

Systematic Review

Advances in Product Design Strategies to Promote Responsible Consumption and Production

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Abstract

Product design strategies play a pivotal role in advancing responsible production and consumption by enabling the transition toward more sustainable industrial practices. In this context, the rapid evolution of technology and artificial intelligence is fostering the development of innovative and sustainability-oriented strategies, which are increasingly embedded in the early stages of the design process, thereby facilitating the transformation and optimisation of contemporary industrial systems. This scoping review presents advances in product design strategies that promote responsible production and consumption, along with the impacts of their implementation, the associated challenges and limitations, and future perspectives. This manuscript was prepared according to the PRISMA[®] guidelines, using scientific literature from databases and repositories such as Scopus, Web of Science, ScienceDirect, and Taylor & Francis. Document selection was conducted by two observers, yielding a Cohen's Kappa coefficient of 0.840. A total of 147 articles were included for reference information extraction. The product design process plays a crucial role in promoting more sustainable production and guiding responsible consumption habits, as it has proven effective in reducing resource use and waste generation from a life cycle perspective. However, its impact also depends on human-related factors such as perceptions, habits, levels of trust, and usage conditions, highlighting the interaction between product design and consumer behaviour.

Keywords: responsible consumption; sustainable product design; circular economy; life cycle assessment; eco-design strategies; sustainable innovation



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1. Introduction

Currently, the linear economic model continues to predominate, despite having demonstrated its unsustainability in the face of contemporary social and environmental challenges [1]. The guiding principles of the linear model often focus on waste management rather than systemic prevention, generating negative environmental impacts and perpetuating practices that compromise ecological balance and long-term social well-being. The circular economy has emerged as a transformative solution that promotes a regenerative

system in which resource inputs, waste, emissions, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops [2]. This model focuses on keeping products and materials in use for as long as possible, preserving their value while minimising waste generation. According to Martin Geissdoerfer, key actions facilitating the transition to a circular model include durable design, maintenance, repair, reuse, re-manufacturing, refurbishment, and recycling. In this context, consumer behaviour is a critical factor in the success of circular business models, as users' decisions about product use, maintenance, and disposal directly affect the model's viability.

Faced with the challenges of obsolescence and increasing waste, design strategies have evolved to integrate user behaviour and circular economic principles (Figure 1a). On the one hand, the literature on Design for Sustainable Behaviour (DfSB) highlights the predominance of Inform and Guide types of interventions [3], while the academic focus on durability prioritises repair (74%) and reuse (72%) over other strategies [4]. This integration is unevenly reflected in consumer perception. For example, in Costa Rica, there is a notable gap between the high recognition of national labels such as Esencial Costa Rica (97.6%) and the low familiarity with global certifications such as Fairtrade International (24.4%) [5]. This dynamic contrasts with the technical and behavioural challenges observed in practice, such as the low recyclability index (0.26) of modular devices like the Fairphone 2 [6], and the rebound effects identified in school-based interventions, which, although successful in reducing energy consumption, unintentionally increased the use of paper towels [7].

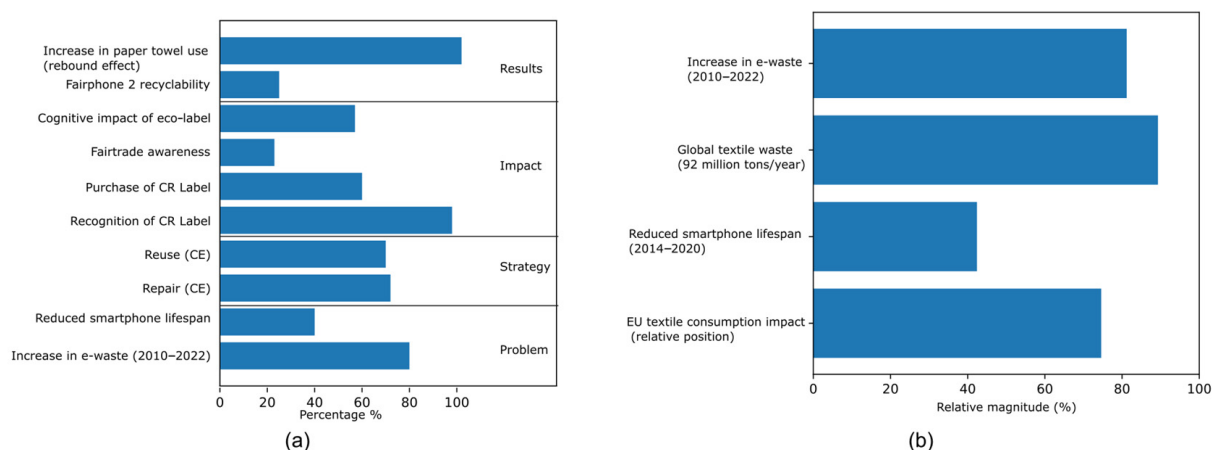


Figure 1. Sustainability indicators related to product consumption and waste generation: (a) Problem, Strategy, Impact, and Results; (b) estadísticas sobre los desperdicios.

The rapid increase in waste generation reflects the unsustainability of current consumption patterns (Figure 1b), particularly evident in the textile industry, where the phenomenon of Fast Fashion drives rapid style turnover, generating substantial volumes of waste from prematurely discarded garments [8]. At the same time, the electrical and electronic equipment sector faces an even greater challenge due to mechanical and technological obsolescence, which drastically shortens device lifespans. This situation generates millions of tons of waste and highlights the urgent need for design strategies focused on durability, reparability, and material recovery in order to mitigate resource depletion and environmental impacts [4,9].

Figure 1a integrates the indicators within a causal framework organised into four blocks (problem, strategy, impact, and outcomes), with their relative magnitudes (%) shown to connect structural phenomena, circular economy responses, and behavioural effects. Within the problem block, the reduction in smartphone lifespan and the increase in e-waste (2010–2022) are presented as processes associated with the dynamics of obsolescence and

the growing consumption of technological devices, as widely described in the literature [10]. The strategy block incorporates reuse and repair as central mechanisms of the circular economy aimed at extending product lifespans and preserving material value [11,12]. The impact block includes cognitive and behavioural variables related to recognition, understanding, and purchasing associated with eco-labels and certifications (including Fairtrade International), highlighting their role as determinants of pro-environmental behaviour [13]. Finally, the outcomes block incorporates both technical metrics (e.g., the recyclability of the Fairphone 2) and unintended effects, such as increased consumption due to rebound effects, a phenomenon consistent with evidence on compensatory responses to measures perceived as sustainable [14,15]. Furthermore, Figure 1b illustrates critical global waste trends within a causal framework that articulates the same four blocks (problem, strategy, impact, and outcomes), integrating evidence on technological obsolescence and the externalities of the textile system. In the problem block, the increase in e-waste (2010–2022), quantified as an 82% rise, and the collapse of smartphone lifespans (from 4.7 years in 2014 to 2.7 years in 2020) are represented, phenomena consistent with the literature on obsolescence and the acceleration of technological replacement cycles [16]. In parallel, the block associated with systemic impact incorporates the textile industry's contribution and the phenomenon of Fast Fashion, highlighting the generation of approximately 92 million tons of textile waste per year and the high pressure on resources (water and raw materials). This aligns with studies describing the intensification of environmental impacts and the shortening of product use cycles due to the accelerated rotation of styles [11]. The strategy block is interpreted as the need for circular economy responses based on lifespan extension, particularly repair and reuse, as mitigation mechanisms against obsolescence and waste accumulation [12,16]. Finally, the outcomes block is expressed in terms of aggregated system consequences, including the net increase in waste and unsustainable consumption patterns, incorporating dynamics compatible with the rebound effect, when improvements in efficiency or perceptions of sustainability fail to reduce overall consumption, a phenomenon widely discussed in the literature on innovation and sustainability policies [13].

Figure 2 presents a bibliometric map of keyword co-occurrence in related studies retrieved from the Scopus database over the last ten years. The analysis of the bibliometric map reveals that research on product design strategies aimed at promoting responsible consumption is structured around a central core composed of product design, consumer behaviour, and sustainable development, indicating that design is increasingly conceived as a strategic tool capable of influencing consumption decisions [15,17]. A strong integration is evident between environmental approaches, represented by eco-design, life cycle assessment, and environmental impact reduction, and social and behavioural approaches focused on consumer attitudes, perceptions, and consumption habits [14,18], demonstrating that product design not only addresses technical and environmental performance but also seeks to guide consumer decision-making toward more sustainable consumption patterns [19]. Furthermore, the analysis highlights specialised attention to specific industrial sectors, such as sustainable fashion, recycling, and packaging design, where design plays a key role in the transition toward more responsible production and consumption models [20,21]. Overall, the bibliometric network reflects a multidisciplinary field of study in which design strategies integrate environmental, social, and economic dimensions to promote consumption practices aligned with the principles of sustainability and the United Nations Sustainable Development Goal 12 [16].

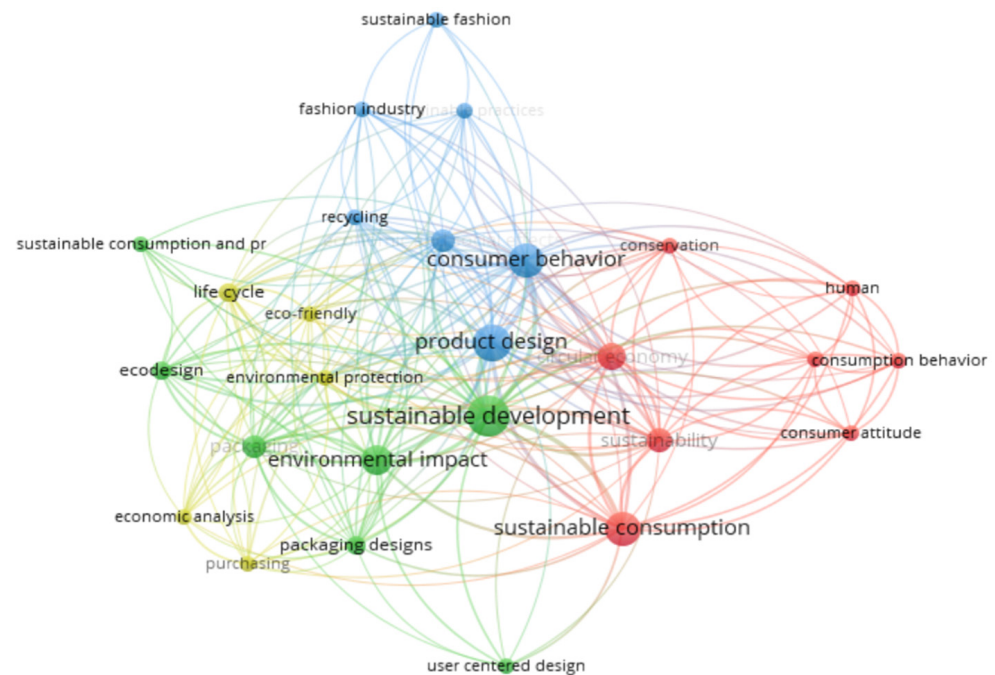


Figure 2. Bibliometric map of keyword co-occurrence in studies related to the use of product design strategies to promote responsible consumption. Generated with VOSviewer 1.6.20.

Circular design strategies have primarily focused on the physical aspects of products, such as the selection of recyclable materials. However, design can also play a crucial role in shaping user behaviour [7] through strategies that promote practices such as reuse, sharing, and product returns at the end of their life cycle. This aspect, known as design for behaviour change, has not yet been extensively explored within the field of the circular economy [22].

Implementing product design strategies that promote responsible production and consumption significantly contribute to several Sustainable Development Goals (SDGs). It directly supports Sustainable Development Goal 12 by fostering sustainable consumption patterns through design approaches oriented toward reuse and recycling. It also contributes to Sustainable Development Goal 13 by reducing pollution indicators and promoting more efficient use of natural resources. Furthermore, it supports Sustainable Development Goal 8 by creating opportunities in sectors such as repair and recycling and promotes Sustainable Development Goal 4 by raising awareness among consumers and designers about the importance of sustainable practices. This work seeks not only to contribute to understanding the roles of consumers and producers in the transition toward a circular economy but also to offer practical strategies for designers and companies aiming to lead this shift toward more conscious, sustainable consumption [23].

This manuscript aims to analyse advances in product design strategies that promote responsible consumption and production, with particular emphasis on their application in specific manufactured products such as packaging, electronic devices, construction, and industrial systems. Studies addressing design strategies in manufactured products were identified, as well as articles that approached this topic from a conceptual perspective. This study is justified by the need to bridge the gap between theoretical developments and their practical application, considering design strategies as a key driver of sustainability and the transition toward a circular economy across different productive sectors.

The article is organised as follows. Section 2 describes the methodology used to review and synthesise previous studies on design strategies that promote responsible production and consumption, following the PRISMA guidelines. Section 3 presents the

main findings of the review and their scope, addresses the challenges and limitations identified in their implementation, and outlines future perspectives for these strategies with the contribution of emerging technologies. Section 4 discusses the findings across five key domains: environmental impact mitigation strategies, technological enablers for sustainable product design, circular economy integration into design processes, social and behavioural implications, and policy alignment and regulatory frameworks.

2. Methodology

This scoping review was conducted according to the PRISMA guidelines. The dataset containing the details of the review process is available in [24]. The bibliographic information analysed includes scientific articles published over the last fifteen years, collected from major academic databases such as Scopus, Web of Science, ScienceDirect, and Taylor & Francis.

To ensure transparency and methodological rigour, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist (Supplementary Materials) was used, specifying the pages where the relevant information can be found in each section of the manuscript. The review process was organised into three main stages: (i) defining the research questions, (ii) establishing the scope of the review, and (iii) conducting a comprehensive search aimed at identifying and extracting relevant information from the selected publications.

The central research question guiding this review was: What product design strategies have been developed to promote responsible production and consumption? This question enabled the identification of emerging innovations and concepts across the product life cycle, including design, assembly, and use. These aspects are increasingly recognised for their potential to reduce resource consumption, enhance productivity, and encourage more efficient and responsible use of materials by users and end consumers. This review adopts a descriptive approach, enabling a clear definition of the study's scope. By doing so, it avoids an overly broad treatment of the topic and instead prioritises solutions and advances documented in the scientific literature.

For the introduction and extraction of reference information, indexed articles were explored in the Scopus database using the following search query: TITLE-ABS-KEY (("product design" OR "design strategy") AND ("responsible consumption" OR "sustainable consumption" OR "conscious consumption") AND ("sustainability" OR "eco-friendly" OR "environmental impact" OR "resource efficiency") AND ("innovation" OR "creativity" OR "development" OR "improvement")).

For the data extraction stage of the selected scientific articles, a set of research questions was formulated to guide the analysis and organisation of the information obtained from the literature. The questions addressed key aspects related to product design strategies and their role in promoting responsible production and consumption: RQ1. What product design strategies have been developed to promote responsible production and consumption? RQ2. What impacts result from the implementation of these strategies? RQ3. What limitations and challenges are associated with the implementation of these design strategies? RQ4. What future perspectives exist regarding the implementation and development of new product design strategies to foster responsible production and consumption? RQ5. What is the contribution of emerging technologies to the implementation of these new product design strategies? These questions served as the analytical framework for extracting and synthesising the most relevant evidence reported in the selected studies.

The Cohen's Kappa coefficient was used as a recognised statistical indicator to assess inter-reviewer reliability in the systematic review process. Two independent reviewers examined all identified records, applying the previously established inclusion and exclu-

sion criteria. The level of agreement between them was measured using Cohen's Kappa coefficient, yielding a value of $\kappa = 0.840$, which indicates a moderate level of agreement above that expected by chance. Any discrepancies identified during the evaluation process were resolved through discussion and consensus between the reviewers, resulting in a final selection of 147 studies for inclusion in the analysis.

