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Integrating eco-design into e-clothing development: an eco-design toolkit framework for e-clothing iterative design

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As e-clothing development evolves rapidly, integrating sustainability into its design processes remains a major challenge. This study investigates how eco-design can be integrated throughout the e-clothing design and development process and the challenges that emerge at different stages of integration. Through a narrative review of academic and grey literature, integrated with semi-structured interviews with related experts in the e-clothing field, the research reflects on the interdisciplinary and iterative nature of e-clothing design, existing eco-design practices, and the limitations of current eco-design tools. It shows that while few eco-design strategies are discussed, their application for e-clothing remain limited. The overall eco-design integration into e-clothing workflows is challenged by early-stage uncertainty, textile and electronics integration conflicts, dual-sector regulatory misalignment, and communication gaps. The results suggest that sustainability considerations in e-clothing development span multiple stages and dimensions, and must be addressed through iterative, collaborative processes. Therefore, the paper presents a synthesized e-clothing workflow model with integrated eco-design intervention points and proposes corresponding eco-design toolkit, providing a methodological perspective that situates eco-design as a distributed, iterative practice evolving alongside e-clothing development.

KEYWORDS
design tools, e-clothing, eco-design, e-textiles, smart textiles, sustainability

1 Introduction

1.1 Defining e-clothing: concepts, origins, and system perspective

There are many terms in literature that are often used interchangeably to refer to textile, wearable and clothing with integrated technologies and high-performative functionalities: for instance "smart clothing" refers to a "smart system" that senses and responds to environmental and wearer conditions, mostly through textile performative augmentation (Cho, 2009); "e-textiles" are related to portion of textiles that are integrated with electronic components but not necessarily extended to entire garments (Stegmaier, 2012). Differently, this research adopts the term "e-clothing" to highlight textile-wearable technologies at the level of entire garment system that integrates electronic components such as sensors, actuators, batteries and circuits (Wang and Casciani, 2024).

The origins of e-clothing can be traced back to the broader field of wearable computing, with early experiments in the 1960s. These pioneering examples offered limited functionality and lacked seamless integration with textiles (Fernández-Caramés and Fraga-Lamas, 2018). A significant shift from "wearables" to "e-clothing" occurred alongside advancements on the Internet of Things (IoT) and the development of miniaturized, flexible sensors made from conductive yarns and inks (Ahsan et al., 2022), enabling electronics to be directly embedded into fabrics. This transition reflects a growing demand for more embedded seamless and flexible wearable system solutions.

Designing such a system solution means considering a cohesive and interconnected network of textiles and electronics. Researchers proposed a "system level" and "embedded system" design process for e-clothing (Lee, 2006; Sun and Kong, 2022), which emphasizes the multiple domains, such as fashion/clothing, hardware, and software engineering, and interaction design to connect the system to the user. These components collectively form a unified product system. E-clothing design requires a holistic approach. This means designers must look not only at individual components but also at how they function together to ensure overall performance, comfort, aesthetics, user experience, and sustainability (McCann, 2009).

1.2 Sustainability and eco-design gaps in e-clothing development

The current e-clothing development is tech-driven, focusing on technological innovation and advanced functions. In addition to this, environmental sustainability remains an underexplored dimension in e-clothing research and development (Sajovic et al., 2023). Sustainability is widely understood as a multidimensional concept encompassing environmental, social, economic, and cultural considerations (Purvis et al., 2018). Despite this broader understanding, current sustainability related study in e-clothing has been firstly addressed on environmental aspects with focus on material and end-of-life (EoL) challenging dimensions. Prior studies have highlighted that embedding electronics into textiles creates critical issues for recyclability, fabric-e-components coupling, and EoL management (Köhler et al., 2011).

In this context, a promising approach to mitigate prospective environmental risks is using a holistic approach that integrates a multidimensional perspective on sustainability into the entire lifecycle of e-clothing system through eco-design principles (Ceschin and Gaziulusoy, 2019; Köhler, 2013b; Ivanoska-Dacikj et al., 2024). Eco-design principles emphasize material minimisation, the selection of low environmental impact materials, lifespan optimisation, material life extension, and design for disassembly (Vezzoli and Manzini, 2008). Typical eco-design process includes LCA and/or qualitative environmental analysis of the reference product, setting environmental design priorities, eco-design-focused idea generation, analysis of the environmental strengths and weaknesses of concept alternatives, and comparative LCA of the final design vs. the reference product (Lewandowska and Kurczewski, 2010; Ceschin and Gaziulusoy, 2019).

However, integrating the eco-design process in the e-clothing development is facing challenges. Eco-design is effective at improving existing products, but less in generating new product concepts (Ceschin and Gaziulusoy, 2019). E-clothing is a new, rapidly emerging product category and has no reference products to compare with; therefore, conventional eco-design processes have no clear starting point. Then, conventional eco-design principles offer general operational guidance, and are limited to the specific integration challenges and material–functional trade-offs inherent in e-clothing.

Current literature and industry discourse on eco-design in e-clothing remain limited. Existing discussions tend to focus primarily on material selection, green manufacturing, or energy efficiency (Dulal et al., 2022; Gurova et al., 2020). Moreover, recent regulatory developments, such as the European Union's Ecodesign for Sustainable Products Regulation (2024) have not included the e-textile and e-clothing category yet. Key sustainable normatives for fashion and electronics (such as OEKO-TEX® Service GmbH, 1992, Global Organic Textile Standard, 2006, RoHS Directive, 2003, ErP, Waste From Electrical and Electronic Equipment (WEEE), 2002) focus on material safety, chemical restrictions, energy efficiency, and EoL management, but do not provide specific guidance for e-textiles or e-clothing.

To address these gaps, this study investigates the current e-clothing design process, identify opportunities and challenges for eco-design integration, and explores what kinds of eco-design tools are suitable for this integration. Section 2 outlines the methodology used in this study. Section 3 presents the results, which are further discussed in Section 4, and the article concludes with key insights in Section 5.

2 Methodology

The study is guided by the following research questions:

(1) How is framed the e-clothing design and development process, and what workflows does it involve?
(2) How can eco-design be integrated throughout the e-clothing design process, and what challenges emerge at different stages of integration?
(3) What eco-design tools can support eco-design principles integration for e-clothing?

This research adopts a qualitative, exploratory approach to examine the complexity and challenges of implementing eco-design in the context of e-clothing development through a narrative literature review (NLR) integrated with interviews with experts of e-clothing, and wearables field. The aim is to build a conceptual foundation for future eco-design supportive tools by identifying e-clothing design process and eco-design implementation challenges.

2.1 Literature review

The narrative literature review (NLR) has been adopted to offer a broad overview of a topic-related research area and include a wide variety of studies to provide an overall summary and deepen understanding (Greenhalgh et al., 2018; Sukhera, 2022). It is suitable for exploring emerging, interdisciplinary fields where the theoretical foundations are still being established. The aim of the review is to develop a conceptual synthesis of knowledge across three relevant domains: (i) the design and development process of e-clothing, (ii) eco-design integration opportunities and challenges, and (iii) eco-design tools and their applicability.

Given the hybrid nature of e-clothing, the review draws on literature from a broad range of disciplines, including sustainable fashion, green electronics, wearable technologies, circular economy, and eco-design methods and tools. Both academic and grey literature were considered. This broader inclusion was necessary to capture not only formal academic insights but also practice-led contributions that are often not yet codified in peer-reviewed data, particularly in fast-evolving design and technology contexts.

The research was conducted iteratively using a concept-driven selection process consistent with narrative review methodology (Sukhera, 2022). Key search terms and phrases were derived from the three target domains as described before, including: ("ecodesign" OR "design for sustainability" OR "circular design" OR "sustainable design") AND ("method" OR "approach" OR "principles" OR "strategy" OR "tool") AND ("fashion" OR "textile" OR "electronic" OR "wearable technology" OR "electronic textiles" OR "smart textiles" OR "smart clothing" OR "e-clothing"). Searches were conducted primarily in Scopus, Web of Science, and Google Scholar, supplemented by manual searches of reference lists, key authors, institutional reports, and industrial reports.

Studies published in English between 2000 and 2025 were considered to capture a broad range of academic knowledge, while more recent publications (2015–2025) were prioritized to reflect the field's rapidly evolving nature. The selection logic followed a conceptual relevance boundary. Studies were included if they explicitly addressed any one of the three relevant domains. Priority was given to studies that examined the intersection of two or three domains, as these were most relevant to understanding the opportunities and challenges of integrating eco-design into e-clothing development. The main selected academic papers are listed in Table 1.

Technical papers focusing solely on material performance or electronics without discussion of design processes or sustainability implications were excluded. Similarly, papers focusing solely on conventional fashion sustainability without relevance to electronic integration were also excluded unless they offered transferable eco-design methods or tools.

As an NRL, this study does not aim to provide an exhaustive or statistically comprehensive coverage of all existing literature. Instead, it seeks to develop an interpretive synthesis that supports conceptual understanding and framework development.

2.2 Semi-structured interview

2.2.1 Participants

Semi-structured interviews were conducted with 10 relevant experts in the e-clothing field, working in academic and industrial contexts, using purposeful sampling (Patton, 2002). Given the qualitative and exploratory nature of this study, the aim was not to achieve statistical representation or large-sample generalization, but to obtain in-depth and cross-disciplinary insights at a broader level of knowledge. Therefore, the participants represented diverse roles, including researcher, designer, electronic engineers, and product manager, reflecting academic and industry perspectives in a balanced way. They possess specific knowledge and experience in e-clothing, by having direct involvement in designing, engineering, or researching e-textile and e-clothing fields. Table 2 details the participants' profile.

