systems

MDPI

Article

Fostering Directions for Digital Technology Adoption in Sustainable and Circular Fashion: Toward the Circular Fashion-Tech Lab

Daria Casciani and Erminia D'Itria *

Design Department, Politecnico di Milano, 20158 Milano, Italy; daria.casciani@polimi.it
* Correspondence: erminia.ditria@polimi.it

Abstract: The fashion sector, recognized for its resource-intensive methods, is currently encountering pressing sustainability issues due to its substantial dependence on natural resources, extensive utilization of chemicals, and exploitation of labor within its supply chain, thus giving rise to notable environmental and ethical apprehensions. In the Industry 4.0 era, which emphasizes the integration of new production technologies to enhance working conditions, productivity, and production facility quality, the fashion sector has discovered opportunities to tackle sustainability challenges by adopting technology for transitioning to circular, greener, and digital systems with reduced environmental impact. Despite promising prospects, the opportunities provided by this paradigm are yet to be fully realized. In this context, design is crucial in enhancing digitally driven production processes for fashion companies within this framework. To explore this, the study suggests an iterative approach to recognizing challenges and opportunities, concentrating on the current alignment with technological advancements. A design-focused strategy aims to devise a comprehensive approach to fashion sustainability and circular economy (CE) principles within the Industry 4.0 framework. The aim is to establish an innovative laboratory model that aids fashion companies in effectively managing the sustainable and digital transition. The study offers insights into potential research opportunities to accelerate the Industry 4.0 transformation in the fashion sector. It envisages a more positive, sustainable, and responsible future by establishing a Circular Fashion-Tech Lab, integrating innovative technologies for sustainable and circular practices in the fashion industry.

Keywords: design innovation; circularity; fashion-tech; industry 4.0; sustainability; laboratory

Citation: Casciani, D.; D'Itria, E. Fostering Directions for Digital Technology Adoption in Sustainable and Circular Fashion: Toward the Circular Fashion-Tech Lab. *Systems* **2024**, *12*, 190. https://doi.org/10.3390/systems12060190

Academic Editors: Pingyu Jiang, Guozhu Jia, Yuchun Xu, Bernd Kuhlenkötter, Petri Helo and Wei Guo

Received: 29 February 2024
Revised: 23 May 2024
Accepted: 28 May 2024
Published: 29 May 2024

1. Introduction

The fashion industry is one of the most resource-intensive sectors due to increasingly rapid production and consumption cycles and the global network of intertwined and complex linear supply chains [1,2]. As a whole system, it is currently responsible for exploiting natural and finite resources for the overproduction of textiles and clothing, generating many different waste streams that end up in landfills, using chemicals in the production and manufacturing of fabrics, and exploiting workers in various steps of the supply chain [3,4]. In today's adoption of the Industry 4.0 (I4.0) paradigm [5–10], fashion companies could exploit I4.0 technologies to overcome the challenges and reach sustainable development goals (SDGs) and a competitive edge. According to McKinsey [11], the COVID-19 pandemic consolidated the role that digital technology could play in the fashion industry, from embedding digital tools in their workflows and decision-making to accelerating e-commerce consumers' fruition. Such technologies aim to impact global fashion companies' operations and move the linear system towards a circular one [12,13]. However, purely tech-driven innovation approaches are claimed to be unable to guarantee a positive transition in the fashion industry due to a partial and techno-positivistic

perspective that leads too linearly toward sustainability [14]. Conversely, a design-driven approach, applying a design-thinking methodology, can be strategic to envision innovation in products, services, systems, and processes that encompass environmental and social sustainability and account for patterns of change in cultural contexts and technological transformations. The design-driven approach could enable a green and digital transition for a long-term systemic transformation of the whole fashion system [14, 15]. Such a twin transition, expressed by the European Green Deal Plan [16], the Green Deal Industrial Plan [17], and the European industrial strategy toward a digital transformation [18], aims to develop a transition toward a net-zero industry, coupling the identification of new business and economic models with clean, affordable technological solutions to lessen the impact of the European sector [19].

This paper considers the fashion industry primarily related to textile and clothing applications, focusing on the design, production, and distribution of textiles, fabrics, and fashion-related non-standard materials and garments. We aim to understand the status of I4.0 and I5.0 technological adoption, implementation, and integration into the Italian and European fashion companies through a comprehensive literature review to identify the different barriers that limit the paradigmatic transition of the industry. Initiatives that foster new sustainability paradigms enabled by technologies and design-driven approaches are scarce, limited, and dispersed. Previous studies that identify best practices in support models for fashion-tech start-ups recognize the importance of networks and ecosystems of public–private players [20]. Therefore, the research is focused on understanding which could be the supportive entities and modalities for ensuring that fashion companies overcome the barriers of purposeful application and integration of technologies toward a sustainable and responsible future.