As part of the quality assessment process for the selected scientific articles, the evaluation questions presented in Table 1 were applied. These criteria served as a structured framework to systematically assess the methodological rigour, relevance, and contribution of each study included in the review.

Table 1. Quality assessment questions for papers.

Quality Assessment Questions	Answer
Does the document address product design strategies to promote responsible production and consumption?	(+1) Yes/(+0) No
Does the document technically describe the advantages and disadvantages of these new strategies?	(+1) Yes/(+0) No
Does the document address new technologies and the contributions of artificial intelligence to the development of new product design strategies to promote responsible production and consumption?	(+1) Yes/(+0) No
Is the journal or conference in which the paper was published indexed in SJR?	(+1) if it is ranked Q1, (+0.75) if it is ranked Q2, (+0.50) if it is ranked Q3, (+0.25) if it is ranked Q4, (+0.0) if it is not ranked

2.1. Inclusion Criteria

In this review, studies addressing product design strategies from a technical and technological perspective were selected; therefore, preference was given to original articles and systematic reviews that examined how these solutions promote more responsible production and consumption. The search strings used for retrieving scientific literature are detailed in Table 2.

Table 2. Search strings used for article retrieval in scientific databases.

Database	String	Number Studies
Scopus	TITLE-ABS-KEY (("product design" OR "design strategy") AND ("responsible consumption" OR "sustainable consumption" OR "conscious consumption") AND ("sustainability" OR "eco-friendly" OR "environmental impact" OR "resource efficiency") AND ("innovation" OR "creativity" OR "development" OR "improvement"))	93
Web of Science	design product strategy (Topic) and responsible consumption (Topic) or sustainability (Title)	181
Science direct	Search: product design strategy, responsible consumption, sustainable	137
Taylor & Francis	[Publication Title: product design] AND [Publication Title: strategy] AND [All: responsible consumption]	28
Total studies		439

2.2. Exclusion Criteria

Articles were excluded when, although they partially matched the search terms, they did not clearly establish a direct connection between design strategies and their contribution

to responsible production and consumption. Likewise, studies focused exclusively on technical aspects, such as machinery control or process optimisation, were not considered when they did not align with the design-oriented perspective of this review.

Figure 3 illustrates the workflow for selecting reference articles. In the initial stage, 439 articles published over the last ten years were identified from well-established databases such as Scopus, PubMed, IEEE Xplore, and ScienceDirect. These sources were chosen for their strong academic reputation, broad coverage, and high editorial standards.

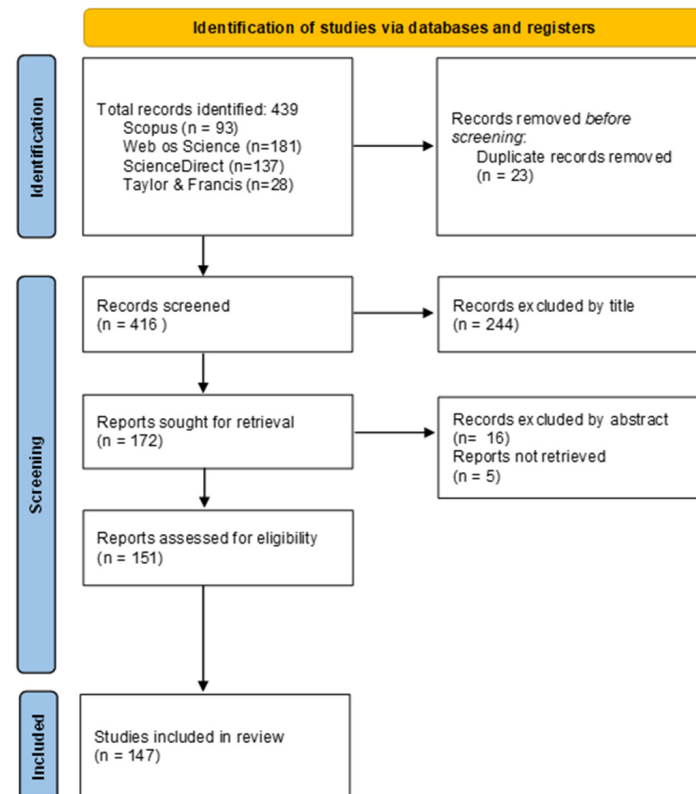


Figure 3. Selection of reference articles according to the guidelines of the PRISMA® methodology.

3. Results

Table 3 presents studies of characteristics that were included in the study and that provided criteria and rationale for this manuscript. These works broaden the scope of recent contributions on design strategies to promote responsible production and consumption in industries. The main characteristics of these studies are addressed comparatively, including authorship, country of origin, type of document, product or concept analyzed, main research question addressed, and main findings reported and related to the content of this manuscript.

