incremental improvements toward inherently regenerative and competitive industrial systems.

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