2. Unlocking Preliminary Contextual Insights: An Overview of the Twin Transition

2.1. The Digital Transition: From Fashion 4.0 toward Fashion 5.0

The breadth and depth of technological applications in fashion are expanding [21]. All the actors along the supply chain are leaning toward technologies to overcome current industrial ecosystem challenges related to sustainability, product quality, regulatory compliance, and clients' dynamic requirements in industries [22]. Through a variety of technologies like big data, artificial intelligence, cloud computing, collaborative robotics, additive manufacturing, virtual, augmented, and mixed-reality, intelligent sensors, the Internet of Things, and radio-frequency identification, I4.0 has embraced the power of digitization and information technology in defining a cyberindustry/intelligent industry [5].

However, several scholars have criticized the scope and values of I4.0 for its strict technocratic focus on maximizing efficiency and flexibility of mass production toward profitable development [23–25]. Therefore, Industry 5.0 (I5.0) emerged to complement the existing I4.0 paradigm, recognizing the importance of values such as environmental respect toward resilient and prosperous growth, societal goal achievement, and workers' well-being improvement in industrial processes as augmented operators trained to work with digital technologies, tools, and machines [26,27].

Taking a critical position for the techno-economic use and application of digital technologies in I4.0, I5.0 promotes a systematic approach to technologies (e.g., human–machine interaction technologies, bio-inspired technologies and intelligent materials, digital twins and simulation of entire systems, data transmission, storage, and analysis toward interoperability, artificial intelligence, technologies for energy efficiency, renewables, storage, and autonomy) with the main goals of human-centricity, environmental sustainability, resilience, and operators' well-being toward the positive future of European industry and society [28–33]. I4.0 is technology-driven, and I5.0 is value-driven; they are interconnected and interdependent, driving a social-techno revolution with digital technologies as enablers and societal needs as the ultimate goal [33].

Some scholars claim that I5.0 could achieve environmental sustainability goals thanks to sustainable thinking, circular intelligent products, value network integration, intelligent automation, and operational and resource efficiency [34]. In addition, the human-centricity objectives could be achieved by system integration and interoperability, data sharing and transparency, workers' upskilling and reskilling, and employees' technical assistance, servitization, and personalization [34].

Therefore, digital technologies empowered by values are crucial for increasing the sustainability of the entire fashion ecosystem [35]. A change in the paradigms of the sector, against resource exploitation and profit-driven industry, is requested and desired. Companies are called to become more resilient to supply chain disruptions and use the technological medium to become responsible, transform their unsustainable performances, and enable transparency as their stakeholders ask for circular solutions to move towards sustainability [36–38].

2.2. The Green Transition: Sustainability through Circularity

Amid the current shift towards sustainability, the circular economy (CE) is acknowledged as the primary framework for tackling the supply chain challenges under discussion [39]. In a circular context, the design role is pivotal for impacting unsustainable practices, as its decisions are responsible for 80% of a product's impacts [40]. The design process shapes values, formulates strategies, and resolves challenges. The notion that design holds a critical technical position in orchestrating the fashion system circle(s) during the evolving sustainability transition is substantiated by the fact that most sustainability advantages stem from procedures and processes established during the design phase [41].

In such a scenario, it is essential to distinguish and assert the difference between the concepts of sustainability and circularity [42]. While these terms are often used interchangeably, a thorough analysis reveals that circularity is a transition mechanism to achieve the state of resource balance that constitutes sustainability. If sustainability is the goal—a state of homeostasis sought to thrive within the constraints imposed by the planet [43]—then circularity becomes a means to attain this objective. This concerns preserving environmental systems at optimal conditions and monitoring improvements rather than declines. It emphasizes the need for minimal human-induced stress on the environment to prevent any noticeable harm to both environmental and social systems, ensuring the safety of people and their communities [44,45]. Today, the circular approach is recognized and adopted as the primary solution to prevent such issues. This is about establishing a framework that shifts away from the idea of resources reaching the end of their life cycle by focusing on minimizing, reusing, recycling, and recovering them in various production, distribution, and consumption stages [46]. This approach applies to the individual (products, companies, and consumers), intermediate (eco-industrial parks), and large-scale (city, region, nation, and beyond) levels, aspiring to implement sustainability for the planet and also for the people. The objective is to simultaneously promote environmental well-being, economic prosperity, and social fairness, benefiting both present and future generations [47,48].