Table 3. Characteristic studies table, n = 147 studies.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Nguyen Quoc et al. (2025) [25]	Vietnam	Empirical study	Green packaging, branding and eco-labeling in products	How do green marketing strategies shape young Vietnamese consumers' attitudes and behavior?	Eco-labeling drives both affective and cognitive attitudes leading to purchase, while green packaging/branding alone has no cognitive effect; environmental concern strengthens eco-labeling effects only.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Gómez Castillo et al. (2025) [5]	Costa Rica	Empirical study (survey)	Sustainable food labels/seals	What consumer profile and degree of knowledge on sustainability seals for agricultural products in Costa Rica?	Essential Costa Rica seal is most recognized; income and link to agricultural sector influence knowledge and consumption; interest does not always translate into purchase behaviour.
Franceschini & Da Rocha (2025) [7]	Brazil	Empirical study (case study)	School washrooms (built environment)	Can a Design for Sustainable Behaviour toolkit promote sustainable behaviour in schools' washrooms?	DfSB toolkits with playful natural motifs were preferred; concepts may indirectly support sustainable behaviour by creating pleasant environments.
Roskladka et al. (2025) [9]	Italy	Literature review	Electronic products	What design for repair features, practices and measures contrast obsolescence in electronic products?	Identifies design-for-repair features, practices and measures that promote reparability and counteract premature obsolescence in electronics.
Ferrer & Ayres (2000) [26]	France	Methodological study (input-output analysis)	Remanufactured durable goods (tires, computers, automobiles)	How would widespread remanufacturing affect labor and inter-industry transactions in the economy?	Remanufacturing raises labor demand (0.2–0.8%) and reduces inter-industry transactions (0.3–0.8%); raw material, component and energy sectors lose the most output.
Hybel et al. (2025) [27]	Denmark	Methodological	Industrial components	How analytically assess target components for remanufacturing through design for disassembly?	Proposes an analytical method to assess components for remanufacturing based on disassembly characteristics.
Gieß & Möller (2025) [28]	Germany	Literature re-view/modeling	Batteries / general products	How model the value ecosystem of Digital Product Passports?	Provides an e3-value model of DPPs identifying actors, needs and connections, applied to EU Battery Regulation.
Kumar et al. (2025) [29]	India	Literature review	Food packaging (biodegradable)	What sustainable modifications are being made in biodegradable food packaging?	Comprehensive review identifies biodegradable materials and modifications driving sustainable food packaging.
Espinoza-Orias & Lundquist (2025) [30]	Switzerland	Methodological/LCA	Reusable food/beverage packaging	What are good practices for LCA of reusable food and beverage packaging systems?	Proposes good practices for LCA of reusable packaging including system boundaries, return rates and number of uses.
Akbarian-Saravi et al. (2025) [31]	Canada	LCA case study	PBAT biodegradable packaging	What environmental impacts of PBAT resin blends used in packaging?	PBAT composting offers clear environmental advantages over PE landfilling; energy efficiency improvements key.
Goridkov & Goucher-Lambert (2025) [32]	USA	Literature review	Digital and physical PSS	How digital vs physical design strategies support sustainable behaviour?	Categorizes DfSB methods across digital/physical technologies and identifies unique affordances of each.
Belkhiri et al. (2025) [33]	Poland/Romania	Literature review	Modular architecture/buildings	How design for disassembly and reuse advance circular economy in modular architecture?	Modular DfD can improve resource recovery up to 50% vs. traditional construction; barriers remain regulatory and financial.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Schomberg et al. (2025) [34]	Germany	LCA case study	Modular smartphone	What environmental benefits of a highly modular, repairable smartphone?	Modular smartphone achieves 40% reduction in climate emissions, energy, materials, water and land vs. conventional.
Zhang et al. (2025) [35]	China/UK	Case study/methodological	Bluetooth speaker (STAGE)	How calculate carbon footprint over a product life cycle for low-carbon design?	STAGE speaker total CF = 227 kgCO ₂ e; use phase dominates (73%); energy efficiency and material substitution are key levers.
Jerome et al. (2025) [36]	EU (JRC)/Sweden	Methodological	Remanufactured/repaired products	Which product lifetime modelling approaches are suitable for LCAs of lifetime extension?	Three approaches (single value, no-fixed, distribution) answer different LCA questions; selection should match goal.
Klose & Fröhling (2025) [37]	Germany	Conceptual	Products in CE (general)	How develop a new CE conception for sustainable product design?	Proposes Circular Economy Design Diagram (CEDD) with four areas of decision integrating CE strategies into design stages.
Gomes (2025) [38]	Portugal	Empirical study (survey)	Circular business models (consumer)	How personality traits influence consumer engagement with circular business models?	Personality traits affect CE engagement directly but not willingness to participate in CBM unless engaged first.
Wagner (2025) [39]	Germany	Literature review	Electronic products	What information barriers exist for circularity in electronics, and can DPPs help?	Identifies 77 information barriers in electronics CE; DPP can address several but data gathering effort must be balanced.
Wang et al. (2025) [40]	China	Conceptual/methodological	IoT-enabled AI products (eco-design)	How IoT and AI enable sustainable product design optimizing eco-efficiency?	Proposes an IoT-AI framework that optimizes eco-efficiency in sustainable product design.
Yang et al. (2025) [41]	China	Conceptual/methodological	Architectural designs	How generative AI support sustainable architectural design optimization?	Generative AI tools can support multi-objective optimization in sustainable architecture.
Bhatia et al. (2025) [42]	India	Conceptual/review	Circular supply chains (blockchain)	How blockchain enable circular supply chains?	Identifies blockchain applications for circular supply chains and outlines implementation pathways.
Nasir et al. (2025) [43]	Malaysia	Conceptual/framework	Industry 5.0 manufacturing	How integrate human-centric Industry 5.0 across design and operations?	Proposes multi-level framework for human-centric Industry 5.0 from design to operations.
Huang et al. (2025) [44]	Taiwan/China	Empirical study	Firms in CE (AI-enabled)	How AI enhance firm circular economy maturity?	AI adoption improves CE maturity but effects depend on organizational and industry factors.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Brouillat & Saint Jean (2020) [45]	France	Modeling study (agent-based simulation)	Hazardous chemical substances and safer substitutes	How do implementation gaps between regulatory stringency and enforcement affect the transition to cleaner technologies?	Combining maximum stringency with the strictest enforcement does not maximize substitution; severe regulation requires lenient enforcement to preserve "maverick" pioneers and enable transition to safer substitutes.
Feng et al. (2015) [46]	China	Case study (survey-based GHG emission accounting)	Energy-related GHG emissions across town-level sectors	How can a survey-based method quantify energy-related GHG emissions at the town level and identify priority sectors for mitigation?	Total GHG emissions of Xiaolan in 2010 reached 2.07 Mt CO ₂ e (68% Scope 2, 32% Scope 1); manufacturing, residents and power/gas/water supply accounted for 90% of emissions, guiding sector-specific low-carbon strategies
Ramírez-Escamilla et al. (2024) [8]	Mexico	Systematic literature review (PRISMA)	Textile/garments	What circular economy strategies have been implemented in the textile industry?	Reuse, recycling, repair and reduction are main strategies; reuse is most economically viable; achieving CE requires a paradigm shift in consumer and corporate behaviour.
Paul et al. (2024) [47]	Germany	Conceptual/empirical	Remanufactured products	How product design for remanufacturing be enhanced and implemented in integrated systems?	Provides design guidelines and implementation approach to enhance integration of remanufacturing in product development.
Psarommatīs & May (2024) [48]	Norway/Greece	Conceptual/methodological	Manufactured products (electronics)	What potential benefits and applications of Digital Product Passports in manufacturing?	Develops a DPP framework that enhances supply chain transparency and supports sustainable manufacturing.
Machado et al. (2024) [49]	Brazil	Empirical study (expert opinion)	Modular products (CE business models)	Can product modularity boost circular business model strategies?	Presents a visual tool mapping benefits and barriers of modularity in supporting circular business models.
Arias et al. (2024) [50]	Colombia	Empirical study (survey)	Repaired/reused products	How perceived value and green consumption values influence pro-circular behaviours?	Functional value is the main starting point; interaction of perceived and green values increases repair/reuse probability.
Sierra-Fontalvo et al. (2024) [51]	Colombia	Methodological	Remanufactured products/components	How diagnose remanufacture potential at product-component level using disassemblability and integrity?	Proposes disassemblability + integrity framework to evaluate remanufacturing potential at component level.
Kurilova-Palisaitiene et al. (2024) [52]	Sweden	Conceptual/empirical	Remanufacturing operations	How remanufacturing maturity be assessed as a circular manufacturing indicator?	Proposes four-level remanufacturing maturity framework and practical assessment tool.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Golinska-Dawson et al. (2024) [53]	Poland	Empirical study	Household appliances (PaaS models)	How mature are product-as-a-service business models for household appliances under R strategies?	Assesses PaaS maturity across R strategies revealing gaps in implementation for household appliances.
Hidalgo-Crespo et al. (2024) [54]	Ecuador	LCA case study	Domestic post-consumer materials	What validated circular end-of-life strategies for domestic waste in Latin America?	Domestic recycling has slightly higher environmental benefits than external recycling in Guayaquil case study.
Farrell et al. (2024) [55]	Ireland	Literature review	Food packaging materials	What functions and properties of food packaging materials and their suitability for reusable packaging?	Reviews material properties to support transition from linear to circular reusable food packaging.
Yadav et al. (2024) [56]	Finland	LCA case study	Reusable plastic food packaging	What environmental performance of reusable plastic food packaging?	LCA shows reusable plastic packaging environmental benefits depend on reuse cycles and return logistics.
Ren et al. (2024) [57]	China	Experimental study	Calcined clay blend cement	How enhance workability of high-volume calcined clay blend cement pastes?	Optimized addition sequences of PCE superplasticizer enhance workability of calcined clay blend pastes.
Neramballi et al. (2024) [58]	Sweden	Literature review /policy analysis	Product-as-a-service (PaaS)	How policies support circular PaaS design in manufacturing?	Proposes prospective policy framework with complementary interventions targeting internal/external barriers to PaaS design.
Jugend et al. (2024) [59]	Brazil/Portugal/Columbia	Empirical study (Fuzzy AHP)	Products in CE (general)	What critical barriers to circular product design in Brazilian context?	Supply chain provision difficulties and reverse logistics are main barriers; low consumer valorization also relevant.
Dervishaj & Gudmundsson (2024) [60]	Sweden	Comparative study	Built environment products	How digital tools support LCA and circular design in the built environment?	Comparative analysis of digital tools reveals gaps in supporting circular design beyond LCA.
Rohsig Lopez et al. (2024) [61]	Brazil	Systematic literature review	Consumer behaviour (CE)	State of research on consumer behaviour in circular economy?	Systematic review identifies key consumer behaviour drivers, barriers and gaps in CE research.
Pratiwi et al. (2024) [62]	Indonesia	Empirical study	Consumer behaviour (CE)	What role of consumers in fostering circular economy in Indonesia?	Consumers play a key role; awareness and infrastructure barriers limit CE adoption in Indonesia.
Toşa et al. (2024) [63]	Romania	Empirical study	Digital transformation/incentives	How digital transformation and incentives affect pro-environmental behaviour?	Digital transformation and incentives positively shape pro-environmental behaviours.
Colley et al. (2024) [64]	UK	Conceptual/agenda paper	Consumer behaviour (CE)	What agenda for behavioural research on circular economy?	Proposes research agenda placing people at the centre of CE behavioural research.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Trienens et al. (2024) [65]	Germany/Netherlands	Systematic literature review	Products with digital twins	How digital twins increase sustainability throughout the system lifecycle?	Systematic review identifies how digital twins contribute to sustainability across lifecycle stages.
Masa'deh et al. (2024) [66]	Jordan	Empirical study	Courier supply chains (blockchain)	How blockchain affect courier supply chains digitalization and sustainability?	Blockchain contributes positively to supply chain digitalization and sustainability outcomes.
Ali Saqib et al. (2024) [67]	Pakistan	Literature review	3D printed products	What outlook and trends for sustainability and innovation in 3D printing?	Reviews sustainability dimensions and innovation trends in additive manufacturing.
Xie et al. (2024) [68]	China	Experimental study	Hydroxyapatite nanomaterials	How hydroxyapatite nanomaterials efficiently remove U(VI)?	Hydroxyapatite nanomaterials show effective U(VI) removal dependent on physical/chemical conditions.
Hassan et al. (2024) [69]	Pakistan	Experimental study/review	3D printed polymer blends	How 3D printing be used to upcycle plastic and biomass waste into polymer blends?	3D printing offers viable routes for upcycling plastic and biomass waste into sustainable polymer blends.
Mesa (2022) [4]	Colombia	Literature review + case study	Circular products (general)	How DFX rules be classified and applied to support a circular economy?	Proposes the Design for Circularity and Durability (DFCD) guideline with 51 rules classified by CE strategies and design stages.
Barros & Dimla (2023) [70]	UK	Empirical study	Smartphones	How repairability scores link to industrial design features of smartphones?	Higher repairability scores are not limited to disassembly-friendly architectures; quality service can also boost scores.
Ruiz-Pastor & Mesa (2023) [71]	Spain/Colombia	Conceptual/methodological	Products (general)	How product repairability be measured through an integrated indicator?	Proposes multidimensional integrated indicator combining product, service and user factors to measure repairability.
Jones & Eckert (2023) [72]	UK	Case study	Hospital building services	How hidden overdesign manifest in building services?	Two UK hospital case studies reveal substantial hidden overdesign in building services, with sustainability implications.
Behvar & Haghshenas (2023) [73]	USA	Literature review	Metal components (very high cycle fatigue)	What mechanisms, methods, materials and models in very high cycle corrosion fatigue?	Reviews state of knowledge in very high cycle corrosion fatigue with implications for durability assessment.
Alkouh et al. (2023) [74]	Kuwait/Algeria	Methodological	Industrial electronics (oil & gas)	How mathematically score the repairability of industrial electronics in the O&G sector?	Proposes Index of Repairability (IOR) using AHP across design, parts, software, documentation criteria.
Kim et al. (2023) [75]	South Korea	Comparative LCA	Fresh food distribution packaging	What comparative environmental performance of reusable vs. disposable distribution packaging?	Reusable packaging (VIP/EPE) reduces GWP by 74–87% vs. EPS after sufficient reuse cycles.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Pietroni et al. (2023) [76]	Italy	Conceptual paper	Modular products/architecture	How modular design support the transition from ‘making to unmake’ to ‘making to remake’ in CE?	Modular design enables a shift toward CE through disassembly and remaking strategies.
Korsunova et al. (2023) [77]	Finland	Empirical study (interviews)	Repaired products (consumer)	How young consumers decide on product repair in a circular economy?	Proposes process model of consumer decision-making for repair based on young adult and stakeholder experiences.
Hild (2023) [78]	Luxembourg	Empirical study (interviews)	Buildings/construction sector	How is the circular economy operationalized in Luxembourg’s building sector?	Circular building practices in Luxembourg focus on circular design, materials passports and digitisation.
Horn et al. (2023) [79]	Finland	Empirical study	Products (ecodesign in companies)	How national public policy promote ecodesign implementation in companies?	Key drivers/barriers identified; stable regulation, clear info and accessible tools needed to support ecodesign.
Appiah et al. (2023) [80]	Ghana/China	Empirical study	Green culture/manufacturing firms	How green culture, environmental innovativeness and intellectual capital affect circular economy performance?	Green culture and environmental innovativeness positively influence CE performance through green intellectual capital.
Ramzan et al. (2023) [81]	Pakistan/UK	Empirical study	Products (consumer education)	How Design for Disassembly educate consumers for circular behaviour?	DfD serves as an educational tool that promotes circular behaviour among consumers.
Vidal-Ayuso et al. (2023) [82]	Spain	Literature review	Consumer behaviour (CE)	State of research on circular economy and consumer behaviour?	Identifies research themes and future directions in CE and consumer behaviour literature.
Henriques et al. (2023) [83]	Portugal	Empirical study	Consumer perspectives (CE products)	What are consumers’ perspectives on circular economy and market valorization?	Identifies main tendencies in consumer perspectives that affect market valorization of CE products.
Alves et al. (2023) [84]	Portugal/Brazil	Empirical study (survey)	Consumer behaviour (CE)	What are consumer attitudes and behaviours toward the circular economy transition?	Surveys consumer attitudes and behaviours and identifies key levers for promoting CE transition.
Muth et al. (2023) [85]	Germany	Conceptual review	Additively manufactured products	How additive manufacturing contribute to sustainable development goals?	Identifies opportunities for additive manufacturing to support SDGs but also notes potential trade-offs.
Seegrün et al. (2023) [86]	Germany	Systematic literature review	Products with digital twins	How digital twins support sustainable product lifecycle management?	Maps how digital twins support sustainability across product lifecycle phases; identifies gaps.
Mesa et al. (2022) [10]	Colombia/Brazil	Literature review	Durable products (general)	How is product design linked to durability and what is the research agenda?	Maps the relationship between design strategies and product durability and proposes a research agenda for design for durability in CE.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Barkhausen et al. (2022) [87]	Germany	Policy/content analysis	Energy-related products (EU regulated)	How is the EU Ecodesign Directive evolving from energy efficiency to circular economy?	75% of regulated product groups now contain CE requirements; lighting focused on durability, white goods on repairability.
Guerritore et al. (2022) [88]	Italy	Experimental study	Flexible food packaging	Can mono-material recyclable-by-design flexible packaging achieve high barrier properties using graphene coatings?	Graphene hybrid coatings enable recyclable mono-material packaging with high barrier performance.
Dangal et al. (2022) [89]	Netherlands	Comparative analysis	Repair scoring systems	How objective and complete are existing repairability scoring systems?	Most scoring system criteria are acceptably objective; gaps exist in health/safety, eDiM database, and reassembly assessment.
Spreafico & Landi (2022) [90]	Italy	Empirical study (comparison)	Products in CE (general)	Which product design strategies are most used by students vs professional designers for CE?	Students prefer systematic innovation strategies; professional designers use industrial design strategies.
Spreafico (2022) [91]	Italy	Meta-analysis (LCA-based)	Products in CE (general)	What environmental impacts of design strategies for CE based on LCA evidence?	Analysis of 156 LCA case studies provides quantitative ranking of CE design strategies by environmental benefit.
Wang et al. (2022) [92]	Australia/New Zealand	Empirical study	Products in CE (general)	What barriers exist to circular product design and how to overcome them?	Identifies and prioritizes barriers to circular product design including organizational, supply chain and consumer factors.
Moreno Rocha et al. (2022) [93]	Colombia	Conceptual/methodological	Products in CE transition	How design strategies for an efficient transition from linear to circular economy?	Proposes strategies and design approaches for an applicative transition to CE in industry.
Torkayesh et al. (2022) [94]	Turkey/Iran	Methodological (LCA + MCDM)	Sustainable products (general)	How integrate LCA and MCDM for sustainable product evaluation?	Integrated LCA-MCDM approach supports robust evaluation of sustainable product alternatives.
Franconi et al. (2022) [95]	Italy/UK	Conceptual paper	Products in CE (general)	How structure circular objectives and design strategies for circular economy?	Proposes structured framework linking circular objectives to design strategies.
Szilagyi et al. (2022) [96]	Romania	Empirical study (path analysis)	Consumer behaviour (CE)	What underlying factors of consumer behaviour in CE?	Path analysis identifies key psychological and contextual factors that drive consumer behaviour in CE.
Laukkanen & Tura (2022) [97]	Finland	Case study	Clothing (library service)	How sustainable value propositions align with customer perceived value in clothing libraries?	Case study reveals mismatches between sustainable value propositions and consumer perceived value.
Gil-Lamata & Latorre-Martínez (2022) [98]	Spain	Systematic literature review	Scientific literature on circular economy and sustainability	What is known and what gaps remain?	Circular economy supports sustainability, but needs more empirical research and practical implementation.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Kamble et al. (2022) [99]	India/UK	Literature review	Digital twins (manufacturing)	What are current trends and research priorities for digital twins in sustainable manufacturing?	Maps digital twin research in sustainable manufacturing supply chains; identifies future directions.
Ma et al. (2022) [100]	China	Conceptual/methodological	Smart manufacturing systems	How digital twins and big data drive sustainable smart manufacturing?	Proposes information-driven sustainable smart manufacturing framework using digital twins and big data.
Gopal et al. (2022) [101]	India	Literature review	Additively manufactured products	What environmental implications of sustainable additive manufacturing?	Reviews sustainability aspects of additive manufacturing and identifies opportunities/challenges.
Gustafsson et al. (2021) [3]	Denmark	Systematic literature review	Product-Service Systems (PSS)	What methods and tools exist to develop sustainable behaviour within PSS, and what are barriers and success factors?	46 methods to achieve sustainable behaviour in PSS were identified and analyzed alongside success factors and barriers for implementation.
Nwankpa et al. (2021) [102]	UK	Simulation study	Remanufactured products	How automated inspection improve remanufacturing processes?	Discrete event simulation shows automated inspection improves remanufacturing efficiency.
Chen et al. (2021) [103]	China	Methodological/case study	Used gearbox parts	How integrate process and tolerance design for remanufacturing of failed parts?	IDP-T method based on failure features optimizes process-tolerance schemes for remanufactured parts.
Goetz et al. (2021) [104]	Germany	Case study/methodological	Ski bindings	How early robust design decisions affect parameter and tolerance optimization?	Early robust design decisions provide measurable benefits in later parameter and tolerance optimization.
Sumter et al. (2021) [105]	Netherlands	Empirical study	Circular design competencies (education)	What key competencies are needed for design in a circular economy?	Identifies gaps in current design knowledge and skills required for circular design practice.
Huang et al. (2021) [106]	China	Literature review	Digital twins/AI in Industry 4.0	What state of AI-driven digital twins in smart manufacturing?	Reviews AI-driven digital twins; identifies applications and research priorities for smart manufacturing.
Majeed et al. (2021) [107]	China	Conceptual/methodological	Additive manufacturing	How big data enable sustainable and smart additive manufacturing?	Proposes big data-driven framework for sustainable and smart additive manufacturing.
Tang et al. (2021) [108]	China	Methodological	Decision-making (general)	How use data mining for large-scale group decision making with multiple attributes?	Proposes multi-attribute large-scale group decision method using data mining and subgroup analysis.
Axon & Darton (2021) [109]	UK	Literature review	Energy systems	How is sustainability linked to energy security risk?	Reviews the relationship between sustainability and energy security identifying integrated risk perspectives.
Hidalgo-Crespo et al. (2024) [110]	France, Poland, and Belgium	Conference paper	Electrical and electronic equipment under PaaS models	Which design guidelines enable circular PaaS systems?	Modularity, durability, repairability, and disassembly extend product life and reduce waste.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Martínez Leal et al. (2020) [6]	France	Conceptual/case study	Smartphone (Fairphone 2)	How Design for Recycling and Design from Recycling be integrated to support a circular economy?	Proposes Re-Cycling; a complete circular design approach linking recyclability assessment with design guidelines and use of secondary raw materials.
Flor et al. (2026) [24]	International	Research dataet	Product design strategies across multiple product categories	Which design strategies promote responsible production and consumption?	Durability, repairability, modularity, and eco-design support circularity and SDG 12.
Coelho et al. (2020) [111]	Netherlands	Literature review	Reusable packaging	What current sustainability situation and trends for reusable packaging?	Identifies sustainability performance, key drivers and trends for reusable packaging systems.
Waldman et al. (2020) [112]	USA	Methodological	Construction materials	How quantify data quality in Environmental Product Declarations (EPDs) of construction materials?	Provides framework for assessing data quality in EPDs supporting reliable embodied carbon assessment.
Kim & Lee (2020) [113]	South Korea	Methodologic-al/case study	Air blower motors (electric vehicles)	How apply Taguchi robust design considering manufacturing tolerance in motors?	Taguchi-based multi-response method improves robustness of motors against manufacturing tolerances.
Knošková (2020) [114]	Slovakia	Literature review	Products in CE (general)	How circular design and consumer involvement enhance circular economy?	Discusses design strategies for slowing/closing loops and consumer behaviour changes required for CE.
Bocken et al. (2020) [115]	Netherlan-ds/UK	Empirical study	Sustainable business models	What are barriers and drivers to sustainable business model innovation and how to overcome them?	Organizational design plays a key role in enabling sustainable business model innovation; specific barriers and drivers identified.
Kravchenko et al. (2020) [116]	Denmark	Conceptual/m-methodological	Sustainable products (CE)	How navigate trade-offs between conflicting sustainability objectives in CE?	Proposes trade-off navigation framework as decision support for conflicting sustainability goals.
Parajuly et al. (2020) [117]	Denmark	Literature review	Electronic waste/products	How behaviour change support circular economy for electronic waste?	Reviews behaviour change strategies for CE with focus on e-waste; identifies effective interventions and gaps.
Testa et al. (2020) [118]	Italy	Empirical study	Consumer behaviour (CE)	What role of information sources in mediating CE and consumer behaviour?	Information sources mediate the relationship between CE awareness and consumer behaviour.
Rojek et al. (2020) [119]	Poland	Conceptual/m-methodological	Manufactured products (general)	How digital twins support sustainability across product lifecycle?	Digital twins improve sustainability outcomes in manufacturing and maintenance phases.
Abbasi (2019) [120]	Norway	Literature review	Materials in seawater (corrosion fatigue)	What methodologies are used for testing corrosion fatigue?	Provides framework for designing corrosion fatigue testing setups and reviews related standards.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Milios et al. (2019) [121]	Sweden	Empirical study (survey)	Remanufactured automotive parts	What is consumer perception of remanufactured automotive parts and policy implications?	Consumer perceptions of remanufactured parts vary; policy interventions could increase market acceptance.
Hristov & Chirico (2019) [122]	Italy	Literature review	Sustainability KPIs	What role of sustainability KPIs in implementing sustainable strategies?	Sustainability KPIs are critical enablers but often poorly integrated into corporate strategic management.
Sauerwein et al. (2019) [123]	Netherlands	Conceptual/e-exploratory	Additively manufactured products	What potential of additive manufacturing for product design in a circular economy?	Additive manufacturing offers opportunities for CE-aligned design strategies including localization and customization.
Nahavandi (2019) [124]	Australia	Conceptual paper	Industry 5.0 systems	What is Industry 5.0 as a human-centric solution?	Defines Industry 5.0 as bringing human creativity and skills back into automated manufacturing.
Wielemaker et al. (2018) [125]	Netherlands	Modeling/case study (Urban Harvest Approach)	Domestic sanitation streams (urine, feces, kitchen waste) and Urban Agriculture	To what extent can New Sanitation systems supply the nutrient and organic matter demand of Urban Agriculture to foster a circular urban metabolism?	Integrating NS and UA can reduce nutrient/OM demand by 65–85% and achieve 100% self-sufficiency for phosphorus, with partial self-sufficiency for nitrogen and organic matter.
Elias et al. (2018) [16]	Canada	Modeling/real-options analysis	Natural gas-fired power plants	Is retrofitting carbon capture and storage to gas-fired power plants economically viable using a real-options approach?	Real-options analysis shows specific conditions where CCS retrofitting becomes financially attractive.
Wu et al. (2018) [17]	China/Netherlands	Case study	New Energy Demonstration Cities	How is decentralized energy governance experimented in China?	Identifies governance challenges and innovations in China's New Energy Demonstration City program.
Wastling et al. (2018) [23]	UK	Literature review/conceptual	Products in CE (general)	How design enable user behaviour changes needed for circular business models?	Develops a theoretical framework for designing products/services to encourage circular behaviour.
Haines-Gadd et al. (2018) [126]	UK	Empirical study (workshops)	Electrical/lighting products	Which design factors influence consumers to retain products for longer?	Develops the Emotional Durability Design Nine framework with 9 themes and 38 strategies for product longevity.
Sonego et al. (2018) [127]	Brazil	Systematic literature review	Modular products (general)	What role of modularity in sustainable product design?	Modularity enables multiple sustainability strategies (repair, upgrade, recycling); benefits depend on implementation.
De Medeiros et al. (2018) [128]	Brazil	Literature review + expert assessment	Products in DfSB (general)	How analyze existing frameworks of behaviour change strategies for design?	Proposes decision support diagram synthesizing existing DfSB frameworks for practitioners.
Milios (2018) [129]	Sweden	Policy analysis	Products in CE (general)	What policy mix is needed for transitioning to a circular economy?	Proposes three-area policy mix: reuse/repair/remanufacturing policies, green procurement, secondary materials markets.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Geissdoerfer et al. (2017) [2]	UK/Netherlands	Literature review	Circular economy concept (general)	How Circular Economy relate to sustainability, and is it a new paradigm?	Identifies similarities and differences between CE and sustainability; CE conceptualized as a regenerative system that minimizes resource input, waste, emissions and energy leakage.
Lu & Chen (2017) [12]	China	Modeling study	Urban ecological footprint	Can a Markov chain accurately predict urban ecological footprint?	Markov chain model is effective for forecasting urban ecological footprint and supports urban sustainability planning.
Kong et al. (2017) [13]	China	Experimental study	Activated carbon from sawdust	Can sawdust-derived activated carbon co-calcined with limestone enhance Acid Orange II dye adsorption?	Co-calcination with limestone significantly enhances adsorption performance of sawdust activated carbon for dye removal.
Onu et al. (2017) [18]	China	Modeling study (Fuzzy TOPSIS)	Acid rain control options	How evaluate sustainable acid rain control options using fuzzy TOPSIS?	Fuzzy TOPSIS multi-criteria framework ranks acid rain control alternatives by sustainability performance.
Hao et al. (2017) [21]	China	LCA/modeling	Electric vehicles	What impact of recycling on energy use and GHG emissions of EV production in China?	Recycling significantly reduces energy consumption and GHG emissions of EV production under China 2025 scenario.
Boiral & Heras-Saizarbitoria (2017) [22]	Canada/Spain	Empirical study (content analysis)	Mining and forestry companies	What drives corporate commitment to biodiversity in mining and forestry?	GRI reports show that drivers vary across sectors; institutional pressures and stakeholder demands are key.
Kirchherr et al. (2017) [130]	Netherlands	Literature review	Circular economy concept (general)	How is the circular economy defined in the literature?	Analyzes 114 definitions of CE; finds CE is often portrayed as combining reduce, reuse, recycle activities.
Vogtlander et al. (2017) [131]	Netherlands	Methodological	Products in circular business models	How combine cost, market value and eco-cost analyses in circular business models?	Combined analysis enables holistic assessment of economic and environmental value in CE business models.
Kojima (2017) [132]	Japan	Policy analysis	Remanufactured products (trade)	How trade regulations affect remanufacturing globally?	Trade barriers significantly affect cross-border remanufacturing flows; policy harmonization recommended.
Bocken et al. (2016) [133]	Netherlands/UK	Conceptual paper	Products in CE (general)	What product design and business model strategies support a circular economy?	Identifies design strategies (slowing/closing loops) and business models for circular economy implementation.
Moreno et al. (2016) [134]	UK	Conceptual framework	Products in CE (general)	What design strategies enable circular economy across business models?	Proposes conceptual framework linking DfX strategies to circular business models.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Mou et al. (2015) [11]	Denmark	Empirical study	Landfill waste (low-organic)	What methane generation rate constant (k value) of low-organic waste at Danish landfills?	Provides updated k values for low-organic waste relevant to landfill gas modelling and emission estimations.
Queirós et al. (2015) [19]	Portugal	Life cycle assessment	Rapeseed (agricultural product)	What environmental life-cycle impact of rapeseed production with alternative fertilization?	Fertilization and management practices significantly affect environmental impact of rapeseed production.
Kurilova-Palisaitiene & Sundin (2015) [135]	Sweden/Germany	Case study	Remanufactured engines	How pull remanufacturing reduce material and information flow uncertainties?	Case study at German engine remanufacturer reveals key uncertainties and improvements toward pull remanufacturing.
Helu & Hedberg (2015) [136]	USA	Conceptual/methodological	Manufactured products (PLM)	How product lifecycle management enable smart manufacturing R&D?	PLM data integration enables smart manufacturing research and supports sustainability assessments.
Bakker et al. (2014) [1]	Netherlands	Book	Focus on a product's "afterlife"	How can designers and entrepreneurs systematically evaluate a product's afterlife to create new value through circular business models?	Provides a practical methodology to analyse a product's afterlife and proposes circular business models (reuse, repair, remanufacturing, recycling)
Farmery et al. (2014) [20]	Australia	Empirical analysis	Seafood/fisheries	How marine resource decisions affect the environmental footprint of seafood?	Management decisions significantly influence environmental performance and footprint of seafood production.
Rodrigues and Lima (2012) [137]	Brasil	Experimental case study	Soapstone powder waste from artisan workshops	Can soapstone waste be purified and valorized for industrial use?	Purification enables waste recovery as industrial-grade talc, reducing disposal and supporting cleaner production.
Schuh et al. (2014) [138]	Germany	Conceptual/methodological	Modular products (general)	How modular product architectures be developed systematically?	Presents a methodology to develop modular product architectures balancing variety and standardization.
Scott & Vigar-Ellis (2014) [139]	South Africa	Empirical study (survey)	Environmentally friendly packaging	What is consumer understanding, perception and behaviour regarding eco-friendly packaging in South Africa?	Consumers show limited knowledge and even less action regarding environmentally friendly packaging.
Agrawal & Ülkü (2013) [140]	USA	Modeling study	Modular upgradable products	When does modular upgradability lead to lower environmental impact and higher profits?	Modular upgradability can increase environmental impact in some cases due to accelerated obsolescence; greener only under certain conditions.
Taddeo et al. (2012) [14]	Italy	Case study	Industrial cluster (chemical)	How eco-industrial parks be implemented in existing industrial clusters?	Provides empirical findings from an Italian chemical site showing factors enabling or hindering eco-industrial park implementation.