2.2.2 Materials and methods

The interviews focused on (i) their experiences with the e-clothing development process and eco-design approaches in interdisciplinary contexts, (ii) perceived barriers, and (iii) perceived needs for guidance or support in sustainable development during e-clothing development toward more responsible and sustainable results. The interviews lasted approximately 60 min for each participant and were audio-recorded for transcription and scientific analysis. To ensure confidentiality, the responses were anonymized, interview and data retrieval has been administered in accordance with the ethical committee.

2.3 Data analysis method

Both the NRL and interview data were analyzed using thematic coding (Guest et al., 2012). First, all sources were mapped to the three research domains (see in 2.1) by relevance. Within each domain, an initial coding frame was developed through careful reading of original materials and combining insights from both datasets. Coding was conducted manually to further categorize and identify the sub-themes, capture recurring patterns, such as "characteristics of e-clothing design process", "eco-design challenges", and "eco-design strategies." All coding were systematically recorded in an Excel file for consistency and traceability across datasets.

The relative weight of the NLR and interview data varied across sub-themes. In some cases, findings from the NLR served as the primary source of evidence, with interview data used to supplement or validate insights from practice. In other cases, practitioner perspectives from interviews played a more central role, with literature providing contextual or conceptual support. This flexible weighting allowed the analysis to capture both established knowledge and emerging practices. Finally, the themes from both NLR and the interviews were interpreted together to construct the analytical narrative explanations to answer the three research questions.

3 Results

An overview of the results provides coverage across the three main themes that correspond to the three investigation domains: (1) e-clothing design process, (2) eco-design related practices appearing in the process, and (3) the need for eco-design support and tools. The literature sources mainly contributed conceptual and methodological perspectives, particularly in e-clothing design process and eco-design frameworks, while interview data provided insights into practical workflows, integration challenges, decision-making processes and eco-design supporting tools in real-world design contexts.

Across the three themes, the analysis further identified recurring sub-themes. These sub-themes provide the analytical structure for the detailed findings reported in the following sections, where insights from the literature and interviews are interpreted together. Table 3 shows how the sub-themes contributed to the main themes.

3.1 E-clothing design process and workflow

3.1.1 Characteristics of the e-clothing design process: interdisciplinary and iterative process

The e-clothing design demands specialized technical knowledge, including understanding of conductive materials, sensor integration, energy consumption, and regulatory standards for both textiles and electronics. This knowledge is rarely held by a single designer, but often spans disciplines and stakeholders (Strand et al., 2020; Ion et al., 2024).

TABLE 1 The main selected academic papers clustered by the relative domain(s).

No.	Author(s) and years	Title	Keywords	Relative domain(s)
1	Li et al. (2022)	The status quo and prospect of sustainable development of smart clothing	Smart clothing, sustainability, design, production, supply chain	(1)(2)
2	Rikanovic and Luible-Bär (2022)	The significance of emotional and sustainable values in smart clothing	Smart clothing, emotional sustainable value	(1)(2)
3	Köhler (2013a,b)	Challenges for eco-design of emerging technologies: the case of electronic textiles	E-textiles, sustainability risk prevention, eco-design strategy	(2)(3)
4	Jones et al. (2021)	Punch-sketching e-textiles: exploring punch needle as a technique for sustainable, accessible, and iterative physical prototyping with E-textiles	E-textiles, prototyping, toolkits, constructive assemblies,sustainability	(2)(3)
5	Perera et al. (2024)	Exploring sustainable approaches for electronic textile products and prototypes	Sustainability, electronic textiles, smart textiles, reusability	(2)(3)
6	Baurley (2005)	Interaction design in smart textiles clothing and applications	Smart clothing, design	(1)
7	Lee (2006)	A model of design process for digital-color clothing	Smart clothing, design	(1)
8	McCann (2009)	The garment design process for smart clothing: from fibre selection through to product launch	Design process tree, end-user design requirements, clothing layering system, textiles and electronics environmental impact, smart clothes, wearable technology	(1)
9	Wang et al. (2018)	A requirement-scenario-experience framework for evaluating wearable and fashionable design: presenting underlying factors of user loss	Design evaluation, wearable and fashionable design, design intention, user motivation, perceived value	(1)
10	Sayem et al. (2020)	Review on Smart Electro-Clothing Systems (SeCSs)	Smart e-clothing, smart garment	(1)
11	Sun and Kong (2022)	Internet of things information system and clothing computer renderings digital art	IoT, smart clothing, design process	(1)
12	Kuusk (2016)	Crafting sustainable smart textile services	Smart textile, sustainability, crafts, longevity	(2)
13	Gurova et al. (2020)	Sustainable solutions for wearable technologies: mapping the product development life cycle	Sustainability, wearable technology, design, fashion, ICT, closed-loop design, design implications	(2)
14	Dulal et al. (2022)	Toward sustainable wearable electronic textiles	Wearable electronics, e-textiles sustainability, biodegradability, recyclability	(2)
15	Shi et al. (2023)	Sustainable electronic textiles towards scalable commercialization	E-textile sustainability, recycle, repair, replacement, reduction	(2)
16	Ivanoska-Dacikj et al. (2024)	Smart textiles: paving the way to sustainability	Smart textiles, sustainablity, end-of-life, eco-design	(2)

(Continued)

TABLE 1 (Continued)

No.	Author(s) and years	Title	Keywords	Relative domain(s)
17	De Oliveira Massi et al. (2024)	Environmental impacts and challenges of smart clothing - a review from the life cycle	Smart clothing, ambient impact, circular economy	(2)
18	Zhu and Liu (2025)	The Ecodesign transformation of smart clothing: towards a systemic and coupled social–ecological–technological system perspective	Smart clothing, ecodesign, product lifecycle, circular economy, social–ecological–technological systems	(2)
19	Tadesse et al. (2025)	Recycling and sustainable design for smart textiles — a review	Circular economy, e-waste recycling, SDGs, smart textiles, sustainable design	(2)
20	Lofthouse (2006)	Ecodesign tools for designers: defining the requirements	Ecodesign, industrial design, product design, tools	(3)
21	van Der Velden et al. (2015)	Life cycle assessment and eco-design of smart textiles: the importance of material selection demonstrated through e-textile product redesign	Life cycle assessment, life cycle design, environmental impact, smart textile products, wearable electronics	(3)
22	Rossi et al., (2016)	Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies	Ecodesign tools, ecodesign methods, implementation barriers, implementation strategies	(3)
23	Chatty et al. (2021)	Examining the user experience of life cycle assessment tools and their ability to cater to ecodesign in early-stage product development practice	Life Cycle Assessment, ecodesign, integrated product development, sustainability	(3)
24	Dulal et al. (2025)	Sustainable eco-design approach for next-generation wearable e-textiles	Eco-design, e-textiles, sustainability, end-of-life, wearable	(3)
25	Wentz et al. (2025)	Integrating environmental assessment into early-stage wearable electronics research	Life cycle assessment, electronic wearables, e-textiles, sustainability	(3)

TABLE 2 The role, year of experience and related field of 10 participants.

Participant code	Role	Year of experience	Professional background	Expertise focus
E1	E-textile designer	6	Academic research	Knitted e-textiles design, e-textile education
E2	Product designer	7	Academic research	Smart sportswear design
E3	Technical key account manager	10	Industry professional	Medical e-clothing development
E4	Designer/Engineer	10	Academic research	Knitted e-textiles design
E5	Freelance designer	17	Academic research and industry hybrid	E-textile and e-clothing design
E6	Fashion designer	3	Academic research	Biomaterials for e-textile
E7	Engineer/Researcher	8	Industry research	E-textile development
E8	Designer/Studio Founder	12	Industry designer	E-clothing design and development
E9	Researcher/Engineer	6	Industry research	E-textile development
E10	Physicist	20	Industry research	E-clothing development

TABLE 3 Main themes and sub-themes identified from the integrated analysis of NLR and interviews.

Main themes	Sub-themes identified	Related coding	Evidence from
E-clothing design process	Characteristics of e-clothing design process	Iterative/loop process Technology-driven Early-stage uncertainty Interdisciplinarity Collaborative work Long development period	Narrative review and interview
	System- and embedded-oriented design process models	Design process E-clothing system Embedded design	Narrative review
	Practice-driven and non-standardized workflows	Research Design Prototype Functional test User test	Interview
Eco-design related practices	Eco-design strategies applied in e-textile or e-clothing	Design for recyclability of materials Design for durability Design for modularity Design for disassembly	Narrative review and interview
	Current sustainability practices used by designers/engineers	Select sustainable textile materials Avoid over engineering Encourage long-term use Minimizing waste in prototyping Design for modularity Design for disassembly	Interview
	Barriers and challenges to eco-design integration	Lack of standards Lack of knowledge Lack of data for LCA Integration complexity and design conflicts Technical constraints	Narrative review and interview
	Practical constraints and design trade-offs in interdisciplinary contexts	Eco-design paradox Lack of unified guidance and regulation Different eco-design priorities and focus Communication gaps	Interview
Need for eco-design support and tools	Limitations of existing eco-design tools for e-clothing	LCA complexity Lack of textile-electronics specificity Not designer-friendly Not suitable for early design phase Usability limitations	Narrative review and interview
	Informal or fragmented use of eco-design tools in practice	Based on experience No systematic framework	Interview
	Explicit needs for accessible, process-compatible eco-design support	Shared understanding Simple tools Early-stage support Decision-making support Systemic framework	Interview

Therefore, e-clothing requires the interdisciplinary integration of fashion design, textile design, electronic engineering, and Human-Computer Interaction (HCI) (McCann, 2023a). Interview participants also reported different roles involved across industries including fashion designer, product designer, textile engineer, electronic and software engineer (E1, E3-E8, E10). This interdisciplinary integration makes e-clothing design process fundamentally different from conventional fashion design.