2.3. Actual Gaps in the Twin Transition

The expected paradigmatic change demands more systemic approaches to transforming the fashion, textile, and clothing industries. The current trend of circularity and sustainable development, as outlined by Sterling [49], calls for a change from homogeneous systems of "doing better things" to holistic systems of "doing things better" to establish a sustainable paradigm. The combination of numerous supporting and core technologies is required for this I4.0 shift.

Although I4.0 promises to offer great opportunities for business profitability and socio-environmental sustainability, the literature reveals that the rate of technology adoption still needs to grow [50]. Khanzode et al. [51] discussed a slowdown in the digitization

of industrial processes and the implementation of digital technologies into traditional processes. As a result, the subsequent shift towards an I4.0 system is challenged [52].

Three major issues are emerging from the literature that limit the adoption, implementation, and integration of I4.0 and I5.0 inside the fashion ecosystem: the intrinsic resistance to change by proper fashion companies, the lack of technological implementation and readiness to specifically support the fashion industry, and the cultural resistance of fashion companies that are commonly handicraft-based and lack technological expertise. Fashion companies have traditionally been based on a linear system and tend to favor established practices and processes until the economic return is guaranteed rather than change their businesses and practices in a disruptive and radical way [53]. Besides, the current technological readiness level (TRL) of I4.0 technologies could be higher, considering their adoption and commercial scaling in fashion applications. In addition to this, I4.0 technologies lack customization and integration into existing fashion practices and processes [35]. Also, fashion companies' digital literacy about technologies is very low, thus compromising the possibility of selecting the best technologies for their purpose of tech-green transformation.

Moving from the context above, this article aims to give a snapshot of the state-of-the-art opportunities of the technologies of I4.0/I5.0 in the fashion industry (clothing and textile sector) for sustainability and circularity purposes. It aims to investigate the (i) achieved level of technological adoption, (ii) barriers, and (iii) initiatives that support the diffusion, application, and implementation of the tech-green transition among fashion companies. Therefore, the supportive initiatives are investigated regarding (iv) research areas of interest, (v) their organizational framework, (vi) infrastructure and enabling technologies, and (vii) achieved sustainability impacts. The investigation results in extracting and codifying working guidelines for setting up a design-driven laboratory.

Therefore, Section 2 illustrates the methodology, which is composed of an initial literature review to understand the level of digital transformation of fashion companies toward sustainability and circularity through the application of I4.0 technologies, followed by case-study research focused on identifying research laboratories and centers engaged in fashion-tech, sustainability, and circularity-related R&D activities. An iterative method models the data to highlight exemplary case studies operating in the I4.0 paradigm toward circularity and sustainability. Section 3 illustrates the literature review results, exploring how academic/research institutions and industries are adopting digital technology, their digital transformation performances, and their digital dynamic capabilities. Section 4 presents the results of the case studies, highlighting the features for the development of a laboratory to support the twin transition of fashion companies in the textile and clothing sectors by mapping the current primary research focus and interests, the typologies of offered services, and the mode of support delivery. Section 5 discusses the investigation's findings by presenting the Circular Fashion-Tech Lab model, where design is seen as an outlier for creating an ecosystem of support for the fashion industry to become more sustainable and close the micro-loops of circularity. Finally, Section 6 concludes the paper by describing the limitations of this work and how the presented project creates opportunities for further research.

3. Materials and Methods

The methodology employed in the research consisted of an initial phase of desk research based on a literature review, followed by a case study approach. This method was selected for its appropriateness in conducting detailed analyses of the existing knowledge related to the subject under investigation [54]. Considering that fashion-tech is a relatively nascent field [20], the case study methodology based on a cross-case design approach emerges as a valuable tool, offering practical insights that facilitate the interpretation of trends and phenomena within the discipline [54]. This approach enables the comparison of individual cases investigated through grey literature and second-hand sources within their broader context, considering a system of variables and characteristics that allow for

a rigorous and solid interpretation, allowing authors to develop inductive theories [55]. The research was conducted from November 2023 to February 2024.