Table 3. Cont.

Author (Year)	Country	Document Type	Analyzed Product	Main Research Question	Main Finding
Zachrisson & Boks (2012) [141]	Norway	Literature review	Products in DfSB (general)	How behavioural psychology support DfSB research?	Explores behavioural psychology theories applicable to design for sustainable behaviour.
Hatcher et al. (2011) [142]	UK	Literature review	Remanufactured products	What current state and future research needs for Design for Remanufacture?	Identifies gaps and research priorities for Design for Remanufacture across industries.
Froehlich et al. (2010) [143]	USA	Conference paper/review	Eco-feedback technology	How eco-feedback technology be designed effectively?	Reviews eco-feedback systems and proposes design principles for behaviour change technologies.
Chapman (2009) [144]	UK	Conceptual paper	Consumer products (general)	How design support emotional durability of products?	Proposes design strategies that foster emotional bonds between users and products to extend product lifetimes.
Kuramochi (2016) [145]	Japan	Techno-economic modeling study	Iron and steel production	What strategies can reduce the sector's CO ₂ emissions by 2030?	Cleaner technologies and greater scrap use could cut emissions by 20 Mt CO ₂ .
Mugge et al. (2008) [146]	Netherlands	Book chapter/conceptual	Consumer products (general)	What design strategies stimulate emotional bonding to products?	Identifies determinants of product attachment and design strategies that strengthen emotional bonds.
Comino et al. (2007) [15]	Italy	Empirical study	Open source software projects	What factors determine the success of open source projects from planning to mature stages?	Identifies key drivers and stages affecting transition from planning to maturity of OSS projects.
Burdekin (2007) [147]	UK	Conceptual/m-methodological	Engineered structures	What general principles govern the use of safety factors in design and assessment?	Provides framework for selecting appropriate safety factors and addressing variability in design and assessment.

3.1. Advances in Effective Design Strategies to Promote Circular Consumer Behaviour

To identify the key aspects addressed in the scientific literature on this topic, Figure 4 presents the distribution of relative frequencies of terms associated with product design strategies aimed at promoting responsible consumption, based on an analysis of abstracts from 209 Scopus-indexed articles that directly link product design strategies to responsible production and consumption. The search and selection of the document corpus were conducted using the query: TITLE-ABS-KEY (product design strategy responsible consumption). Subsequently, the relative occurrence of the following keywords was examined: circular economy, durability, recycling, remanufacturing, packaging, modularity, labelling, and sustainable behaviour. In Figure 4, the articles have been automatically grouped into ten categories with a specific criterion for relative frequency analysis.

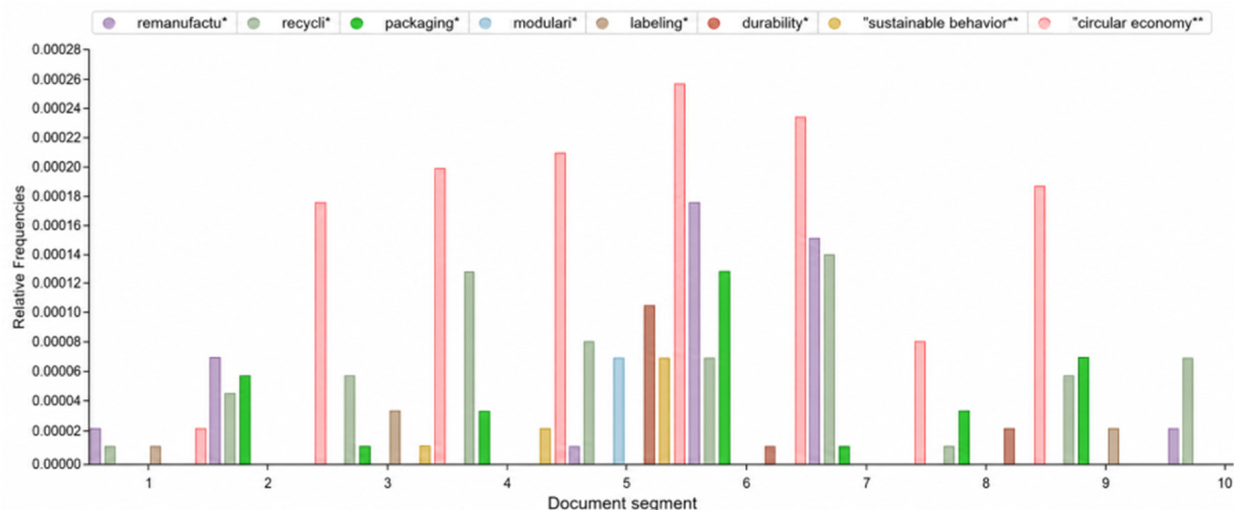


Figure 4. Bibliometric map of relative keyword occurrence in publications related to product design strategies for promoting responsible production and consumption. * represents a bounded search, ** represents a narrowed search.

Figure 4 shows a higher concentration of studies focused on four predominant aspects: circular economy, remanufacturability, packaging, and recyclability. In contrast, aspects such as durability, sustainable behaviour, and modularity have been explored less frequently. These findings suggest that scientific literature has not yet consistently addressed many modern, innovative, and technology-driven approaches that have emerged over the past few decades.

Based on the references, the types of products addressed are shown in Figure 5. The results illustrate the distribution of scientific literature according to the type of manufactured product, considering only studies focused on specific products and excluding those of a theoretical or conceptual nature without direct application. Under this criterion, the packaging sector shows the highest concentration of research, followed by electronic products, while the construction and automotive/industrial sectors exhibit a moderate level of participation. In contrast, the textile sector is significantly underrepresented. This methodological refinement enables a clearer identification of areas with greater applied development in the circular economy, as well as highlighting research opportunities in sectors with lower coverage.

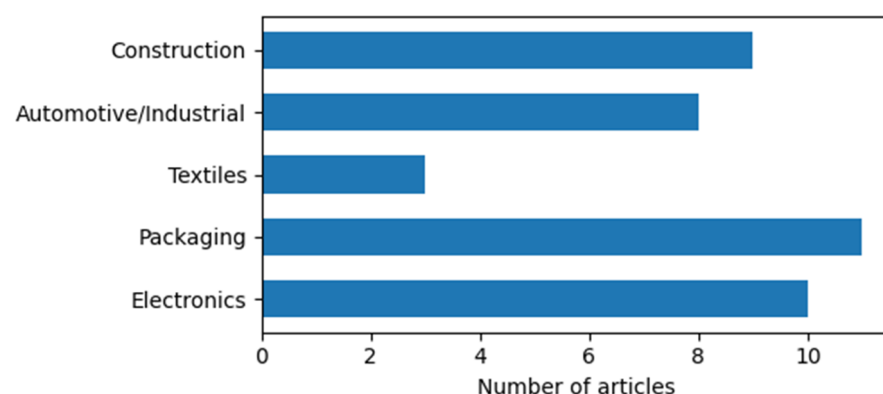


Figure 5. Distribution of scientific articles by type of manufactured product (excluding conceptual studies).

In recent years, a wide range of design strategies have been developed as effective means of influencing both producer and consumer behaviour, aligning with the principles

of the circular economy, which seeks to minimise waste and maximise the reuse of resources. These advances are not only focused on creating more sustainable products but also on reshaping consumption practices by transforming consumer expectations and habits. The identified strategies have been organised into 11 categories, which are illustrated in Figure 6.

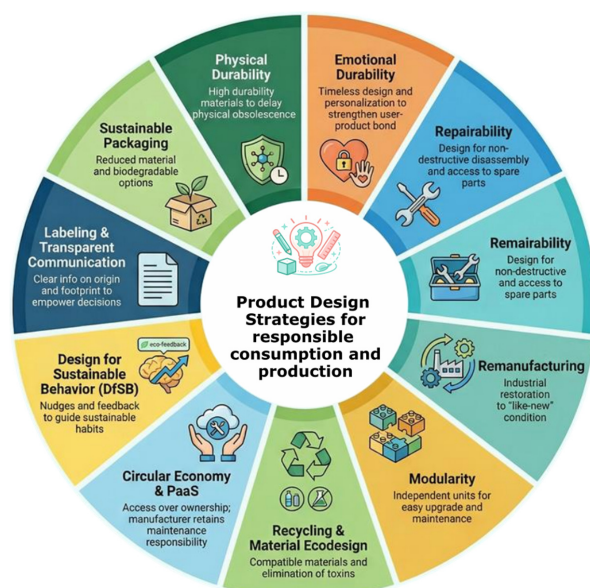


Figure 6. Strategies for product design that promote responsible production and consumption.

According to the review, the Design Strategies for Responsible Production and Consumption were organised as a coherent set of design interventions spanning the entire product life cycle. First, physical durability focuses on specifying robust materials and architectures that delay obsolescence caused by failure or degradation, aligning with integrative Design for X (DfX) approaches oriented toward circularity and durability [94]. In parallel, emotional durability aims to extend product lifespan through the user–object relationship, through timeless design, personalisation, and meaning, supported by explicit design tools for longevity [84]. Furthermore, repairability (design for non-destructive disassembly and access to spare parts) operationalises lifespan extension by enabling access to components, standardising fasteners, ensuring availability of technical documentation, and providing spare parts [52,53].