According to the literature (Watkins, 1988; Lamb and Kallal, 1992; Renfrew and Renfrew, 2009; Sinha, 2015; Bertola et al., 2018; Munasinghe et al., 2021), in conventional fashion design, product development is organized around seasonal collections, each comprising multiple garments designed to form a coherent aesthetic whole collection. The process typically begins with the designer's creative vision, informed by past sales data, and is expressed through a mood board that defines the style, colors, and fabrics of the collection. Prototypes are then developed through collaboration between designers and pattern makers, with models providing feedback on fit and comfort. Several refinement cycles may occur before final approval, after which buyers and managers decide on production quantities and presentation.

By contrast, e-clothing design cannot follow this creative-driven, and collection-based structure. Instead, it is more technology-driven (McCann, 2009) and closer to industrial or product design in creating and developing concepts and specifications that optimize the function and appearance of products for the benefit of the end-user (McCann et al., 2005). Therefore, e-clothing design must integrate creative and functional approaches while also considering purpose and use scenarios (Holland and Harrison, 2005).

Furthermore, e-clothing development involves iterative prototyping of textiles, electronic components, and embedded systems. This leads to longer development cycles, a focus on testing performance, and repeated design adjustments. Interview participants also reported prolonged development timelines, ranging from 6 months to over 10 years, including frequent, iterative prototyping (E1–E5, E7–E10) that spans from low-fidelity non-functional mock-ups to high-fidelity functional integrated prototypes (Rachael, 2021). Each iteration often requires concurrent adjustments to both clothing forms and embedded electronics, creating a feedback loop process that challenges traditional linear design models (Wang and Casciani, 2024).

3.1.2 E-clothing design process

3.1.2.1 Systemic and embedded e-clothing design process

From prior studies, e-clothing design requires "system-level" planning that integrates both garment and hardware development from the outset. The design process involves a "system-level design" phase, including idea development, appearance design, and first mock-up; followed by a "detailed design" phase that covers device detail design, interior design, and appearance design modification. Finally, a "refined design" phase includes design review, second sample modification, and complement (Lee, 2006).

This workflow from "system" to "detail" has been further studied in the design process for *"intelligent clothing"* based on *"embedded system"* (Sun and Kong, 2022), which includes design point analysis such as requirements of the demand object and the characteristics of the application scene, clothing design, hardware system design and software system design, combination of clothing and hardware, embedded system testing and improvement.

Li et al. (2022) contribute to the details of the "intelligent module design" and *"carrier design."* The first focuses on embedding technology into the clothing, such as sensor modules, communication modules and feedback modules, while the latter encompasses material design, appearance and comfort design, and overall integration of these technologies into wearable and functional garments.

While these system-oriented models emphasized the concurrent development of textiles, hardware, and embedded systems, they reflect an engineering view of e-clothing as an integrated technological system. In contrast, McCann et al. (2005) proposed a more user-centered design pathway, positioning e-clothing development within a product lifecycle that begins with identifying end-user needs, and proceeds through textile and garment development before integrating smart and wearable technologies, then continues with garment manufacture, distribution or product launch, and end-of-life recycling.

As mentioned in Section 3.1.1, the e-clothing design process is interdisciplinary, and collaboration challenges frequently arise. To address this issue, Holland and Harrison (2005) proposed a strategic, non-linear e-clothing design process that replaces traditional stage-based models with a responsibility and collaboration-centred approach. Instead of sequential phases, the process is organised into four overlapping areas: research, fashion input, electronics input, and strategic planning. The tasks of different disciplines are positioned according to how they interact with one another.

3.1.2.2 Practice-driven design process across participants' professional backgrounds

The interview data complement the secondary research. The findings indicate that practitioners employ practice-shaped unaligned design processes that rely heavily on individual expertise and disciplinary background.

Participants with an electronic engineering background described detailed workflows for e-textile prototyping, focusing on material innovation and functional performance (E4, E7, E9). Their process began with background research on existing technologies, materials, and manufacturing methods. They then defined the project's direction and developed early prototypes, including simple e-textile samples. These early prototypes also served as proofs of concept (PoC) to test electronic integration and functions. After several rounds of iterative prototyping and testing, they proceeded to design and prototype the e-clothing itself. The testing will then focus on functionality, reliability, and durability.

Participants with a design background contributed more details about the research and concept stages at the beginning of an e-clothing project (E1, E2, E5, E8). Their creative concepts may be inspired by the user's needs or the new capabilities introduced by e-textile technology. They then conducted technical research and user research to understand the application opportunities. During prototyping, they relied on external collaborators, such as electronic and software engineers or manufacturing experts, because electronic component integration was outside their expertise. Designers emphasised the garment design and the aesthetic integration of technology. Their prototype testing focused on user experience and comfort.

Both groups of practitioners mentioned research, design, prototyping, and testing of e-clothing. However, some differences emerged between academic and industry practitioners in their approaches to this process. Academic researchers tended to prioritise exploration, PoC prototyping, and methodological experimentation, often focusing on demonstrating new functions (E4, E8, E10), material integration (E1, E6, E9), or interaction possibilities (E2, E5, E10). Sustainability considerations were considered especially if they aligned with the innovative objectives of the project. Main process is focused on conception and prototyping, typically involving iterative testing of materials, components, and integration strategies to assess technical feasibility and user interaction, rather than progressing toward standardised and market-ready product development.

In contrast, industry practitioners focus on creating a commercial product for a specific problem or market demand. So they emphasised product feasibility, reliability, manufacturability, and regulatory compliance, with decisions strongly shaped by cost, supply chains, user requirements, and maintenance constraints (E3, E5, E10). Besides the similar workflow described before, industry practitioners reported additional stages aimed at bringing the e-clothing prototype, or a minimal viable product (MVP) to a market-fit product (PMF) (E3, E8, E10). They conducted more extensive technical, market, and user research in the early phase to define precise product requirements. During design and prototyping, they prioritised functionality, usability, and scalability. Their testing protocols were strict and often involved multiple organisations, especially in medical applications. One participant described a lengthy testing phase that included washability, functional, and durability tests, and multiple rounds of usability testing with real users (E3). The final prototype needed to satisfy both regulatory requirements and user needs. After certification, the product transitioned to mass production, which necessitated further adjustments to accommodate manufacturing constraints.

3.1.3 Synthesized e-clothing design process and workflow model

The analysis of the literature and interview data reveals that the theoretical and practical understandings of the e-clothing design process share several common elements, but also diverge in detail. Research, design, prototyping, and testing consistently appear as the core stages of e-clothing development, forming the basic framework of the process. This framework is inherently iterative. Research activities lead into design, design leads into prototyping, and prototyping leads into testing, but each stage may loop back as new insights emerge. Although PMF is an important consideration in e-clothing development, it was mentioned by only a small number of interview participants due to the limited representation of industrial experts in this study. Moreover, PMF involves complex organisational and operational dynamics, and integrating sustainability considerations at this stage requires further dedicated investigation. For these reasons, PMF is considered beyond the scope of this study.

Within this overarching framework, the specific activities conducted in each stage vary according to practitioners' disciplinary backgrounds and levels of experience, as discussed in Section 3.1.2. Interview participants emphasised that both the activities and their sequence often depend on the expertise available within a team, and that the involvement of different disciplines shifts across stages (E2, E9). Holland and Harrison's (2005) model recognises the contributions of different disciplinary groups but does not fully capture how participants engage at each stage of the workflow or how expertise shapes the evolution of the process.

Based on the combined findings, a synthesized e-clothing design workflow model was developed to reflect both conceptual understanding and real-world practices (Figure 1). The purpose of this workflow is not to propose a single, standardised process for e-clothing design, since such uniformity does not exist in practice, but to outline the shared structural elements of the process to clarify where eco-design can take place and be integrated most effectively.

The process begins with an early design phase characterized by contextual research, including investigations into technology, market, and user needs. After the project concept is defined, the workflow enters the design iteration phase, which typically involves two iterative development cycles. The first cycle focuses on PoC development, where early prototypes are created and subjected to functional testing to validate basic electronic integration. Insights from this stage inform the second cycle, in which an MVP e-clothing prototype is designed and refined through function, reliability, and durability testing. User testing follows, with evaluations centred on usability, comfort, and aesthetic integration. The workflow concludes with a PMF stage, where prototypes undergo adjustments for manufacturing feasibility and regulatory certification before approval for production. This model will be discussed again in later sections to examine how eco-design principles can be integrated into the workflow.

3.2 Eco-design implementation and challenges in e-clothing design

3.2.1 Current eco-design strategies and sustainability practices in e-textile or e-clothing

Eco-design is inherently a multi-criteria approach that requires balancing diverse environmental, functional, and user-centered priorities across all stages of a product's lifecycle (Serafini et al., 2015;

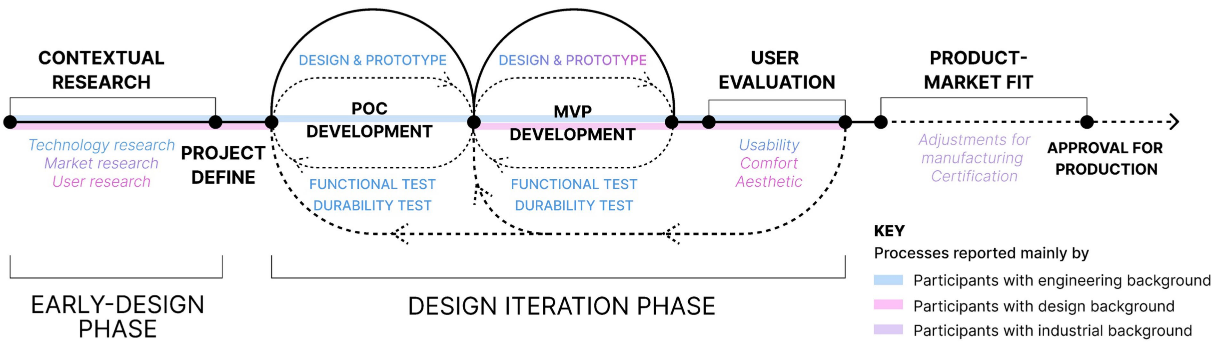

FIGURE 1
Synthesized e-clothing design workflow model based on literature and interview findings. The process is characterised by an iterative, practice-driven workflow moving from contextual research and project definition to POC and MVP prototyping, functional and durability testing, user evaluation, and eventual product–market fit. The figure highlights the centrality of iterative prototyping and testing in the design iteration phase, as well as the interdisciplinary nature, by showing the different emphases of participants with engineering (blue) and design (pink) backgrounds. PMF, production, distribution, and end-of-life processes are excluded, as they fall outside the scope of this research and are not yet consistently present in current e-clothing practice due to its limited commercial maturity.