We initially explored the existing literature to establish the theoretical foundation for this research. This review encompassed various sources, including academic articles, papers, conference proceedings, book chapters, and industry reports, sourced from databases such as Scopus, Web of Science, and Google Scholar. To ensure comprehensive coverage of the topic, we examined material spanning from 2016 to 2023, a period of eight years. This timeframe was chosen to capture the evolution of concepts related to Industry 4.0, which gained prominence following Schwab's work in 2016. According to the selected databases, this timeframe is also in line with the increasing publication trend on these topics. Nine keywords were identified and researched: state-of-the-art, fashion, textiles, digital, technol*, innovation, Industry 4.0, sustab*, and circ*. Starting from those nine keyword equations, the research was further filtered through the limitation to specific keywords that emerged from the query, and 143 documents were identified (see Table 1). The study applied to titles, abstracts, and keywords for Scopus and WOS and to "any type" for Google Scholar. Also, the search was limited to only open-access documents that had reached the final publication stage. The filtering process necessitated several stages to categorize the extensive and varied literature, spanning fashion design, business management, and engineering disciplines. Initially, titles and abstracts were scrutinized to eliminate publications unrelated to exploring digital innovations in the fashion industry. After removing duplicates, 38 publications remained. A comprehensive assessment followed, guided by three distinct inclusion criteria. Firstly, publications were required to be written in English or Italian. Secondly, studies were conducted to determine whether they employed qualitative or quantitative methodologies. Finally, publications were chosen based on their emphasis on cutting-edge analyses, frameworks, and guidelines.

The articles have been categorized based on three overarching dimensions that have defined the scope of this study. This categorization is undertaken to facilitate an understanding of the status of Industry 4.0 technological adoption, implementation, and integration within fashion companies. These dimensions encompass adopting digital technology, applying CE principles, and the digital transformation process. Digital adoption involves investigating how digital technologies can be a pivotal factor in gaining a competitive advantage for a company [56]. Industry 4.0 possesses the potential to revolutionize interactions with the market, employees, and customers, enabling the establishment of a digital advantage. This entails creatively merging digital information and physical resources to create value and generate revenue [37,57]. The CE aspect refers to elements that utilize digital technologies to advance and fulfill broader sustainability objectives, such as reducing the carbon footprint and overall impacts associated with energy generation and industrial production [58]. This area emphasizes incorporating circularity principles, ensuring a more responsible and resource-efficient approach across the entire lifecycle of products and processes to progress towards sustainability [7,59]. Digital transformation involves integrating digital operational technologies into the fashion transformation process, representing a natural progression to uphold and enhance the current market standing by enabling the incorporation of elements for building an Industry 4.0 ecosystem [6,60].

Furthermore, the second reading session considers only 29 publications on which we based the framework (see Table 1).

Table 1. Literature review process and final list of selected publications.

Included Documents (typology)	Scientific Articles Papers Conference Proceedings Book Chapters Industry Reports
Time Horizon	2016–2023
Keywords (1st query)	state-of-the-art AND fashion AND textiles AND digital AND technol* AND innovation AND Industry 4.0 AND sustab* AND circ*
Search Applied to Titles, Abstracts, and Keywords	Scopus → 26 references WOS → 17 references Google Scholar → 100 references
Screening of Titles and Abstracts	38 references, excluding publications unrelated to the study
Full-Text Analysis and Final Selection	29 references were selected based on language, methodology, and outcomes

Title	Type	Source	Year	Digital Technology Adoption	Circular Economy	Digital Transformation
4.0 Technology Within Fashion and Luxury Production	Scientific article	Google Scholar	2019			✓
Boosting Emerging Technology Adoption in SMEs: A Case Study of the Fashion Industry.	Scientific article	Scopus	2021	✓	✓	
Challenges and Driving Forces for Industry 4.0 Implementation	Scientific article	Scopus	2020	✓		✓
Design principles for Industries 4.0 scenarios.	Scientific article	Google Scholar	2017	✓	✓	✓
Digital technology adoption, digital dynamic capability, and digital transformation performance of textile industry: The moderating role of digital innovation orientation.	Scientific article	Scopus	2022			✓
Exploring the nature of digital transformation in the fashion industry: opportunities for supply chains, business models, and sustainability-oriented innovations.	Scientific article	Scopus	2022		✓	✓
Fashion Industry: Exploring the Stages of Digitalization, Innovative Potential and Prospects of Transformation into an Environmentally Sustainable Ecosystem.	Scientific article	Google Scholar	2023	✓		✓
Fashion 4.0. Innovating fashion industry through digital	Scientific article	Google Scholar	2018	✓		✓