Multi-cycle remanufacturability is the capacity of a product to undergo successive cycles of disassembly, restoration, and reassembly while preserving tolerances, interface integrity, and functional performance. The strategy of repairability extends beyond repair by redesigning products to maintain tolerances, critical interfaces, and technical reliability under uncertainty during inspection and refurbishment across successive loops [43,60,105]. Furthermore, remanufacturing, understood as the industrial restoration of products to a “like-new” condition, formalises post-use value recovery through standardised recovery processes [104]. A fusion of the capabilities associated with repairability and remanufacturability may be referred to as remairability, a conceptual term that integrates the benefits of both strategies from the earliest stages of the design process. This approach encompasses design decisions related to modularity, disassembly, component accessibility, material selection, and reusable interfaces in order to facilitate both repair and remanufacturing across multiple life cycles. Consequently, remairability promotes the development of products designed to extend their functional service life through planned and sustainable technical interventions.

Modularity enables product updating, maintenance, and component replacement through independent units, supported by systematic review evidence highlighting its role

in sustainable design [99] and by principles of interchangeable modules and standardised interfaces [68,123]. At the end-of-life stage, recycling and material eco-design integrate material compatibility, the avoidance of inseparable mixtures, and the elimination of hazardous substances to improve recyclability and safety [4,38,142].

At a systemic level, circular economy and product-as-a-service (PaaS) models shift from ownership to access, retaining manufacturer responsibility for maintenance and product return [42,44]. Complementarily, Design for Sustainable Behaviour (DfSB) introduces interventions such as nudges and feedback mechanisms to guide users toward more sustainable habits.

From a communication perspective, labelling and transparent communication aim to reduce information asymmetries regarding product origin, environmental footprint, and sustainability attributes, thereby enabling more informed consumer decisions. A relevant empirical reference on consumer understanding and behaviour toward environmentally friendly packaging is provided in [107]. Sustainable packaging emphasises material reduction and the adoption of reusable, recyclable, or biodegradable alternatives; a direct reference to the sustainability of reusable packaging systems is reported in [93].

Table 4 conceptualises circularity as an integrated system rather than an isolated product attribute, organising strategies into five axes: (1) lifespan extension through physical and emotional durability, repairability, and modularity; (2) post-use value recovery via remanufacturing and recycling/eco-design; (3) transformation of provision models through circular economy and product-as-a-service (PaaS); (4) influence on user behaviour; and (5) reduction in packaging impacts. These axes highlight that circular performance depends on early design decisions—materials, interfaces, tolerances, accessibility, and information—which determine both functional stability and the feasibility of subsequent recovery cycles.

Within this framework, physical durability plays a structural role, supported by robust material selection [4], overdimensioning under uncertainty [72,148], protection against fatigue and corrosion [73,120], and realistic tolerances [104], indicating that reliability must be embedded from initial design stages. This is complemented by emotional durability, where personalisation [144], timeless aesthetics [4], and the creation of meaning and attachment [146] influence product longevity through the user–product relationship.

Table 4 shows that repairability and modularity are not auxiliary but essential conditions for sustaining circularity beyond the first use cycle. Repairability relies on non-destructive disassembly [27,89], access to components [70,71], standardised fasteners [27], and the availability of documentation and spare parts [78,81], highlighting that repair depends not only on physical disassembly but also on a supporting technical and informational ecosystem that ensures feasibility and economic viability.

Similarly, modularity—through interchangeable modules [140], standardised interfaces, and subsystem-based architectures [132]—shifts the focus from individual components to system-level design, where the quality of mechanical, electrical, and informational interfaces becomes a key determinant of circular performance.

In the post-use phase, although remanufacturing seeks to restore products to a “like-new” condition [47], design for disassembly [6,27], alone is insufficient. Its feasibility depends on reducing technical uncertainty during inspection [102], enabling multi-cycle remanufacturability through redesign [142], and protecting critical interfaces to preserve performance across cycles [103]. Thus, effective circularity relies on sustaining multiple viable cycles without significant degradation.

Material compatibility [87], the avoidance of inseparable combinations [88], and the elimination of hazardous substances [4] improve recoverability but introduce trade-offs

with durability, showing that circular strategies require balancing robustness, separability, and recoverability.

At a systemic level, Product-as-a-Service (PaaS) models shift from ownership to access, integrating maintenance and facilitating product return [93,131,134], thereby aligning incentives beyond user behaviour. In parallel, behaviour-oriented strategies—such as nudges, feedback, transparency [112], traceability [28,48], and clear instructions [48,71]—position the user as an active agent shaped by the design environment.

Reducing packaging impacts through lightweighting [29], mono-materials [88], reuse systems [30,76], and compostable alternatives [31] connects products with their logistical infrastructure and material flows.

Table 4. Advances identified over the last decade in scientific articles regarding product design strategies to promote responsible consumption and production.

Design Strategy (Macro-Level)	Sub-Strategy	Design Tool/Operational Action	Evidence (DOI)
Extend Product Service Life	Physical durability	Selection of robust materials	[4]
		Critical overdesign (design safety margins)	[72,148]
		Protection against fatigue and corrosion	[73,120]
		Tolerances for real-world use conditions	[104,113]
	Emotional durability	Personalization	[144]
		Timeless aesthetics	[4]
		Meaning/identity	[146]
		Design for user attachment and satisfaction	[146]
	Repairability	Non-destructive disassembly	[27,89]
		Access to components/parts	[70,71]
		Standardisation of fasteners	[27]
		Technical manuals/documentation	[71]
		Availability of spare parts	[71]
	Modularity	Interchangeable modules	[140]
		Standardised interfaces	[138]
		Subsystem-based architecture	[138]
Recover post-use value (technical circularity)	Remanufacturing	Restore to “like-new” condition	[47]
		Design for disassembly	[27,102]
		Inspection and reconditioning/refurbishment	[27]
	Remanufacturability across multiple cycles (“Repairability”)	Redesign to ensure remanufacturability across multiple cycles	[142]
		Minimise technical uncertainty in inspection and reconditioning	[27]
		Protect critical interfaces to preserve tolerance and functional performance across successive loops	[103]
	Recycling and material eco-design	Material compatibility	[87]
		Avoidance of inseparable material mixtures	[88]
		Elimination of toxic/hazardous substances	[4]
Change the provision model (systemic)	Circular economy & product-as-a-service (PaaS)	Access over ownership	[133]
		Maintenance included	[134]
		Product return to the manufacturer	[130]

Table 4. Cont.

Design Strategy (Macro-Level)	Sub-Strategy	Design Tool/Operational Action	Evidence (DOI)
Influence user decisions and use habits	Design for Sustainable Behaviour (DfSB)	“Nudges”	[128]
		Feedback	[143]
		Friction reduction for the sustainable option	[32]
	Transparent labelling and communication	Disclosure of origin/impact	[112]
		Traceability	[28,48]
Reduce packaging impacts	Sustainable packaging	Clear maintenance and end-of-life instructions	[48,71]
		Material reduction (lightweighting)	[29]
		Mono-material solutions	[88]
		Reuse	[30,75]
		Compostable options where appropriate	[31]

Figure 7 illustrates the relationships between product design strategies, their corresponding sub-strategies, and the associated design tools.

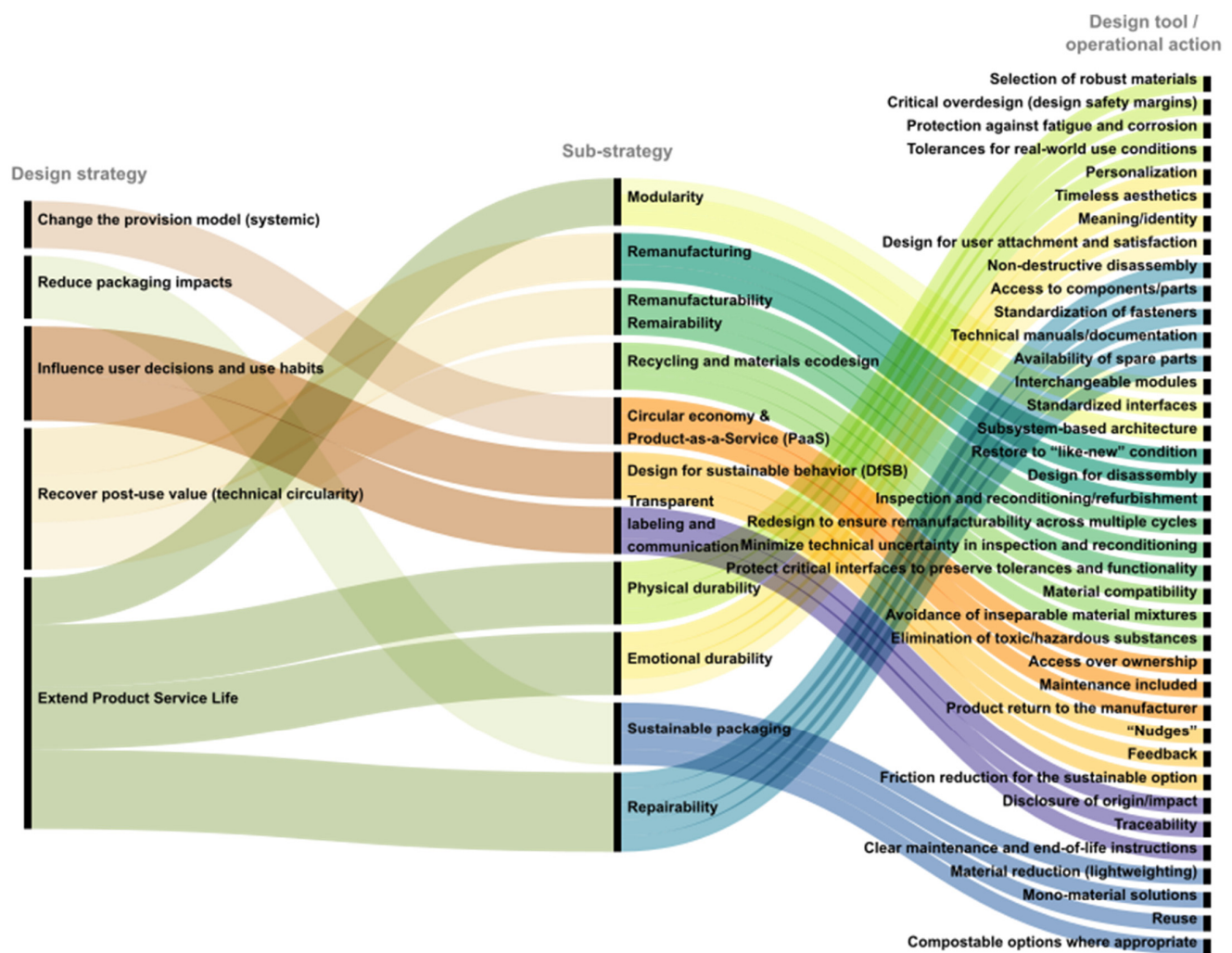


Figure 7. Product design strategies, identified subcategories, and tools/operational actions for their implementation.

Repairability and modularity function as key operational conditions to avoid complete product replacement in the event of localised failures or partial obsolescence. Repairability depends on access to components, the complexity of disassembly and reassembly processes, the availability of instructions and spare parts, and the ability to diagnose faults without damaging the system. Therefore, repairability is not limited to mere disassembly; rather, it requires that the product be intentionally designed so that intervention is technically feasible and practically reasonable [71].

Modularity, in turn, organises the product into interchangeable subsystems, facilitating upgrades, localised replacement, and functional adaptation over time. Recent evidence further suggests that modularity can serve as a strategic pathway to achieving circular benefits, particularly when it aligns with explicit objectives related to repair, refurbishment, and material recovery [33,49,76].

3.1.1. Design for Extending Product Service Life

Design for extending the product/service lifespan is a central strategy in circularity, as it aims to slow premature replacement and preserve the system's functional value over time. This approach first encompasses "physical durability", understood as the product's ability to maintain performance under both expected and non-ideal usage conditions. Within this framework, decisions related to material selection, tolerance definition, resistance to fatigue, corrosion, and wear, as well as the incorporation of safety margins, are not secondary considerations but structural determinants of reliability. Recent literature emphasises that durability should be addressed from the earliest stages of product development, rather than treated as a corrective measure after the initial design phase [4].

In addition, "emotional durability" expands this perspective by demonstrating that product longevity also depends on the meaning, identification, and attachment that users develop toward the artefact, as well as on design strategies that foster more stable and lasting relationships between users and products [50,127].

3.1.2. Recover Post-Use Value (Technical Circularity)

Post-use value recovery first encompasses remanufacturing, the process by which a used product is restored to a functional condition equivalent to that of a new product. From a circular design perspective, this requires that the product be conceived with disassembly, inspection, cleaning, refurbishment, and reassembly in mind. Consequently, value recovery should not be treated as a residual phase, but rather as a capability embedded within the product's architecture from the outset. Recent evidence highlights that many process barriers originate from design decisions that hinder access to critical components, limit condition assessment, or reduce the efficiency of refurbishment processes [47]. A more demanding level is represented by multi-cycle remanufacturability, defined as the capacity to sustain multiple successive recovery cycles without unacceptable functional degradation. In this case, the key issue is not only whether a product can be remanufactured once, but whether its interfaces, materials, fasteners, and tolerances can withstand repeated cycles of disassembly, restoration, and reassembly. Recent studies propose evaluating this capability at the product-component level, simultaneously considering disassemblability and the integrity of returned components [51]. Moreover, remanufacturing can be understood as a mature organisational capability within circular manufacturing systems rather than as an isolated practice, as reflected in the maturity framework proposed [52]. Complementarily, recycling and material eco-design aim to preserve material value at the end of life by promoting material compatibility and avoiding inseparable combinations. In packaging and complex products, mono-material design emerges as a relevant strategy to improve recoverability and facilitate recycling processes [88].

3.1.3. Change the Provision Model

Changing the provision model involves shifting the focus from one-time product sales to schemes that deliver value through use, access, or performance. Within the framework of the circular economy, this shift is particularly relevant because it reconfigures business incentives: when profitability is no longer based solely on unit volume, greater importance is placed on durability, maintenance, upgrading, and product recovery. In this sense, design strategies and business models do not operate independently but rather reinforce each other within a value-retention logic [88].

Multi-cycle remanufacturability refers to the capability of a product to undergo successive cycles of disassembly, restoration, and reassembly while maintaining dimensional tolerances, interface integrity, and overall functional performance. Within this transformation, the product-as-a-service (PaaS) approach becomes particularly significant, as it integrates design, operations, maintenance, and product returns within a single organisational framework. When the provider retains responsibility for the asset, the feasibility of decisions such as preventive maintenance, planned repair, component traceability, and end-of-use recovery increases. Recent evidence highlights both the potential and the limitations of these models in consumer products and electrical and electronic equipment, emphasising that their actual circularity depends on the extent to which they incorporate R-strategies such as repair, refurbishment, and remanufacturing [53,54]. Therefore, PaaS should not be understood merely as a commercial innovation, but as a technical and organisational reconfiguration of the product life cycle.

3.1.4. Influence on User Decisions and Use Habits

Influencing decisions and usage habits requires recognising that circularity depends not only on a product's technical attributes but also on how users interact with it in real-world contexts. From the perspective of Design for Sustainable Behaviour (DfSB), practices such as maintenance, repair, return, or end-of-life separation can be guided by feedback mechanisms, signals, choice architecture, and reduced friction toward the desired option. In this sense, repair practices and product lifespan extension depend on situated decision-making processes, prior experience, access to services, and supportive social frameworks [77].