Rossi et al., 2019). Previous studies proposed different eco-design strategies for e-textile and e-clothing, such as design for recyclability of materials (DfR), design for durability (DfDu), design for modularity (DfM), and design for disassembly (DfD) (Kuusk, 2016; Shi et al., 2023; Köhler, 2013b; Gurova et al., 2020).

DfR has primarily focused on material and technological innovation. Dulal et al. (2022) explore the potential for sustainable materials, manufacturing techniques, and sustainability assessment for developing eco-friendly e-textiles. The sustainable material innovations include biodegradable textiles (Pan et al., 2022), bio-based sensors (Banitaba et al., 2023), smart textiles for electricity generation (Chen et al., 2020) and carbon-based alternatives (Bozó et al., 2021). Additionally, sustainability guidelines emphasize the selection of materials, energy consumption, and principles of the circular economy (Ossevoort, 2013). Interview participants also emphasized the importance of selecting eco-friendly textile materials as a core strategy for sustainable e-clothing design, such as biodegradable or recycled textiles, to reduce the environmental impact of e-clothing (E1, E6, E8).

Additionally, "avoiding over-engineering" is also noted by participants (E7, E8). Not all garments need complex electronic integrations. In certain cases, adding electronics may not provide significant benefits to the user. For instance, if a textile's core function can be fulfilled without sensors or electronic components, it's better to avoid their inclusion. This reduces the complexity of recycling and disassembly at the end of the product's life.

Instead, DfDu, DfM, and DfD focus more on the holistic garment perspective with different design emphases.

DfDu aims to address the technological (progressive) and psychological obsolescence of e-clothing (Slade, 2006). Though the technological obsolescence is unavoidable due to disruptions from new technologies, psychological obsolescence is avoidable. For example, timeless design (Köhler, 2013b), design with emotional value (Rikanovic and Luible-Bär, 2022), and the use of craft to enhance the user experience of e-clothing (Kuusk, 2016) are discussed as solutions to extend the lifespan of garments and reduce waste. One interviewee mentioned that a key challenge is ensuring that users find value in the product beyond its novelty, and that the design encourages long-term engagement (E10). For example, apps and software paired with the e-clothing need to be continuously updated to maintain user interest and ensure that the product remains relevant and useful over time.

DfM has explored detachable components that enable repair, replacement, and customization of e-clothing (Kazemitabaar et al., 2016; Jones et al., 2020; Garbacz et al., 2021). Companies like Funktion (2023) have developed magnetic electronic modules that allow for easy detachment and reconfiguration to meet user needs. One participant described designing products that allow for sensor replacement, thereby extending the garment's lifespan (E2). Additionally, another participant highlighted the use of thermoplastic glues, which allow components to be detached and replaced as needed (E3). While DfM facilitates repairability and enhances user interaction, its application to fully integrated e-clothing remains limited. Key challenges include the absence of standard attachment and detachment methods (Simegnaw et al., 2021; Stanley et al., 2021; Lin et al., 2024), the lack of established reverse supply chains for modular components, and difficulties in achieving traditional garment design by introducing placement and wiring constraints (Ahn et al., 2025).

DfD emphasizes minimizing permanent fastening techniques, using standardized connectors, and enabling easy component separation (Crowther, 2005). In relation to e-clothing, pioneering research studied the disassembly of the conductive threads (Jones et al., 2021; Chen, 2023), yarns (Wu and Devendorf, 2020) and textile circuit (Linz et al., 2010). Toeters and De Kok (2018) designed a sportive e-clothing using de-lamination to disassemble the printed circuit and sensor from the fabric base to ensure the reassembly and reuse of the sensor for at least 25 cycles (Veske et al., 2019). Interview participants also mentioned some examples used in their work such as disassembling conductive threads and electronic components (E5, E9). However, this disassembly design requires manual work; achieving this in practice can be difficult due to the technical requirements of embedding electronics securely while still ensuring they can be disassembled.

3.2.2 Challenges of integrating eco-design in the e-clothing design process

Although the eco-design strategies discussed earlier are potential, integrating eco-design methods into the e-clothing design process is still reported with many challenges, including (1) the absence of base or reference products, (2) the uncertainty in early design stages, (3) the eco-design conflicts caused by textile–electronics integration, (4) the misalignment of eco-design regulations and priorities in dual sector, and (5) the misalignment of values and communications within interdisciplinary teams.

(1) The absence of base or reference products

As outlined in the Introduction, typical eco-design processes often begin with a lifecycle assessment of an existing product, with LCA being one of the most commonly used tools. While individual LCAs have been conducted for specific materials used in e-clothing, such as PCBs (Grant et al., 2023; Kettle et al., 2024), printed electronics (Nassajfar et al., 2023), and conductive fabrics (Radulescu et al., 2020), only one study has assessed the environmental impact of an e-clothing prototype (van Der Velden et al., 2015). This study underscored the importance of sustainable material selection at the design stage. The lack of LCAs for e-clothing is primarily due to the complexity of data collection for emerging technologies (Dulal et al., 2022).

Researchers had to simplify assessment procedures or rely on hypothetical data, particularly when modelling use scenarios, and prototype-level data rarely correspond to the realities of industrial production. Thus, the challenge is that e-clothing, as an emerging product category, lacks established supply chains and well-defined use contexts, making the first step of lifecycle environmental assessment difficult. Besides this, challenges also emerge in later stages of the eco-design process of setting environmental design priorities and the generation of eco-design focused concepts.

(2) The uncertainty in early design stages

The eco-design practices are typically situated in the early stages of the design process (Ceschin and Gaziulusoy, 2019). However, in the context of e-clothing, the early design phase is marked by high uncertainty. Material and component choices are often provisional, with prototypes undergoing repeated modifications, making it difficult to apply eco-design strategies in a meaningful or consistent way. This situation reflects the theory of the *"design paradox"* (Ullman, 2010), and extends to what has been termed the *"eco-design paradox"* (Lindahl, 2005; Chatty et al., 2024), wherein decisions with the greatest environmental impact must be made when the least information is available. There is still limited literature addressing how eco-design can be integrated into such iterative prototyping cycles involving emerging technologies, and validated methods remain scarce (Kunnari et al., 2009; Köhler, 2013a; Chebaeva et al., 2020; Chatty et al., 2021). As a result, interdisciplinary design teams often lack concrete methodological guidance for implementing eco-design during the early design phases of e-clothing development.

The interviews reveal that due to the iterative and design process of e-clothing, there is a temporal mismatch between rapid design iteration and the slow pace of sustainability assessment. While quick prototyping cycles enable teams to test functionality and user interaction rapidly, sustainability evaluations require a longer assessment period, a detailed Bill of Materials (BoM) and structured data of the entire lifecycle. The lack of support that can operate in real-time or adapt to iterative changes discourages sustainability integration in early-stage development. One participant mentioned that early prototype materials and components are replaced multiple times before the right combination is identified (E8). This uncertainty makes it nearly impossible to assess sustainability meaningfully during early development, as final material decisions have yet to be made. As a result, sustainability is often addressed only conceptually or deferred to later stages of the process.

(3) The lifecycle eco-design conflicts caused by textile–electronics integration

Köhler (2013b) acknowledged that most of the existing eco-design solutions from the other sectors (such as textile or electronic sectors) are impractical because they do not match the expected properties of e-textiles. E-textiles have specific performance requirements due to their hybrid product properties. These requirements arise from several design conflicts of e-textiles, including material incompatibility between flexible/soft textile and rigid/soldered electronics (Cherenack and Van Pieterson, 2012; Ossevoort, 2013; Rossi et al., 2016), mismatched structure and aesthetics (Torah and Beeby, 2017), and integration and disassembly challenges (Torah and Beeby, 2017; Simegnaw et al., 2021).

E-textiles combine two distinct material systems: textiles (natural or synthetic fibers) and electronic components (metals, plastics, PCBs). These two material ecologies are different both in their environmental footprints and in their functional requirements. These dual-material systems also create material compatibility conflicts (Ossevoort, 2013). Apparel products are typically composed of soft, flexible materials and may incorporate single or multi-layered constructions. In contrast, electronic devices rely on rigid, multi-component structures with layered architectures that are not compatible with textile substrates. As a result, integrating electronic components into textile systems introduces material incompatibility and further design tensions for eco-design strategies (Rossi et al., 2016).