Moreover, the sustained modification of usage habits requires accessible information, traceability, and transparency, as sustainable decisions are less likely when users or system actors lack data regarding product composition, maintenance, repair, or end-of-life processes. In this context, digital product passports and data-sharing ecosystems emerge as relevant tools to facilitate maintenance, reuse, remanufacturing, and material recovery [28,48]. From an analytical standpoint, this reinforces the idea that influencing behaviour is not about shifting responsibility onto the user, but about designing material and informational conditions that make behaviours aligned with circular objectives more likely.

3.1.5. Reduce Packaging Impacts

The reduction in packaging-related impacts constitutes a key dimension of circular design. From an eco-design perspective, priority strategies include mass reduction, the use of mono-material solutions, and improvements in recyclability, while avoiding complex configurations that hinder separation and end-of-life processing. Recent literature on recyclable-by-design mono-material packaging reinforces the idea that material compatibility must be addressed at the design stage, particularly when barrier properties and recoverability are required simultaneously [88]. Furthermore, recent evidence indicates that mono-material solutions can improve certain environmental indicators; however, their

advantages depend strongly on production scenarios and end-of-life conditions and should therefore not be assumed to be universally superior [55,126].

A second line of action relates to reuse and, in specific contexts, to compostable or bio-based alternatives, provided that their evaluation is grounded in a systemic perspective rather than simplified assumptions. Recent comparative studies show that reusable systems can offer environmental advantages; however, their performance critically depends on factors such as the number of use cycles, return logistics, cleaning processes, and real operating conditions [30,56]. Additionally, reviews on materials and properties of reusable packaging emphasise that material suitability for repeated use cannot be taken for granted, as it depends on degradation, contamination, and cumulative washing effects [55].

3.2. Impacts of Product Design Strategies

The implementation of product design strategies has had transformative impacts across multiple dimensions, ranging from how products are manufactured to how consumers interact with them, and their long-term environmental and economic implications. This section examines these impacts in detail, focusing on the most representative cases and the associated challenges. A generalised overview of both positive and negative impacts is presented in Figure 8.

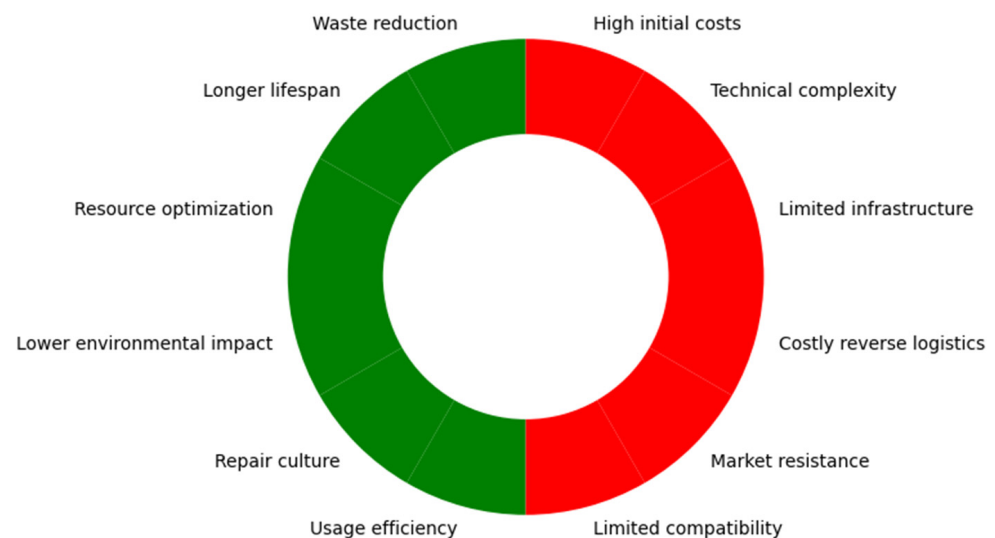


Figure 8. Positive and negative impacts of product design strategies for responsible production and consumption.

3.2.1. Environmental Impacts

Figure 9 presents a comparative assessment of five product design strategies using two complementary indicators: relative carbon footprint (panel a) and resource savings (panel b). The data reveal that circular economy strategies achieve the highest environmental benefits, reducing the carbon footprint by 55% (to 45% of the conventional design baseline) and generating 60% in resource savings through closed-loop material recovery systems and design for disassembly [34]. Eco-design achieves moderate reductions of 35% in carbon footprint and 35% in resource savings through material optimisation and energy efficiency improvements during the use phase [35,57], while modularity and design for longevity offer intermediate benefits with 50% and 45% carbon footprint reductions, respectively, primarily through extended service life and component replaceability [33,36].

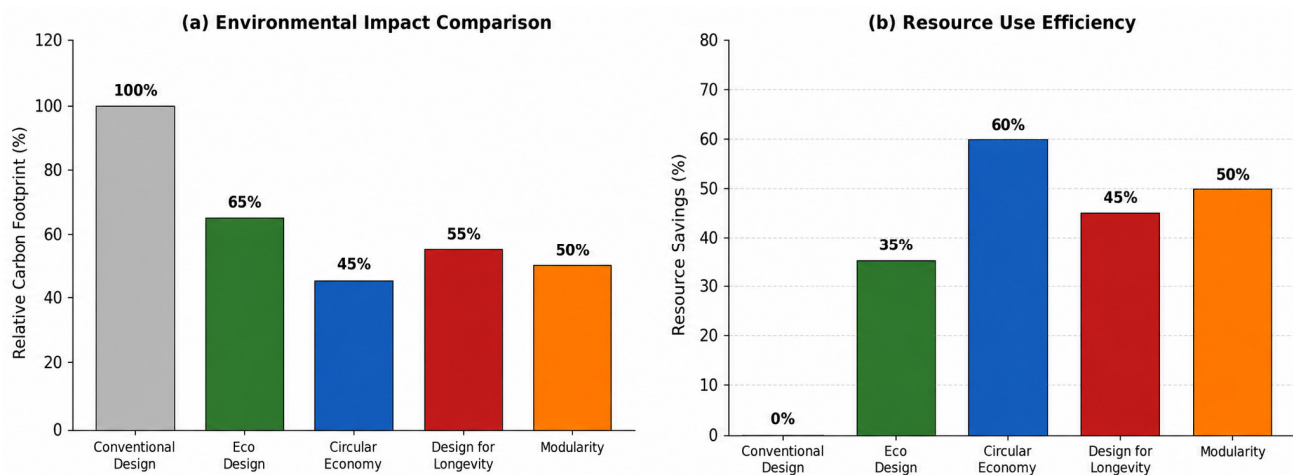


Figure 9. Comparative assessment of the environmental impact of different strategies. (a) Environment impact comparison, (b) resource use efficiency.

These findings demonstrate that strategy effectiveness varies significantly across implementation contexts and infrastructure availability. While circular economy approaches have significant potential, they require complex reverse logistics systems [91], whereas design for longevity and modularity offer more accessible alternatives in contexts with limited resources. The values represent sectoral averages derived from peer-reviewed LCA studies, with actual performance depending on product category, energy intensity, and local waste management conditions [37]. Importantly, combining multiple strategies can generate synergistic effects that exceed the sum of individual reductions, suggesting that integrated approaches should be prioritised in sustainable product development [34].

Circular design strategies have the potential to address some of the most pressing environmental challenges of the 21st century, including pollution and resource overexploitation. In this context, two key aspects are particularly relevant: reducing carbon emissions and promoting closed-loop resource flows.

Carbon Emission Reduction

Among European countries that have recorded the most significant reductions in greenhouse gas emissions in recent years, and where a clear link to product design strategies can be documented, Luxembourg, Finland, and Germany stand out. In Luxembourg, the 27.3% reduction observed in 2023 compared to pre-pandemic levels has been associated, among other factors, with the consolidation of circular design approaches in the construction sector, particularly through the use of material passports, design for disassembly, and component reuse [78].

In Finland, the 22.8% decrease has coincided with greater adoption of eco-design strategies to reduce material and energy consumption and extend the lifespan of industrial products [79]. Meanwhile, in Germany, where emissions were reduced by 15.4%, the application of design for remanufacturing to engines and industrial components has helped lower both material and energy demand [135].

Taken together, these cases suggest that circular-oriented product redesign represents a technically relevant pathway for supporting emission mitigation.

Closed-Loop Resource Flows

Effective management of closed-loop resource flows not only helps reduce environmental impacts but also ensures a more sustainable, long-term availability of materials, a critical aspect in addressing resource scarcity [114].

The environmental impact of design strategies can be further understood by integrating the data and strategy groupings proposed [91] with the design practices identified in this study, as illustrated in Figure 10. This relationship allows for the quantitative assessment of environmental performance through key indicators such as Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Particulate Matter Formation (PMF), Resource Depletion (RD), and Water Consumption (WC). Figure 10 presents a comparative analysis demonstrating that the environmental impact of these design practices is significant when evaluated through these metrics.

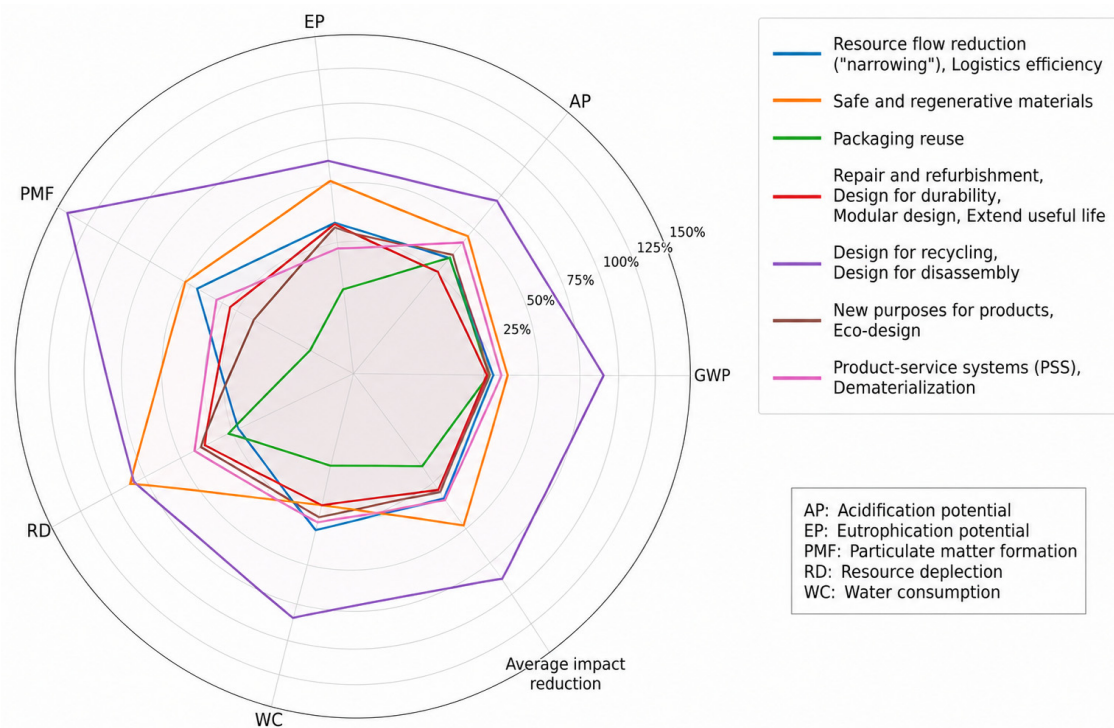


Figure 10. Percentage reduction in environmental impacts and key indicators achieved through the proposed design practices.

Figure 10, presented as a radar chart, illustrates that the evaluated design practices exhibit differentiated impacts depending on the environmental indicator considered, revealing a non-uniform level of effectiveness among them. From a comparative perspective, certain strategies achieve higher percentage reductions in global indicators such as Global Warming Potential (GWP) and Resource Depletion (RD), suggesting a strong effectiveness in mitigating impacts associated with intensive material and energy use. In contrast, other indicators, such as Water Consumption (WC) and Particulate Matter Formation (PMF), show more moderate reductions, indicating that not all strategies address environmental dimensions with the same intensity. This pattern demonstrates that design strategies do not operate in isolation or uniformly; rather, their impact depends on the type of intervention (e.g., recycling, modularity, or eco-design) and the specific indicator assessed. Overall, the chart suggests that the most effective solutions are those that integrate multiple design approaches, as they achieve a more balanced reduction across different indicators, thereby reinforcing the need to adopt systemic approaches to maximise environmental performance in the design process.

3.2.2. Impacts on Consumption Habits

Consumer behaviour plays a central role in the success of the circular economy (CE). In this regard, the present study has focused on exploring design strategies that promote

circular consumer behaviour, as discussed in previous sections, and on illustrating their effectiveness through representative examples.

The deposit and refund system implemented in Sweden is a notable example of how closed-loop resource strategies can foster circular habits. This approach, based on incentivising the return of beverage containers through a reward system, has achieved a return rate of approximately 85% [141], demonstrating its effectiveness in promoting responsible behaviour and reducing waste. Its positive impact extends beyond recycling rates, fostering active consumer awareness of waste reduction. The act of returning containers becomes a tangible form of participation in the circular economy, reinforcing the idea that products retain value beyond their initial use. Moreover, such systems function as educational tools, helping consumers understand how their individual actions contribute to broader sustainability outcomes and how consumption and disposal decisions directly affect system-level performance.

Similarly, in the textile industry, design for reuse has significantly influenced consumption habits. Design for disassembly stands out as a relevant strategy, enabling garments to be dismantled and reassembled, thereby increasing both functionality and perceived value. A recent study [141] reported that 18 garments designed under this approach were used an average of 198 times across three participants, compared to a previous average of 11 uses per garment, far exceeding initial expectations. These findings not only validate the effectiveness of design for disassembly in extending product lifespan but also highlight its potential to address key issues such as overconsumption and rapid obsolescence driven by changing fashion trends.

Furthermore, the study emphasises that emotional durability may be even more influential than physical durability in counteracting the premature disposal of textile products. Consumers who develop an emotional connection with their garments are more likely to repair, adapt, or redesign them rather than discard them. This suggests that adding both functional and emotional value is essential to mitigating the effects of hedonic consumption and encouraging more sustainable practices. For instance, designing garments and accessories that can be reconfigured or personalised after disassembly not only reduces consumer costs but also fosters a deeper and more enduring relationship between users and products.

3.2.3. Economic Impacts: Job Creation and Competitiveness

Circular design strategies drive economic development by creating new opportunities for businesses and fostering innovation. According to projections by Gomes [38], the transition toward circular models could generate up to 18 million jobs and increase global economic output by approximately 4.5 billion dollars by 2030.

Table 5 presents a synthesised overview of the principal economic implications associated with product design strategies that promote responsible consumption. Each strategy is examined through a balanced lens, considering both its potential positive contributions and its possible negative impacts or operational risks. In addition, the table situates these strategies within the supporting scientific literature, thereby providing an evidence-informed perspective on their practical and economic relevance. The table highlights that while responsible design approaches can generate substantial value in terms of resource efficiency, product longevity, and market innovation, their implementation may also involve technical, financial, and organisational challenges that must be carefully addressed.

Table 5. Economic impacts of product design strategies for responsible consumption, evaluated according to their impact balance, operational risks, and hierarchy of scientific evidence.

Strategy	Positive Impacts	Negative Impacts/Risks	Ref.
Durability	Extends product life; reduces waste and resource extraction	Higher initial cost; potential technological obsolescence	[4]
Repairability	Facilitates maintenance; creates jobs in technical services	Increased design complexity; conflicts with warranties	[9]
Modularity	Enables partial upgrades; supports customisation	Compatibility costs; structural complexity	[127]
Eco-design for recycling	Enhances material recovery; reduces environmental impact	Requires infrastructure; material limitations	[6]
Circular economy/product-as-a-service (PaaS)	Reduces total production; optimises product use	Costly reverse logistics; potential rebound effects	[58]
Design for Sustainable Behaviour (DfSB)	Reduces water/energy consumption; promotes environmental awareness	May be ignored by users; information overload	[7]
Eco-labelling/green communication	Improves informed decision-making; supports green markets	Risk of greenwashing; consumer confusion	[25]
Emotional durability	Increases user attachment; delays product replacement	Potential emotional manipulation; not applicable across all sectors	[5]
Sustainable packaging	Reduces packaging waste; optimises transport efficiency	Redesign costs; technical barriers	[34]
Remanufacturing	Reduces demand for raw materials; lowers environmental footprint	Recovery costs; quality control challenges	[26]

3.3. Challenges in the Implementation of Product Design Strategies

The implementation of product design strategies oriented toward sustainability and responsible consumption is conditioned by a set of multilevel determinants that transcend the strictly technological domain and respond to complex systemic dynamics. These determinants encompass organisational, financial, infrastructural, regulatory, technological, knowledge-based, and sociocultural dimensions, whose interaction shapes both the opportunities and the constraints for the effective adoption of circular design approaches. In this context, uncertainty associated with profitability and return on investment emerges as a critical factor at the organisational level, limiting strategic decision-making and the integration of sustainability into corporate governance processes. This phenomenon highlights the need to reconfigure business decision-making frameworks by incorporating sustainable performance metrics and strengthening strategic leadership as a necessary condition for advancing toward more resilient production models aligned with the principles of the circular economy [137].

From a financial perspective, high initial costs constitute a significant constraint on long-term investments, underscoring the importance of risk-adjusted financial mechanisms and green public procurement schemes, as widely documented in studies on circular economy and sustainable finance [125]. In terms of infrastructure, the fragmentation of logistics systems leads to operational inefficiencies and increased costs, underscoring the need to strengthen reverse logistics and waste management networks as key pillars of circular models [145].

At the regulatory level, policy gaps and slow implementation processes hinder the green transition, aligning with evidence that underscores the importance of coherent regulatory frameworks and their effective enforcement to accelerate sustainable innovation [45]. Finally, within the social and market dimensions, low demand for sustainable

products is recognised as a key bottleneck, justifying interventions focused on evidence-based awareness campaigns, economic incentives, and transparency mechanisms, such as environmental labelling, strongly supported by research on sustainable consumer behaviour [46].

Overall, the transition toward responsible consumption requires coordinated interventions across organisational governance, financial instruments, circular infrastructure, public policy, and demand activation, forming a systemic approach aligned with contemporary sustainability and circular economy frameworks.

Table 6 provides a structured overview of the main challenges associated with implementing product design strategies to promote responsible consumption. The identified barriers are organised by category, including financial, infrastructural, governmental, technological, knowledge-related, social, market, and organisational dimensions. For each limitation, the table also outlines a corresponding primary solution from the scientific literature, thereby offering an evidence-based framework for understanding both the obstacles to implementation and the pathways to overcoming them. The table underscores that the transition toward more responsible and sustainable design practices depends not only on technical innovation but also on supportive policy frameworks, institutional capacity, market transformation, and interdisciplinary knowledge development.

Table 6. Challenges in implementing product design strategies to promote responsible consumption.

Category	Barrier/Limitation	Primary Solution	Ref.
Financial	High material costs for sustainable alternatives, low profit margins, and certification costs	Government subsidies and tax incentives; green public procurement; improved environmental accounting	[59,92]
	Lack of working capital for SMEs; high startup costs for circular systems	Extended producer responsibility schemes; circular business models; shared financial risk mechanisms	[92]
Infrastructural	Inadequate reverse logistics, lack of recycling facilities, and missing waste collection systems	Investment in waste-to-resource infrastructure; industrial symbiosis networks; localised supply chains	[25]
	Lack of material marketplaces; fragmented supply chains	Digital Product Passports (DPPs); blockchain traceability; collaborative platforms	[39]
Governmental	Inaction and lack of favourable legislation; inconsistent global standards	Mandatory eco-design regulations; international standardisation; right to repair legislation	[92]
	Weak enforcement of extended producer responsibility; lack of CE-favourable taxation	Performance-based taxation; landfill diversion charges; public procurement criteria	[129]
Technological	Lack of suitable tools for designers; data intensity of LCA; interoperability issues	Simplified assessment tools; BIM integration; AI-driven design optimisation	[60]
	Data standardisation challenges for Digital Product Passports: legacy system integration	Open data standards; incremental implementation; sector-specific protocols	[39]
Knowledge/Skills	Lack of design expertise in circular strategies; insufficient CE education	University curriculum integration; professional training programmes; industry–academia partnerships	[105]

Table 6. *Cont.*

Category	Barrier/Limitation	Primary Solution	Ref.
Social/Market	Low consumer valuation of circular products; perception of lower quality	Consumer education campaigns; clear warranties; marketing of economic benefits	[121,132]
	Global market barriers: Inconsistent regulations across regions	Regional supply chain localisation; international harmonisation of standards	[132]
Organisational	Unclear link to profitability; lack of top management support	Strategic integration of DfS; leadership commitment; clear sustainability KPIs	[115,122]
	Difficulty handling trade-offs between sustainability and performance	Multi-criteria decision tools; design for X approaches; life cycle thinking integration	[87,116]

The transition toward a circular economy (CE) presents significant challenges that go beyond product or service redesign and require profound transformations across economic, social, cultural, and technological systems. Companies and designers must overcome complex barriers in order to effectively implement design strategies, business models, and innovative approaches aligned with circular principles.

3.3.1. Structural and Regulatory Limitations

The fragmentation of value chains, inadequate infrastructure, and outdated regulatory frameworks hinder the efficiency and scalability of circular systems. Gomes et al. [9] highlight that cooperation among key actors within value chains remains limited, with only a small proportion of companies (15%) having established the necessary collaborations to implement effective circular strategies. This reflects the difficulty of aligning interests and sharing responsibilities within complex business networks.

Inadequate infrastructure represents another major challenge, as many regions lack facilities for collecting, sorting, repairing, and redistributing products. This issue is particularly evident in industries such as fashion and electronics, where linear systems continue to dominate. In the Fast Fashion sector, for instance, collection and recycling processes remain insufficient to manage the high volume of discarded products [141].

Regarding inconsistent regulatory frameworks, existing legal systems are often not designed to support the circular economy (CE). The lack of appropriate regulatory incentives or subsidies slows down the transition toward circular models [93], particularly in emerging markets and in highly regulated sectors such as food and energy.

3.3.2. Costs and Technological Barriers

The implementation of circular strategies often entails substantial investments in technology, workforce training, and product redesign, which can be financially challenging and, in some cases, insufficiently profitable for many companies. Transitioning from a linear to a circular model typically involves high costs associated with infrastructure, research and development (R&D), and capacity building [5]. For small- and medium-sized enterprises, these requirements can be particularly difficult to meet, especially when short-term returns are uncertain or not clearly defined [80].

In addition, technological barriers remain a significant constraint. Key enabling solutions, such as design for disassembly, advanced chemical recycling, and digital tracking systems, are not yet widely accessible or fully mature across industries [81]. This limited availability not only restricts the practical implementation of circular design strategies

but also increases operational costs and, in many cases, places circular approaches at a competitive disadvantage compared to established linear systems.

3.3.3. Complexity in Product Design and Business Models

Implementing circular design strategies requires a systemic approach that balances sustainability objectives with commercial viability, a challenge compounded by multiple interacting factors. Designing for multiple life cycles, for instance, involves creating products capable of functioning across different stages, such as repair, reuse, or recycling, while integrating objectives that may at times be conflicting. For example, a design that promotes strong emotional attachment may conflict with the need for easy disassembly to enable efficient recycling [61].

Another factor that adds complexity is the rebound effect. If not carefully managed, strategies intended to improve sustainability can lead to unintended outcomes. Products designed to be repairable, for example, may encourage increased consumption if users perceive them as having a lower environmental impact [134].

Additionally, the lack of practical frameworks and tools to support the application of these approaches further complicates their implementation [95]. This limitation makes it difficult for companies and designers to systematically adopt and scale product designs aligned with the CE principles.

3.3.4. Social and Cultural Barriers

Consumer behaviour is a decisive factor in the effective implementation of design strategies aligned with the CE; however, its adoption is often constrained by barriers related to attitudes, values, and perceptions. Several studies indicate that a significant proportion of consumers do not fully understand the fundamental principles of the circular economy, which limits their willingness to engage in sustainable initiatives [96]. This challenge is further reinforced by scepticism toward corporate sustainability practices, particularly when they are perceived as instances of greenwashing—superficial actions aimed at projecting an environmentally responsible image without substantive changes in production processes [82]. As a result, recycled or repaired products may generate distrust, often due to limited information about their quality and unclear evidence of their environmental benefits. Addressing this issue requires not only educational efforts to correct misconceptions but also the implementation of transparent, verifiable mechanisms that enhance the credibility of companies' sustainability claims [82].

Even among consumers who express interest in sustainable products, a persistent gap between intention and actual behaviour remains, hindering the consolidation of circular practices [62]. This discrepancy is influenced by factors such as lack of convenience, insufficient economic incentives, and infrastructural limitations that make actions like recycling, reuse, or product return less accessible. Thus, even when a favourable disposition exists, the absence of user-friendly systems, such as efficient collection points or clear, understandable information, reduces active participation [117]. Similarly, social and emotional values associated with sustainability do not always translate into concrete actions, particularly when circular solutions are perceived as less practical than conventional alternatives [97]. Bridging this gap requires integrated strategies that combine financial incentives, improved infrastructure, and effective communication to highlight both the functional benefits and the environmental and social value of circularity.

3.4. Future Lines

The future of circular design strategies lies in a set of perspectives that address both technological and cultural transformation, with the aim of fostering more sustainable consumer behaviour. As the circular economy continues to expand and evolve, the scien-

tific literature highlights emerging directions that can encourage consumer behavioural shifts, ultimately supporting a successful transition toward more circular and sustainable consumption systems.

3.4.1. Digital Transformation and Adaptive Regulatory Frameworks

From a long-term perspective, digitalisation and the integration of emerging technologies are expected to play a pivotal role in advancing the circular economy. Recent studies suggest that tools such as a circular readiness index could be scaled at both global and sectoral levels, enabling a more nuanced and practical assessment of how prepared companies are to adopt circular practices [63].

At the same time, the development of more efficient data management systems, together with adaptive and responsive regulatory frameworks, can help ease the transition toward circular models. These elements are not only important from a technical standpoint but also contribute to aligning economic competitiveness with job creation and broader social well-being [60]. Digital and regulatory advancements are likely to act as enablers, helping the circular economy move from a conceptual framework to a more widely implemented and impactful model for transforming consumption systems.

3.4.2. Cultural Change and Integrated Interdisciplinary Models

The transition toward a circular economy should not be limited to technical innovations or isolated improvements in process efficiency, but rather requires a profound cultural shift that places people at the centre of systemic transformation [44]. From this perspective, it becomes essential to adopt integrated, interdisciplinary models that incorporate psychological, social, and environmental variables into the design of products, services, and strategies for responsible production and consumption. This approach acknowledges that consumer decisions are not driven solely by functional or economic attributes, but also by values, habits, social norms, trust perceptions, and institutional contexts that shape everyday behaviour.

Consumer behaviour remains an underdeveloped dimension within circular economy research, despite its strategic importance in activating practices such as reuse, repair, repurchase, and recycling [82]. Moreover, the acceptance of circular solutions has been shown to depend heavily on access to clear, reliable information, particularly in contexts where doubts persist about the quality or performance of such products [115]. In this regard, further emphasis is needed on how a people-centred perspective enables the design of more effective systems to influence consumer decisions and actions, recognising that circularity involves reshaping deeply embedded socio-material relationships rather than simply introducing new products to the market [64].

Complementary studies also highlight that consolidating circular markets requires a broader understanding of consumer perceptions, barriers, and motivations, as well as the roles of individual agency and institutional structures in shaping the adoption and valuation of sustainable practices [83].

3.4.3. Consumer Education and Participation

Education is consistently highlighted in the scientific literature as a key enabler of circular practices. Universities and educational institutions play a crucial role not only in generating knowledge but also in shaping behaviours aligned with the circular economy. In this context, it is increasingly recommended that educational programmes incorporate circular economy principles into their curricula and encourage students to actively participate in circular initiatives [84]. At the same time, a deeper understanding of consumer values and motivations is needed to design more effective strategies that promote engagement in circular systems, particularly those that integrate social, emotional, and convenience-related

factors [97]. These educational and participatory approaches can contribute to broader acceptance and long-term adoption of circular practices among younger generations.

Furthermore, it is important to recognise that each of the perspectives discussed is closely linked to the challenges identified in this study. This representation helps clarify how current barriers connect to future solutions and opportunities, emphasising the need for comprehensive approaches that address structural, technological, regulatory, cultural, and social dimensions simultaneously.

Table 7 synthesises the scientific literature on future perspectives for integrating artificial intelligence into product design, development, and production processes, while Table 8 highlights broader technological contributions to promoting responsible production and consumption. Looking ahead, the 2025–2032 horizon points toward a transformative convergence of advanced artificial intelligence, digital twins, the Internet of Things (IoT), and additive manufacturing technologies. Together, these innovations are shaping a new paradigm for product design oriented toward responsible consumption, with the potential to overcome current limitations of sustainable design strategies by enabling truly adaptive, predictive, closed-loop life cycle systems [99].

Table 7. Future perspectives of product design strategies to promote sustainability.

Strategy	Future Perspectives	Role of AI	Ref.
Durability	Advanced materials (nano and self-monitoring); LCP design.	AI predicts failures and optimises preventative maintenance.	[4]
Repairability	AR/VR for repair guides; service economy.	Computer vision identifies damage and suggests repairs.	[9]
Modularity	Universal platforms; module updates.	Generative design creates modules optimised for AI.	[127]
Recycling/Eco-design	Life cycle simulation; new materials.	AI classifies waste and optimises recycling processes.	[6]
Circular economy/PaaS	Massive digital services; usage economy.	IoT and ML improve collection and redistribution routes.	[58]
Design for behaviour	Smart interfaces; sustainable gamification.	AI personalises suggestions based on user profile.	[7]
Labelling/Communication	Interactive digital tags (blockchain).	AI validates authenticity and communicates life cycle to the user.	[25]
Emotional durability	Personalised narratives; massive co-design.	AI generates tailored experiences to strengthen attachment.	[5]
Packaging/Eco-design	Bioplastics of optimal design; eco-friendly 3D printing.	AI optimises packaging design to minimise material.	[34]
Remanufacturing	Standard second-life ecosystems.	AI diagnoses product condition for safe reuse.	[8]

Table 8. Future perspectives are supported by technological advancements in product design strategies to promote sustainability.

Technology	Development Timeline	Primary Application	Impact on Responsible Consumption	Key Enablers	Barriers	Ref.
Generative AI & Deep Learning	2025–2028	Multi-objective design optimisation; sustainable material selection	25–40% improvement in eco-efficiency metrics; automated design for disassembly	Cloud computing; big data analytics; simulation tools	Data quality; model explainability; computational cost	[41,92]

Table 8. Cont.