During manufacturing, apparel is built on layered and flexible construction methods, such as stitching, weaving, or knitting, that accommodate deformation and user movement. Electronic manufacturing, then, is made by precision assembly and rigid bonding to achieve conductivity, reliability, and long-term stability. The eco-design conflicts appear in different levels of electronic integration (removable, semi-integrated, fully integrated), which correspond to radically different production strategies (Dias, 2015; Torah and Beeby, 2017; Simegnaw et al., 2021; McCann, 2023b). In fully integrated designs, textiles and electronics are merged through knitting, printing, or coating (Gonçalves et al., 2018; Komolafe et al., 2021; Mattila, 2014), creating products with limited reparability or potential for material separation. In these products, few eco-design strategies such as design for disassembly or mono-materiality are seen as potentially applicable (Köhler, 2013b; Gurova et al., 2020; Shi et al., 2023), however, they were not applied effectively.

When extending the perspective from e-textiles to e-clothing, additional problems emerge during product use and at the end of the product's life. At the use stage, the conflicts start shifting from product level to product system level (Vezzoli et al., 2022). Eco-design decisions must account for energy consumption, wearability, and lifespan (van Der Velden et al., 2015; Casciani and Wang, 2024). However, the lifespan of e-clothing is generally dictated by the most fragile components, usually the electronic ones, rather than the textile itself (Li et al., 2022). Electronic failures due to washing, sweat exposure, or lack of maintenance knowledge often led to premature disposal (Lazar et al., 2015). Moreover, studies found that current e-clothing products lack sufficient maintenance guidance, and repairs are often perceived as difficult to perform by the final users (Hardy et al., 2020). In this context, design for sustainable behaviors (Busalim et al., 2022) and maintenance becomes particularly relevant, as it seeks to educate end users through simple care and usage tips and create longer-term emotional attachment (Kuusk, 2016). However, care requirements for textiles and electronic components differ significantly, and integrating these distinct maintenance logics into a coherent and user-friendly strategy for e-clothing remains an essential design challenge.

The e-clothing EoL is the most discussed in literature. Due to embedded electronics, most e-clothing cannot be recycled through conventional textile or e-waste systems (Köhler et al., 2011). Manual separation is often required but rarely economically viable (Köhler, 2013b). Without standardized connection methods or disassembly protocols, most products will be incinerated or landfilled, posing environmental risks through the release of hazardous substances into the air or soil (Köhler, 2013b). Even when reuse is possible, it is limited to cases where electronics can be easily removed without damaging the garment.

(4) The misalignment of eco-design regulations and priorities in the dual sector

The different eco-design regulations in the apparel/textile and electronics sectors have different sustainability focus and eco-design principles, leading to different eco-design priorities in e-clothing design.

The apparel and textile domain mainly relies on established sustainability standards and certifications, including the EU Ecolabel (2023), OEKO-TEX® Service GmbH, 1992, the Global Organic Textile Standard, 2006, (Niinimäki, 2006; Muthu, 2023), which address factors like material sourcing, chemical use, and energy efficiency. Thus, eco-design primarily focuses on material sustainability, production efficiency, and post-use circularity. Key principles (Cooper et al., 2014; Vezzoli et al., 2022) include:

- Use low environmental impact, recycled materials, select non-exhaustible and nontoxic materials;
- Reduce material variety and consumption (zero-waste pattern design, mono-material strategy);
- Minimise energy consumption, minimization of waste (pattern efficiency, digital prototyping, or on-demand production);

- Design for longevity (extend durability, increase functionality, timeless aesthetics, and emotional attachment);
- Alternative business models such as rental, resale, and repair;
- Design for recycling.

In the electronics domain, regulations such as the RoHS Directive, 2003, Eco-design Requirements for Energy-related Products (2012) (ErP), and the Waste From Electrical and Electronic Equipment (WEEE) (2002) directive provide frameworks for restricting hazardous material and promoting circular waste management (Schischke et al., n.d.). Due to these regulations, key eco-design principles (Stevels, 2001; Li et al., 2014) include:

- Material restriction and substitution, especially hazardous substances;
- Energy efficiency during production and product use;
- Design for disassembly and recyclability to facilitate EoL processing;
- Product miniaturization and integration to reduce material use.

While textiles are evaluated for biodegradability, dyeing toxicity, and resource intensity, electronics raise concerns about the extraction of critical minerals, the depletion of rare metals, and hazardous waste.

In comparison, the apparel/textile domain leans more toward material and consumer-centric strategies, while the electronics industry is governed by functionality, durability, and regulatory compliance. When they are integrated into an e-clothing product, designers and engineers face a compounded challenge: they must handle two distinct sets of environmental imperatives, regulations, and design requirements. The lack of integrated, cross-sectoral eco-design frameworks makes it challenging to make holistic and effective eco-design decisions, which involve evaluating trade-offs and selecting materials, processes, and product design configurations that balance sustainability goals with technical performance, aesthetic quality, and regulatory compliance. For instance, prioritizing recyclability may compromise technical performance, and designing for user repair may not be compatible with embedded electronic circuits.

Guided by these regulatory directions, design priorities and methods differ between the two sectors. Design priorities in fashion emphasize aesthetics, performance, wearability, comfort, and alignment with trends and consumer culture, often optimizing for production efficiency and visual appeal (Wang and Casciani, 2024). In contrast, electronic products prioritize technical performance, reliability, durability, and ease of disassembly to meet functional and regulatory requirements (Perry et al., 2017; Wang and Casciani, 2024). When these priorities converge in e-clothing, tensions arise, and these tensions necessitate trade-offs between design goals, such as wearability, durability, aesthetic, and disassembly, making it challenging to apply conventional eco-design strategies without adaptation.

(5) The misalignment of values and communications within interdisciplinary teams

In parallel, disciplinary differences create additional challenges. While this cross-disciplinary collaboration is essential for designing and developing e-clothing systems, it also creates communication barriers and value misalignments (Lynch et al., 2024). Fashion and textile designers are often familiar with knowledge of textiles and fabrics, aesthetics, and visual storytelling, bringing sensitivity to form, comfort, emotional durability, and cultural relevance. Engineers contribute technical expertise in system integration, component selection, reliability, energy efficiency, and product safety. These differing priorities are not only operational but also rooted in distinct disciplinary languages, perspectives, and approaches.

When discussing sustainability, neither designers nor engineers are typically experts. Their understanding is shaped largely by their past experiences and disciplinary backgrounds. Each group tends to use a distinct set of vocabulary related to sustainability. Interviews revealed that designers often associate eco-design with textile sustainability, circular economy, and garment-specific strategies such as "zero-waste pattern design" (E1-E2, E4, E6, E8), while engineers are more likely to link eco-design to durability, disassembly, and technical aspects related to electronic production, such as "print electronics" (E3, E7, E9-E10). The complexity lies not only in "bringing together" experts but also in negotiating what sustainability means in shared practice. When collaborating on e-clothing projects, it is essential to develop a shared glossary that bridges the disciplinary vocabularies and ensures a unified understanding of sustainability concepts across the team.

Interviews also revealed that these mismatches often lead to friction in decision-making, especially when sustainability considerations are involved. For example, decisions about textile-electronics integration can result in trade-offs between functionality and wearability, or between durability and disassembly at the EoL for recycling (E2, E5, E8, E10). In these situations, the absence of a clearly shared eco-design goal makes it difficult for teams to align on common eco-design objectives, leading to a lack of cohesive strategy and guidance.

Moreover, the question of who is responsible for eco-design within the team remains ambiguously defined. Some experts noted that sustainability is often perceived as the manufacturer's responsibility (E3–E4), while others expected sustainability experts to take the lead (E2, E10). This undefined responsibility often leads to delayed decisions and superficial engagement with eco-design.

3.3 Tools to support eco-design integration in e-clothing design process

3.3.1 Existing eco-design tools and their limitations

The integration of eco-design into e-clothing development requires tools and methods that support designers and engineers in making informed sustainability decisions throughout the design process. However, both the literature and the interview findings indicate that while eco-design tools have been developed and applied in the apparel and electronics sectors, the existing eco-design tool landscape is insufficient for the specific needs of e-textiles and e-clothing.

The literature highlights several categories of eco-design tools that are widely used in apparel, electronic, and product design. These tools are categorized into seven types, as identified in a previous study (Rossi et al., 2016): LCA tools, CAD-integrated tools, diagram tools, checklist and guidelines, design for X approaches, methods for supporting the company's eco-design implementation and innovation, life cycle analysis, and user-centered methods.

Building on this classification, we analysed each category in terms of classification, example, application context, objective, and accessibility. Then we conducted interviews in which participants were asked about their prior experience using these tools and methods, and the challenges they encountered when applying them in the context of e-clothing eco-design.

As stated in Table 4, most existing tools were originally designed for mature product categories, therefore they are often optimized for static, standardized development models. However, e-clothing constitutes a hybrid product system and involves more complicated and circular design loop (as shown in Figure 1), which challenges the fundamental assumptions in existing eco-design tools regarding product composition, use patterns, and end-of-life scenarios.

Moreover, expertise and usability limitations hinder the eco-design practices in interdisciplinary collaboration. Within e-clothing design teams, no specific role is typically dedicated to sustainability assessment, nor is anyone skilled in applying existing eco-design tools.

TABLE 4 Comparison of eight common eco-design tools from literature and interview results.