Technology	Development Timeline	Primary Application	Impact on Responsible Consumption	Key Enablers	Barriers	Ref.
Digital Twins (DTs)	2024–2027	Real-time life cycle monitoring; predictive maintenance; end-of-life optimisation	30–50% extension of product lifespan; 20–35% reduction in resource consumption	IoT sensors; cloud platforms; AI analytics	Interoperability; data security; standardisation	[65,100,119]
IoT-enabled AI (BiLSTM and GNN)	2025–2029	Real-time eco-efficiency optimisation; energy consumption prediction	23.5% improvement in energy efficiency; 97.6% prediction accuracy for sustainability metrics	Edge computing; 5G connectivity; sensor networks	Sensor reliability; real-time processing; cybersecurity	[45,92]
Blockchain for Supply Chain	2026–2030	Transparent material provenance; circular supply chain tracking; Digital Product Passports	40–60% increase in consumer trust; 25% improvement in reverse logistics efficiency	Distributed ledger tech; smart contracts; IoT integration	Scalability, energy consumption, and regulatory frameworks	[42,66]
Additive Manufacturing (3D Printing)	2024–2028	On-demand production; localised manufacturing; spare part fabrication	50–90% material waste reduction; 40% decrease in transportation emissions; extended product life via repair	Advanced materials; design software; distributed manufacturing networks	Surface quality, production speed, and material limitations	[67,107,123]
Industry 5.0 (Human-centric)	2027–2032	Collaborative human–robot manufacturing; personalised sustainable production	30–45% reduction in overproduction; enhanced worker wellbeing; mass customisation with minimal waste	Cobots; AI assistants; sustainable manufacturing frameworks	Skills gap; safety standards; cultural adaptation	[43,68,124]
Machine Learning for Circular Maturity	2025–2028	Genetic algorithms for supply chain optimisation; predictive analytics for circularity	15–25% cost reduction in circular operations; optimised resource allocation	Historical data; algorithm development; cloud infrastructure	Algorithm bias; data privacy; integration complexity	[44,108]
AI-driven Material Informatics	2028–2032	Discovery of sustainable materials; biodegradable polymer design; recyclability prediction	50–70% faster material innovation; 30% improvement in recyclability rates	Materials databases; quantum computing; molecular modelling	Experimental validation; industrial scaling; cost	[69,101]

Emerging digital technologies are redefining eco-design by enabling predictive, adaptive, and fully integrated approaches across the entire product life cycle. In this context, generative artificial intelligence and deep learning are emerging as particularly promising tools, as large language models and generative adversarial networks allow the exploration of complex design spaces where energy efficiency, sustainable material selection, manufacturability, and aesthetic criteria can be balanced simultaneously. Recent evidence shows that genetic algorithms and multi-objective optimisation can improve energy and thermal

performance in sustainable architecture by between 23% and 28% [41], while BiLSTM models integrated with real-time IoT data have achieved prediction accuracies of up to 97.6% for sustainability parameters, with energy efficiency improvements of 23.5% [92].

In addition, digital twins, understood as virtual replicas of physical assets, play a central role by enabling real-time simulation, monitoring, and optimisation of environmental performance. Their integration with IoT sensors, big data, and energy management systems supports more efficient resource use, reduced emissions, predictive maintenance, and extended product lifespans, with reported reductions of 20% to 35% in resource consumption in energy-intensive industries [65,100,119,137].

Similarly, AI-enabled IoT systems enable continuous data collection on real product usage, while graph neural networks and attention-based models facilitate early anomaly detection and failure prediction. These capabilities contribute to reducing premature replacements and minimising waste, reinforcing the role of advanced digital technologies as key enablers of more sustainable and circular design strategies [106].

Complementarily, other technologies such as blockchain, additive manufacturing, Industry 5.0, machine learning for circular maturity, and AI-driven materials informatics are significantly expanding the potential of design for sustainability. Blockchain is increasingly recognised as an enabler of traceability and transparency in circular supply chains, allowing the immutable tracking of materials, strengthening supply chain integration, and supporting the development of Digital Product Passports that contain information on composition, repair, and recycling [42,66]. Additive manufacturing, in turn, has evolved into a more sustainable production alternative by reducing material waste by 50–90%, lowering transportation emissions through localised production, and enabling decentralised manufacturing of spare parts that extend product lifespans [67,85]. At the same time, Industry 5.0 promotes human–machine collaborative systems oriented toward sustainability, resilience, and customisation, helping to reduce overproduction [68,124]. In parallel, machine learning applied to circular economy processes supports the optimisation of disassembly, reverse logistics, recycling systems, and financial return assessments [44,108]. Likewise, materials informatics accelerates the discovery and development of biodegradable, recyclable, and sustainable materials, contributing to more efficient material cycle closure [69,101].

Taken together, this technological convergence, conceptualised as a Sustainable Twin System, has the potential to reduce the overall environmental impact of products by 60–80% by 2035 [99]. However, its adoption still faces important challenges, including interoperability issues, data security and privacy concerns, the need for standardised protocols, the development of specialised talent, and the energy consumption associated with technologies such as artificial intelligence and blockchain. These limitations highlight the need for a “sustainability of technology” perspective when advancing digital solutions for sustainability [119].

4. Discussion

4.1. Environmental Impact and Reduction in Ecological Burdens

The findings of this review suggest that product design strategies should not be understood as isolated technical decisions, but rather as interventions with measurable environmental consequences across the product life cycle. In this sense, design becomes a critical lever for influencing key sustainability indicators such as carbon footprint, resource consumption, and the effectiveness of closed-loop material systems. This perspective allows for a more robust linkage between product design and standardised environmental metrics, enabling more consistent and comparable evaluations of sustainability performance. Evidence indicates that circular economy strategies offer the greatest potential to reduce ecological burdens, with reported reductions of up to 55% in carbon footprint and 60% in

resource use [34]. These results position circular design not only as an environmental improvement approach but as a systemic mechanism for decoupling production from resource depletion. Similarly, strategies such as eco-design and modularity contribute to impact reduction through material optimisation, energy efficiency, and extended product lifespans, although their effectiveness is strongly influenced by contextual factors such as energy intensity, product category, and waste management systems [35,37,57]. However, the results also highlight that the environmental performance of design strategies varies across contexts. While circular approaches demonstrate the greatest theoretical benefits, their real-world effectiveness depends heavily on the availability of supporting infrastructure, particularly reverse logistics systems and material recovery networks [90]. This implies that even well-designed products may not achieve their intended environmental benefits if they are implemented within systems that are not prepared to support circular flows.

In contrast, strategies such as durability and modularity emerge as more accessible and scalable alternatives, especially in regions where circular infrastructure is still underdeveloped [109]. By extending product lifespan and enabling partial upgrades or repairs, these approaches provide incremental yet meaningful reductions in environmental impact. From a practical standpoint, they represent viable entry points for organisations seeking to transition toward more sustainable models without requiring immediate systemic transformation.

At the same time, an important tension becomes evident between different design objectives. Enhancing durability by using more robust or complex materials can inadvertently reduce recyclability, particularly in multi-material configurations or with permanent bonding techniques [88]. This reveals that sustainability in product design is not achieved through the isolated optimisation of individual strategies, but through the careful management of trade-offs.

These findings reinforce the idea that sustainable product design requires a holistic and multi-criteria approach. Designers must balance durability, repairability, and recyclability while considering the broader system in which the product operates. The reduction in ecological burdens, therefore, depends not only on the design of the product itself but on its alignment with infrastructure, user behaviour, and recovery systems, highlighting the inherently systemic nature of sustainability.

4.2. Integration of the Circular Economy into the Product Life Cycle

A key insight of this study is that the circular economy must be integrated into the product life cycle as a coherent and systemic design approach rather than as a set of isolated strategies. The organisation of design interventions into interconnected dimensions, such as lifespan extension, post-use value recovery, transformation of provision models, influence on user behaviour, and reduction in packaging impacts, demonstrates that circularity emerges from decisions distributed across the entire life cycle. In this sense, design becomes a strategic driver that defines the environmental and functional performance of products from the earliest stages, supported by evidence on durability, repairability, remanufacturing, and service-based models [4,71,88].

The findings reinforce that circularity cannot be addressed at the end of a product's life; it must be embedded in the design phase. Decisions related to materials, interfaces, tolerances, and disassembly determine whether products can be repaired, reused, or remanufactured [103,143]. Moreover, a critical distinction arises between products designed for single recovery cycles and those capable of sustaining multiple cycles without functional degradation, which represents a more robust form of circularity [4,143]. At the same time, tensions between strategies, such as durability versus recyclability, highlight the need to manage trade-offs rather than assume inherent compatibility [88].

From a broader perspective, product-as-a-service (PaaS) models strengthen life cycle integration by aligning business incentives with circular design, extending responsibility beyond product sale and promoting maintenance, repair, and recovery [133]. However, these models may also generate rebound effects if increased efficiency leads to higher consumption levels [7]. Overall, integrating the circular economy into product life cycles requires a systemic, anticipatory approach that coordinates design, business models, and user behaviour to enable sustained value retention across multiple use cycles.

4.3. Consumer Behaviour and Acceptance of Circular Strategies

Another key aspect is the central role of consumer behaviour, which distinguishes the manuscript from studies that address sustainability solely from a product engineering perspective. The study appropriately highlights that the viability of the circular economy depends on real user decisions related to use, maintenance, return, repair, and disposal, and that these decisions are shaped by factors such as trust, understanding, convenience, and social values. This perspective is particularly relevant for publication, as it aligns with the recent literature that positions the user as an active agent within the system rather than as an external variable.

Furthermore, the discussion of eco-labelling, greenwashing, traceability, and digital product passports strengthens the article's contribution to the field of sustainability by integrating design, information, and behavioural governance into a unified analytical framework [28,48,64,77,118]. The inclusion of practical examples, such as the Swedish deposit–refund system and textile reuse initiatives, further enhances the applicability and transferability of the findings.

4.4. Use of Emerging Technologies and AI

An important contribution to this review lies in integrating emerging technological enablers as key drivers of sustainable product design. The incorporation of technologies such as artificial intelligence, digital twins, Internet of Things (IoT), blockchain, additive manufacturing, and Industry 5.0 positions the discussion at the forefront of contemporary sustainability research. Rather than presenting technology as an end in itself, the analysis emphasises its role as an enabling layer that supports eco-efficiency, predictive maintenance, life cycle optimisation, and enhanced transparency. This perspective is particularly relevant, as it demonstrates that the transition toward sustainable products increasingly depends on the convergence of design strategies with intelligent and data-driven systems [45,92,99].

Emerging technologies are reshaping how sustainability is embedded into product design by enabling continuous monitoring, analysis, and optimisation across the entire life cycle. Tools such as IoT systems, artificial intelligence, and digital product passports allow for real-time data collection and decision-making, facilitating more adaptive and responsive design processes [28,49]. In particular, artificial intelligence stands out for its capacity to process large volumes of data, identify patterns, and generate predictive insights that enhance decision-making throughout the product life cycle. AI models, such as deep learning architectures and predictive algorithms, enable failure prediction, optimisation of material selection, and improve energy efficiency, contributing to more sustainable and resilient design solutions [92]. This evolution represents a shift from static design approaches to dynamic systems in which product performance, maintenance needs, and environmental impact can be actively managed during use.

However, despite their transformative potential, the implementation of these technologies remains uneven. A significant gap persists between technological capabilities and their practical adoption, largely due to barriers related to cost, interoperability, data integration, and the lack of standardised frameworks [86]. As a result, many of these solutions are cur-

rently concentrated in specific sectors or large-scale industrial contexts. This highlights that the effective contribution of emerging technologies, particularly artificial intelligence, to sustainability depends not only on technological advancement but also on the development of supportive ecosystems, including regulatory frameworks, data governance models, and organisational capabilities. Overall, the integration of emerging technologies into product design strategies reinforces the transition toward more intelligent, connected, and circular systems, while also underscoring the need to address structural challenges to fully realise their sustainability potential.

4.5. Critical Implications and Perspectives on Sustainable Design

Overall, the results of this review demonstrate that progress toward sustainable production and consumption models depends not only on the development of design strategies, but also on their alignment with systemic conditions, infrastructures, and social dynamics. Despite conceptual advances in circular design, remanufacturing, and product-as-a-service models [47,97,143], limitations persist regarding the comparability of results due to methodological heterogeneity in life cycle assessment (LCA) studies [34,37], as well as in the empirical validation of these strategies in real-world contexts.

Furthermore, the evidence suggests that many behaviour-oriented interventions yield results based on intention rather than actual usage, which, together with phenomena such as the rebound effect, calls into question their real impact on consumption reduction [7]. Additionally, the increasing use of enabling technologies—such as artificial intelligence, the Internet of Things (IoT), and blockchain—introduces new tensions related to their environmental cost and to challenges in implementation, interoperability, and scalability [42,99,119].

In this context, sustainable design must evolve toward integrative approaches that simultaneously consider technical performance, economic feasibility, and social acceptance, recognising that circularity emerges from the interaction between product, system, and user, rather than as an isolated property of the designed object. Therefore, there is a need to advance toward longitudinal, multiscale, and context-sensitive research that enables a more precise evaluation of the effectiveness, coherence, and net sustainability of the proposed strategies, thereby strengthening the empirical foundation for decision-making in sustainability-oriented design.

From a geographical perspective, the literature reveals an uneven distribution in the development and implementation of sustainable design strategies, strongly influenced by the level of industrialisation, infrastructure availability, and regulatory frameworks. European countries such as Germany, Finland, and Luxembourg stand out for more systematically integrating circular economy principles into product design, supported by public policies, technological capabilities, and advanced waste management systems [52,78]. In contrast, in many regions of the Global South, the adoption of these strategies faces structural limitations related to insufficient infrastructure, weak regulatory frameworks, and economic constraints, which condition their scalability and effectiveness. This asymmetry is also reflected in scientific production, where studies conducted in developed contexts predominate, while empirical evidence from developing countries remains limited, despite the significant pressures these regions face in terms of waste management and increasing consumption.

Additionally, cultural and social factors influence the adoption of circular practices, demonstrating that design strategies are not universally transferable but require adaptation to local contexts. In this regard, advancing toward global sustainability entails not only transferring technologies or models but also strengthening local capacities, adapting solu-

tions to specific realities, and fostering greater inclusion of diverse geographical contexts in both research and the application of sustainable design.

5. Conclusions

Sustainable design emerges as a structural pillar in the transformation of contemporary production and consumption systems, moving beyond fragmented approaches focused solely on materials, processes, or operational efficiency. The findings show that a product's sustainability depends on the coherent integration of principles such as durability, reparability, modularity, maintainability, reuse, and post-consumption value recovery. When these elements are considered from a life cycle perspective, they help reduce pressure on natural resources, extend product functionality, and minimise waste generation. In this context, design is no longer a purely technical or instrumental activity; it becomes a strategic capability that directly influences circularity, eco-efficiency, and the resilience of production systems. Ultimately, this reinforces the idea that achieving responsible consumption requires a profound rethinking of design's role as a bridge between innovation, environmental sustainability, and systemic transformation.

The evidence confirms that the transition toward circular practices depends not only on the availability of technical solutions but also on how these solutions interact with people's perceptions, values, habits, levels of trust, social norms, and real-life usage conditions. Persistent barriers, such as lack of awareness, scepticism toward environmental claims, limited convenience of circular systems, and the well-known gap between intention and action, highlight that sustainability cannot be treated as an inherent product attribute detached from user behaviour. In this sense, one of the main contributions of this study is showing that sustainable design must integrate technical performance with communication, traceability, symbolic value, and user experience. Only then can solutions be not only environmentally sound, but also understandable, acceptable, and viable in everyday contexts.

Looking ahead, the future of sustainable design will largely depend on aligning technological innovation, institutional governance, and cultural change within a shared transformation framework. Emerging technologies significantly expand the possibilities for monitoring, predicting, and optimising environmental performance; however, their full potential can only be realised when supported by coherent regulatory frameworks, adequate infrastructure, interoperable systems, specialised skills, and organisational readiness. For this reason, sustainability in design should not be seen as an automatic outcome of technological progress, but rather as a complex, multidimensional process that requires coordination among stakeholders, policy alignment, institutional strengthening, and a culture of responsible resource use. From this perspective, the main contribution of this study lies in demonstrating that the transition toward truly sustainable models will not be driven by isolated solutions, but by the consolidation of design ecosystems capable of integrating circularity, technological intelligence, economic viability, and social legitimacy. This interpretation not only strengthens the scientific relevance of the manuscript but also highlights its value for broader discussions on sustainability, innovation, and the future of responsible production.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life cycle assessment
DfSB	Design for Sustainable Behaviour
DfX	Design for X
PaaS	Product-as-a-sustainable
GWP	Global warming potential
AP	Acidification potential
EP	Eutrophication potential
PMF	Particulate matter formation
RD	Resource depletion
WC	Water consumption
CE	Circular economy
R&D	Research and development

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