Type of tools/ methods	Classification	Example	Function category	Objective	Issue/limitations
LCA	Quantitative	LCA for Experts (2025) (formerly GaBi), SimaPro (2025), OPenLCA (2025)	Environmental analysis	Quantify the environmental impact of a specific process, product or service	Skill required (E1, E8); large amount of data required (E9); Inaccurate life cycle assumptions (E3)
CAD integrated tools	Quantitative	CAD/LCA integration methods (Marosky et al., 2007), EcoAudit (Ansys Granta EduPack, 2025)	Environmental analysis	Analyse the product in environmental terms during the design phase, compare different product versions, and understand key product environment criticalities	Not compatible with fashion software, and e-textile materials; database gap; embedded in engineering-dominated platforms; simplified results (Rossi et al., 2016)
Diagram tools	Qualitative/semi-quantitative	Ecodesign strategy wheel (Brezet et al., 1997), Eco compass tool (Fussler and James, 1996; Boavida et al., 2020)	Life cycle evaluation	Evaluate and visualize the initial environmental assessment of product's life cycle when no detailed information is available	General results (E6); miss key dimensions of e-textiles (E6); lack of technical resolution (E7); lack of identification of sustainability criticality (E8)
Checklist and guidelines	Qualitative	Electrical and Electronic Practical Ecodesign Guide (Nuij, 2002), Ecodesign Pilot (2001), smart design checklist (Adams, 2006)	Life cycle evaluation; idea generation	Quick evaluation of the product's environmental profile, and the results are useful during the design phases. No-expertise need	Generality, difficult to translate them into design choices, not provide possible solution strategies for specific product category (E1, E2, E8)
Design for X approaches	Qualitative/ quantitative	DfD (Ostapska et al., 2024), DfL(Clothing Longevity Protocol, 2014; Carlsson et al., 2021), DfM (Erixon, 1996; Chen and Lapolla, 2020)	Idea generation	To optimize specific product requirements, with the main objective to satisfy customer needs and respond to the high market pressure for product competitiveness.	Miss the overall life cycle perspective, need to have a certain requirement or existing prototype to start (E7)
For company/business innovation	Hybrid	The Circular Design Guide (2016), EcoDesign Sprint (2018), Product Ideas Tree (Jones et al., 2001)	Decision making; Idea generation	Supporting the implementation of eco-innovation and eco-design approaches	Cannot be translated easily into technical design choices (De Jesus Pacheco et al., 2018); workshop-based and business oriented; not specific for e-clothing
Life cycle and user-centred methods	Hybrid	Product Life Cycle (Kobayashi, 2005), TRIZ based methodology (Russo et al., 2014; Cherifi et al., 2015)	Life cycle evaluation; idea generation	Improve sustainability for entire product lifecycle, especially for products that has high impact during use phase	Not very well-known tools (E5); highly structured and abstract (E8); limited strategy plan for E-clothing context (E9)

The usability of these tools is often constrained by differences in professional focus and workflow. For example, quantitative tools are often highly technical and not easily integrated into creative design processes, while qualitative tools such as sustainability frameworks may be perceived as difficult to operationalize within an engineering-driven development process and generate concrete, actionable design or technical solutions.

3.3.2 Needs of eco-design support and suggested tools

The interview findings also provide insight into the types of support and tools for integrating eco-design into e-clothing. Participants reported relying mainly on informal tools or general principles/guidelines rather than integrated eco-design methods. They mentioned basic sustainability guidelines, eco-design strategies, design-for-X approaches, and early concept checklists that help structure their decision-making (E1, E3, E5, E6, E8). However, they also raised some unmet needs.

First, participants emphasised the need to align their understanding of sustainability and eco-design within interdisciplinary teams. They explained that different practitioners often hold different interpretations of what sustainability means and what actions are feasible within their discipline. As a result, they require tools that can support communication, clarify shared sustainability goals, and help teams establish a common language for eco-design. Participants also highlighted the lack of accessible information on sustainable material choices, responsible sourcing, and low-impact production methods, which further limits their ability to make informed decisions.

Second, participants expressed a need for a more holistic and operational eco-design framework that can guide them throughout the entire e-clothing design process. They noted that such a framework should not be disruptive to current practices, but must be compatible with existing workflows and should not require substantial methodological or organisational changes to be effectively adopted.

Third, participants described the need for more specific eco-design strategies that can be applied during the design process, when key decisions are made. They emphasised the importance of visual, easy-to-use tools that support early decision-making without requiring specialised environmental expertise. Participants also noted the lack of tools that clearly link design decisions to environmental consequences, making it challenging to understand the implications of alternative materials, integration methods, or product architectures.

Finally, participants indicated a need for sustainability evaluation tools to assess the sustainability of a product and identify areas for improvement. They noted that such tools should provide actionable insights rather than abstract metrics, enabling the team to understand the environmental performance of their prototypes and refine the product accordingly.

The expressed needs suggest that new tools must not only support early-stage conceptualisation but also facilitate interdisciplinary collaboration and provide accessible guidance for sustainability trade-offs and evaluations.

4 Discussion

4.1 Integrating the co-design approach into e-clothing design process

This section discusses how the eco-design approach could be integrated into this workflow in a compatible manner. Figure 2 visualises this integration by mapping the key eco-design stages onto the corresponding phases of the e-clothing workflow, showing where eco-design actions can be embedded and how they align with existing design activities.

Typical eco-design processes begin with understanding the environmental problem, then set goals, then guide ideation, and finally support evaluation. When we compare this logic with the synthesized e-clothing workflow, several opportunities for integration become

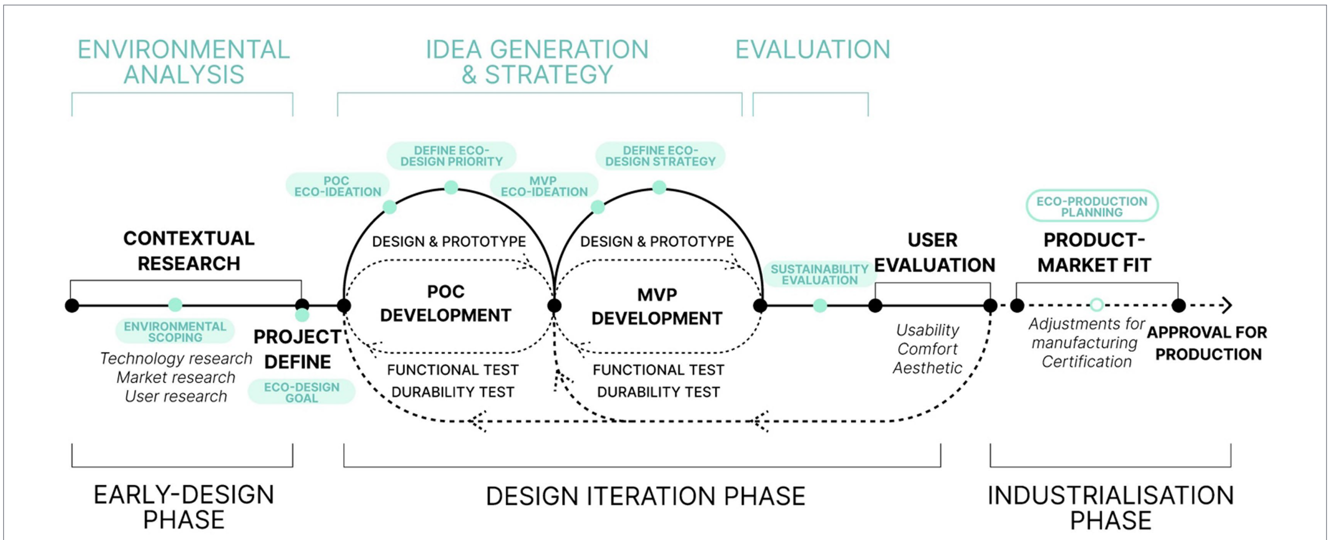

FIGURE 2
Integrated eco-design intervention points within the e-clothing workflow model. The figure shows the three typical eco-design processes, environmental scoping, idea generation, and sustainability evaluation, can be embedded across early-design and design iteration phase. In each phase, the specific eco-design activities are indicated by the green dots as the intervention points. These interventions points are provided to support the inclusion of eco-design actions aimed at sustainability at different stages of the project.

apparent. The early design phase can host the first steps of the eco-design process. At this point, contextual research already includes technology, market, and user investigations. An environmental investigation can be added to this phase. This can take the form of simple qualitative environmental analysis of materials and integration methods, hotspot identification, or a case study analysis of existing projects. This step does not require precise manufacturing data and therefore aligns with the uncertainty inherent in early e-clothing development.

The definition of eco-design goals can also take place during the *"project define"* stage. After the contextual research, the team defines the project concept and the functional direction. Environmental focus and goals can be established together with functional and aesthetic goals. These goals may relate to material selection, durability, repairability, disassembly, or EoL considerations to be addressed in later design iterations. Defining eco-design goals at this stage helps guide subsequent design decisions before technical constraints and system architectures become fixed.

Eco-design-focused idea generation can be embedded at the start of the design iterative cycle. The PoC stage is most experimental. It allows the team to develop the early prototype by exploring the core electronic functions and different integration approaches or material combinations. Introducing eco-design ideation here encourages the team to test alternative, lower-impact functions, materials, fabricating methods, or prototype architectures. This stage is ideal for small, exploratory trials that support environmental reasoning.

Defining the eco-design priority and the corresponding design choices for concept alternatives can take place after PoC eco-ideation. At this point, teams have gained technical insight from early prototypes. They can compare different strategic options and decide on the priorities. This process allows the team to identify the strategies with the greatest sustainability impact and the options that are most feasible within their practical constraints.

Then, the MVP stage takes the early prototype into a complete e-clothing prototype. At this point, the design aspects become more defined. In this stage, idea generation focuses on the complete e-clothing system rather than isolated components, and therefore, the ideas must be more specific and closely linked to real design constraints. Strategy definition also becomes more concrete. The team takes the previously defined eco-design priority and translates it into direct actionable design choices of the e-clothing prototype. For example, prioritising a material-reduction strategy may encourage the simplification of circuit layouts or the selection of zero-waste pattern design. These adjustments translate high-level eco-design intentions into concrete design actions that shape the final e-clothing prototype.

After these refinements, a sustainability evaluation can be conducted once the MVP prototype has stabilised. This evaluation focuses on the most relevant impact categories, such as material use, durability, repairability, and end-of-life pathways. The process does not need complete lifecycle data. Instead, it can rely on qualitative comparisons, partial datasets, teardown analysis, or scenario-based reasoning. The purpose of this step is not to produce precise quantitative results but to identify remaining weaknesses and guide improvements before the PMF stage.

The final opportunity for eco-design integration appears at the PMF stage. At this point, the team assesses the feasibility of large-scale production, regulatory requirements, and long-term performance in real use scenarios. Although this stage lies outside the scope of the present research and offers less design flexibility than earlier phases, it remains important for aligning production plans with sustainability goals related to manufacturing methods, supply chain choices, and product–service models.

4.2 Proposed eco-design tools for the e-clothing workflow

The integration of eco-design into the e-clothing workflow requires tools that support various design activities at different stages of development. In this section, existing tools are analysed according to their functions in Table 4. They can be broadly grouped into four stages that align with the different functions: (1) environmental analysis, (2) idea generation, (3) decision-making, and (4) life cycle evaluation. This section critically discusses these alignments and explains how the proposed tools address the limitations and challenges of integrating eco-design into the e-clothing design process identified in Section 3.2.2.

Environmental analysis is the starting phase; existing tools in this phase are largely LCA-oriented. While they are effective for impact quantification, they conflict with the uncertainty of early e-clothing development. At this stage, there are no stable reference products, manufacturing data are incomplete, and use scenarios are still speculative. As a result, conventional LCA tools cannot provide meaningful guidance. The proposed early environmental scoping tool addresses this limitation by shifting the focus from quantitative analysis to qualitative research, such as the shared canvas and qualitative mapping worksheet, enables teams to identify potential environmental hotspots related to materials, integration methods, and expected use scenarios without relying on detailed data. This suggestion addresses the lack of base products and the uncertainty inherent in early design stages.

In the eco-design goal stage, decision-making is necessary as support. The interview shows that tools to support eco-design orientation are currently missing. They often rely on implicit values or discipline-specific priorities. This leads to misalignment within interdisciplinary teams and between sustainability, functionality, and aesthetics. The structured goal-setting tool is then proposed to support the definition and prioritisation of eco-design goals at the project level. A visual diagram or map format has been proven to facilitate understanding and discussion in group work (Sibbet, 2010). This tool supports not only aligning values but also aligning eco-design goals across disciplines.

The PoC and MVP eco-ideation clearly need tools to support idea generation. Existing guidelines and ideation tools are generic and descriptive. They lack domain specificity for e-textiles and do not reflect the conflicts introduced by electronics integration. Moreover, because design and prototyping at the PoC and MVP stages are highly iterative, eco-design tool support must be dynamic and visual, enabling teams to continuously reflect evolving design and sustainability changes. The proposed brainstorming prompt tool responds to this limitation by embedding eco-design considerations directly into the specific e-clothing material, structure, and use scenario. Visual inspiration, structured diagrams, and prompt card formats have already been introduced in other sectors (Jones et al., 2001; Lofthouse, 2006; Ræbild and Hasling, 2019) to promote eco-design ideation. By applying the same format to the e-clothing system-level design requirements, these tools can support eco-design under uncertainty and continuity across iterations while encouraging more concrete ideation.

The stage of defining eco-design priority needs to be again aligned with decision-making. Existing tools at this stage are often derived from business or company-level innovation frameworks. These tools focus on strategic positioning rather than design-related decisions. There is a need for a strategy comparison and decision-making tool. One commonly used decision-making tool is a 2 × 2 matrix (Hood et al., 2008). It is easy to adapt to the e-clothing context to support eco-design priorities based on sustainability impact and practical feasibility. This format facilitates team trade-off discussions and helps reconcile conflicting priorities that arise from dual-sector regulations and performance requirements.

When defining eco-design strategy, existing checklists and guidelines lack operational guidance and fail to translate strategies into concrete design actions. This is particularly problematic in e-clothing, where strategies such as disassembly or durability must be implemented across both textile and electronic components. The potential tool should guide eco-design strategies to actionable design parameters. The TRIZ method has already been studied in eco-design innovation (Cherifi et al., 2015), as it provides a systematic way to resolve design contradictions and to translate abstract sustainability goals into technical solutions. However, conventional TRIZ applications remain generic and technology-oriented, and they require adaptation to address the hybrid material systems and user-centred constraints of e-clothing.

Finally, at the sustainability evaluation stage, conventional LCA and lifecycle-centred methods identify environmental weak points but fail to translate them into design improvements. The proposed evaluation and feedback tool addresses these limitations by combining evaluation with actionable feedback. The life cycle radar map (Johansson and Schmidt, 2023) visualises performance across key impact categories, while the accompanying action guide links identified weaknesses to potential design improvements. This format supports learning and iteration rather than certification-level assessment. It directly responds to the lack of reference products and enables evaluation under uncertainty.

Overall, as shown in Table 5, the proposed tools emphasise lightweight, shared, visual, and qualitative formats that respond to the absence of base products, the uncertainty of early design stages, the conflicts introduced by textile and electronics integration, the misalignment of dual-sector design priorities, and the communication challenges within interdisciplinary teams.

4.3 A cyclical eco-design toolkit structure for e-clothing development

The combination of tools described above is proposed into an eco-design toolkit that functions as a workflow, embedding methodological support for integrating sustainability considerations into e-clothing development. Because e-clothing design evolves through repeated cycles of concept exploration, prototyping, and evaluation under high uncertainty, the toolkit is structured to support iterative co-design activities across different development stages. In this way, it offers a practical way to operationalise eco-design principles in a field where design decisions are distributed across multiple disciplines and evolve through repeated prototyping cycles.

The toolkit is organised into a cyclical structure composed of four main steps that align with the four eco-design tool functional categories: environmental analysis, idea generation, decision-making, and life cycle evaluation (Figure 3). This structure can be applied across different phases of e-clothing development with only small adjustments in the content specification of each tool.

In the early design phase, teams often lack existing product references, material data, and validated use scenarios. In such conditions, the environmental analysis can be done through qualitative scoping of comparable products and related hybrid materials, energy use, maintenance requirements, and potential end-of-life risks. These initial findings support the definition of eco-design goals and priorities at the project level, helping teams align sustainability intentions across disciplines before major design commitments are made.

During the design iteration phase, the toolkit supports the transition from concept to PoC prototypes. Brainstorming prompts and decision-mapping tools can be used to generate and select design options. In this phase, these tools focus on the eco-design of the function justification, material sustainability, durable and reliable use, and

TABLE 5 Mapping eco-design stages to tools, limitations, and proposed support for e-clothing design.

Eco-design stages	Eco-design stages	Limitations	Proposed tool	Suggested format
Environmental analysis	Environmental scoping	LCA-oriented tools conflict with the uncertainty of early e-clothing development	Early environmental scoping tool	Shared canvas/qualitative mapping worksheet
Idea generation and strategy	PoC eco-ideation	Generic and descriptive; lacks domain specificity for e-textiles	Brainstorming prompt tool	Visual diagram/prompt cards
	MVP eco-ideation	Generic and descriptive; lacks domain specificity for e-textiles	Brainstorming prompt tool	Visual diagram/prompt cards
Decision making	Eco-design goal	Currently missing tool to support eco-design orientation	Structured goal-setting tool	Visual diagram/map
	Define eco-design priority	Focus on strategic or business-level decisions	Strategy comparison and decision-making tool	2×2 Matrix
	Define eco-design strategy	Lack operational guidance that define strategies into specific design actions	Structured strategy to design tool	TRIZ or simplified matrix
Evaluation	Sustainability evaluation	Miss the translation of the weak point and improvements	Evaluation and feedback tool	Life cycle radar map and action guide

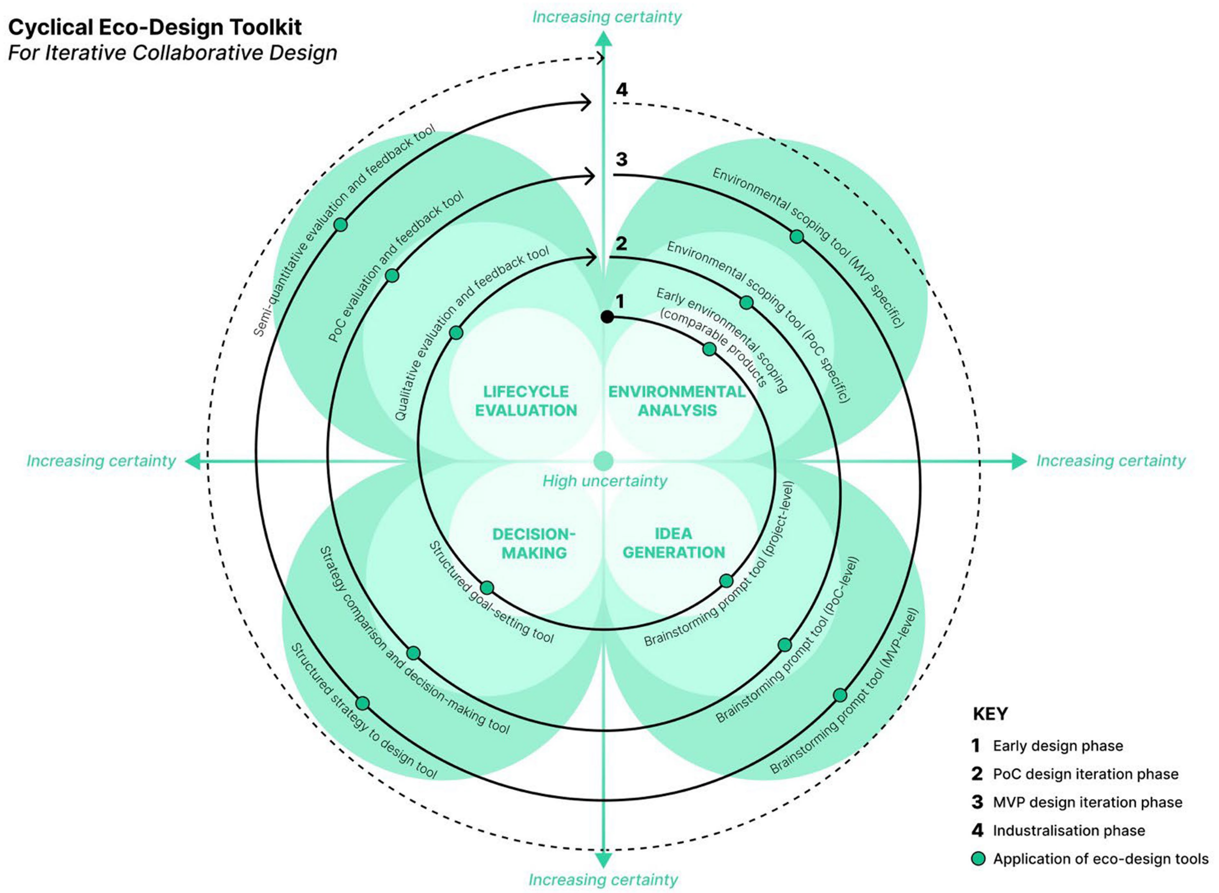

FIGURE 3
Cyclical eco-design toolkit embedded in the e-clothing development workflow. This diagram illustrates that the toolkit supports iterative and collaborative eco-design activities across multiple stages of e-clothing development, from early design to design iteration, and potential industrialisation phase. At the core of the framework is a recurring cycle consisting of four functional tool categories: environmental analysis, idea generation, decision-making, and life-cycle evaluation. They are repeatedly applied throughout the development process. This cyclical structure reflects the iterative nature of e-clothing design, where sustainability considerations are revisited as prototypes evolve and design knowledge matures.

the EoL of the PoC itself. Then the prototype is evaluated using the lifecycle radar and feedback tool, which highlights sustainability strengths and weaknesses and suggests directions for improvement. These evaluation results can go into a new cycle of analysis and ideation, guiding the transition from PoC to MVP.

At the MVP stage, the same loop is repeated but with a broader system perspective. The focus needs to extend eco-design considerations beyond material and integration decisions toward the use phase and long-term product–user relationships. In e-clothing systems, environmental impact is shaped not only by materials and disassembly structure, but also by energy consumption during use, software update cycles, maintenance practices, and users' understanding of how to care for hybrid textile–electronic products. The shifts from the sustainability of a single prototype to the eco-design of the entire e-clothing system should also consider realistic use scenarios, user interaction, repairability, functional and emotional durability, and end-of-life management. As the product structure becomes more defined and data becomes more reliable, sustainability evaluation can also become more concrete and detailed.

The iterative toolkit structure can also inform later industrialisation phases. In industry contexts, sustainability considerations are often addressed through compliance-oriented LCA or material substitution at later stages. The proposed toolkit instead supports earlier, more collaborative sustainability decision-making within the team. Although manufacturing adaptation is beyond the scope of this study, future work could explore how the toolkit might be extended to address production-scale considerations for e-clothing systems.

Through this cyclical application, the toolkit encourages interdisciplinary teams to revisit environmental priorities as design knowledge matures, data become more reliable, and prototypes evolve. The proposed structure, therefore, aligns with the iterative nature of e-clothing development and addresses key challenges identified in the interviews, including uncertainty in early stages, the absence of reference products, and the need for shared understanding across disciplines.

4.4 Implications for e-clothing eco-design research and practice

In e-clothing development, sustainability decisions cannot be fully defined at a fixed system level because the system itself, including material composition, electronic integration, use scenarios, maintenance and EoL management, can only be stabilised through successive prototyping. The findings suggest that sustainability considerations in e-clothing development are distributed across multiple stages and disciplines and must therefore be addressed through iterative and collaborative design processes. The mapping of workflow intervention points (Figure 2) and the proposed toolkit structure (Figure 3) together offer a methodological perspective that situates eco-design as a distributed and iterative design practice that evolves together with the e-clothing product.

An implication of this study is that eco-design in e-clothing can be actively used as a decision-shaping mechanism during development. In research, this means that the mapping of workflow intervention points and the proposed cyclical toolkit structure can serve as a support for coordinating sustainability reasoning across evolving prototypes and teams. For example, in a conceptual research project developing an e-clothing for posture monitoring, the early design team may use qualitative environmental scoping to identify where are sustainability risks, such as choosing a permanently laminated conductive layer or a non-replaceable battery placement. By making these risks visible, the team can replace irreversible integration decisions and test alternatives (e.g., modular sensor attachment or detachable power modules) across PoC iterations. As different iterative prototypes are developed, they can be compared and analysed using a decision-making matrix to identify the most suitable options, while further refinements can be guided through lifecycle radar mapping and feedback.

In commercial e-clothing development practice, even though sustainability was not considered at the beginning. In contrast, applying the distributed and iterative framework proposed in this study would prompt the company to revisit sustainability decisions at key transition moments. For example, in developing a smart sports shirt with integrated biometric sensors, the team may initially prioritise signal stability and seamless comfort by embedding sensors and conductive pathways directly into the textile structure. As the project moves from concept validation to MVP preparation, the cyclical structure could prompt the team to reassess whether this fully integrated approach would prevent the need for repairs, component replacement, or textile recycling. By revisiting these decisions at the transition between iterative prototype stages, the team could explore alternative configurations that preserve performance while improving maintenance and EoL options.

From a broader perspective, these applications suggest that eco-design integration in e-clothing development depends less on identifying a single optimal solution and more on structuring when and how sustainability questions are revisited as the product evolves. This perspective also foregrounds the role of interdisciplinary coordination in shaping sustainable results: in e-clothing projects, responsibilities for durability, repairability, energy use, and disposal are often distributed across fashion and textile designers, electronics engineers, software developers, and product managers. Treating eco-design as an iterative coordination practice enables these actors to negotiate trade-offs progressively and to refine sustainability goals as technical feasibility and user requirements become clearer.

5 Conclusion

This study examined how eco-design can be more effectively integrated into e-clothing development. The results from the literature and interviews indicate that only a limited number of studies simultaneously address eco-design methods, the e-clothing design process, and eco-design supporting tools, suggesting that current research remains fragmented across disciplinary boundaries. This distribution highlights the need to more explicitly connect eco-design approaches with the interdisciplinary workflows through which e-clothing systems are actually designed and realised.

E-clothing development is an interdisciplinary and iterative process. These characteristics were reflected in the synthesized workflow model developed in this research. The model describes a process that begins with contextual research, followed by iterative design cycles that include PoC development, MVP prototyping, user testing, and a final product-market fit stage.

Integrating eco-design into the e-clothing design workflow faces five main challenges: the absence of base or reference products, the uncertainty in the early design stages, the eco-design conflicts arising from textile–electronics integration, the misalignment of eco-design regulations and priorities across the dual sectors, and the misalignment of values and communication within interdisciplinary teams. To address these challenges, this study visualised several integrated eco-design intervention points within the e-clothing workflow model and proposed corresponding eco-design tools for each intervention point. The results suggest that lightweight, shared, visual, and qualitative tool formats are particularly effective in responding to these challenges.

The proposed eco-design toolkit framework and its cyclical structure provide a workflow-embedded methodological support that enables teams to revisit sustainability questions as design knowledge matures and prototypes evolve. The toolkit supports iterative co-design activities across concept, PoC, and MVP stages, allowing sustainability reasoning to shape design directions while decisions remain flexible. By linking sustainability reflection to key decision points and interdisciplinary collaboration, the study offers a methodological framework that can support both experimental research prototypes and commercially oriented product development.

However, several limitations of this research should be acknowledged. First, while the narrative review integrated academic and grey literature, the field of e-clothing remains emergent and fragmented, which may have limited the completeness of the conceptual landscape. Therefore, this study did not encompass all systemic dimensions influencing eco-design in e-clothing. External dimension interests, such as e-clothing manufacturing, economic and market-driven constraints, and supply-chain or post-consumer management systems, were beyond the scope of this research but remain critical to achieving holistic sustainability transitions. They should be examined in future studies to create a more comprehensive understanding of this study.

Moreover, noted the selected sources and participants are mainly from Europe, North America, and East Asia, reflecting the current concentration of research activity in sustainable design and wearable technologies within these regions. While this distribution mirrors dominant academic and industrial developments, it may limit the representation of perspectives from other contexts. Future research could therefore further explore regional differences, particularly with regard to eco-manufacturing practices, local material infrastructures, and supply chain configurations for e-textiles and e-clothing.

Second, the semi-structured interviews involved a relatively small and selective sample of participants. Therefore, the findings may reflect certain disciplinary or regional biases and should not be generalized without caution. Additionally, this study focused primarily on review and reported practices, rather than direct testing or measurement of tool performance within active design projects. Future research could build on this work through longitudinal case studies, participatory tool prototyping, or quantitative assessment of tool impact in real-world design contexts.

Despite these limitations, this study offers a structured, methodological perspective on eco-design integration in e-clothing design. Future work may further focus on structuring and designing the toolkit, testing, validating and adapting to real-world design and industrial contexts, to explore how iterative sustainability decision-making can be obtained throughout the full development stages of e-clothing products. Overall, this study contributes to support the sustainable design research for education contexts, researchers and practitioners by providing a conceptual approach for embedding eco-design into the evolving workflows of e-clothing systems, strengthening the connection between early-stage prototyping, interdisciplinary collaboration, and long-term environmental performance.

Author contributions

WW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Resources, Software. DC: Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2026.1772804/full#supplementary-material

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