transformation						
Fashion's digital transformation: Now or never.	Industry report	Google Scholar	2020	✓		
Il livello di maturità digitale delle aziende lombarde	Industry report	Google Scholar	2023	✓		✓
Implementation of Digitalized Technologies for Fashion Industry 4.0: Opportunities and Challenges.	Scientific article	Science Direct	2022	✓		
Industry 4.0 readiness assessment for apparel industry: A study in the Sri Lankan context	Scientific article	Google Scholar	2020	✓		
Industry 4.0 and Technology Adoption in The Garment Industry.	Scientific article	Google Scholar	2021	✓		
Industry 4.0: The barriers and opportunities for implementation of digital technology in the fashion and textile industry	Report	Google Scholar	2018	✓		✓
Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants	Scientific article	Google Scholar	2021	✓		✓
Industry 4.0 Disruption and Its Neologisms in Major Industrial Sectors: A State of the Art.	Scientific article	Google Scholar	2020			✓
Industry 4.0 in Textile and Apparel Industry: A Systematic Literature Review and Bibliometric Analysis of Global Research Trends	Scientific article	Google Scholar	2022	✓		✓
Industrial districts and the fourth industrial revolution	Scientific article	Science Direct	2021	✓		✓
Fashion 4.0–digital innovation in the fashion industry.	Scientific Article	Google Scholar	2018	✓	✓	✓
Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: Interpretive structural model and triple helix framework	Scientific article	Science Direct	2021	✓		✓
Maturity model toll to diagnose Industry 4.0 in the clothing industry	Scientific article	Google Scholar	2022	✓		

Maximizing performance of apparel manufacturing industry through CAD adoption.	Scientific article	Scopus	2020	✓		✓
New product development process in apparel industry using Industry 4.0 technologies.	Scientific article	Google Scholar	2021	✓		
Secondo Rapporto Industria 4.0 nelle PMI italiane.	Academic report	Google	2018	✓		✓
Technology adoption in the apparel industry: insight from the literature review and research directions.	Scientific article	Google Scholar	2021	✓		
The Emperor's New Clothes or an Enduring IT Fashion? Analyzing the Lifecycle of Industry 4.0 through the Lens of Management Fashion Theory	Scientific article	Scopus	2020	✓	✓	
The Intersection of Fashion, Immersive Technology, and Sustainability: A Literature Review.	Scientific article	Google Scholar	2023	✓		
The State of Fashion Technology Report 2022.	Industry report	Google	2022	✓	✓	✓
Towards sustainable textile and apparel industry: Exploring the role of business intelligence systems in the era of industry 4.0.	Scientific article	Google Scholar	2020	✓		

The case study research phase employed a cross-case study approach, examining various cases to discern similarities and differences and predict comparable outcomes [61]. We mapped laboratory and research entities whose activities focus on the intersection of fashion and technology for sustainability and circularity (see Appendix A). Therefore, the keywords we used for the research were Innovation, Digital*, and Tech* combined with at least one of the sectoral terms Fashion or Textiles and containing Sustainab* and Circularity. The desk-research process for the case studies encompassed academic research using databases such as Scopus, WOS, and Google Scholar; industry-based grey literature using research engines such as Google and Confindustria; and fashion-tech community platforms such as Euratex, Wearsustain, and Tcbl, which have already mapped research entities offering services in between fashion-tech, sustainability, and circularity. To complement the academic and industrial perspectives, we also performed research at the policy level of the EU platform, investigating government publications and thus providing a holistic perspective on the subject. This framework aligns with the qualitative case study approach adopted [61], enabling the investigation of the designed lab as an innovative and interconnected research space and infrastructure geared towards facilitating the digital transformation of the fashion industry. The criteria for selecting and skimming the preliminary collection of case studies were data availability and the level of maturity/progress of the entities.

For this study, we have identified 43 research centers demonstrating engagement with sustainable or technological knowledge in fashion situated across 15 countries all

around the world (Figure 1, Appendix A). The heterogeneous typology of mapped initiatives from university research labs to competence centers allows for a comparison of similarities and differences that have been analyzed in terms of low-level codes (specific innovations and initiatives of each case) and higher-level codes (initiative nature, typology of conducted research, laboratory model, scale, partnerships, disciplinary fields) (for details, refer to Bocken et al. [41] and Appendix A).

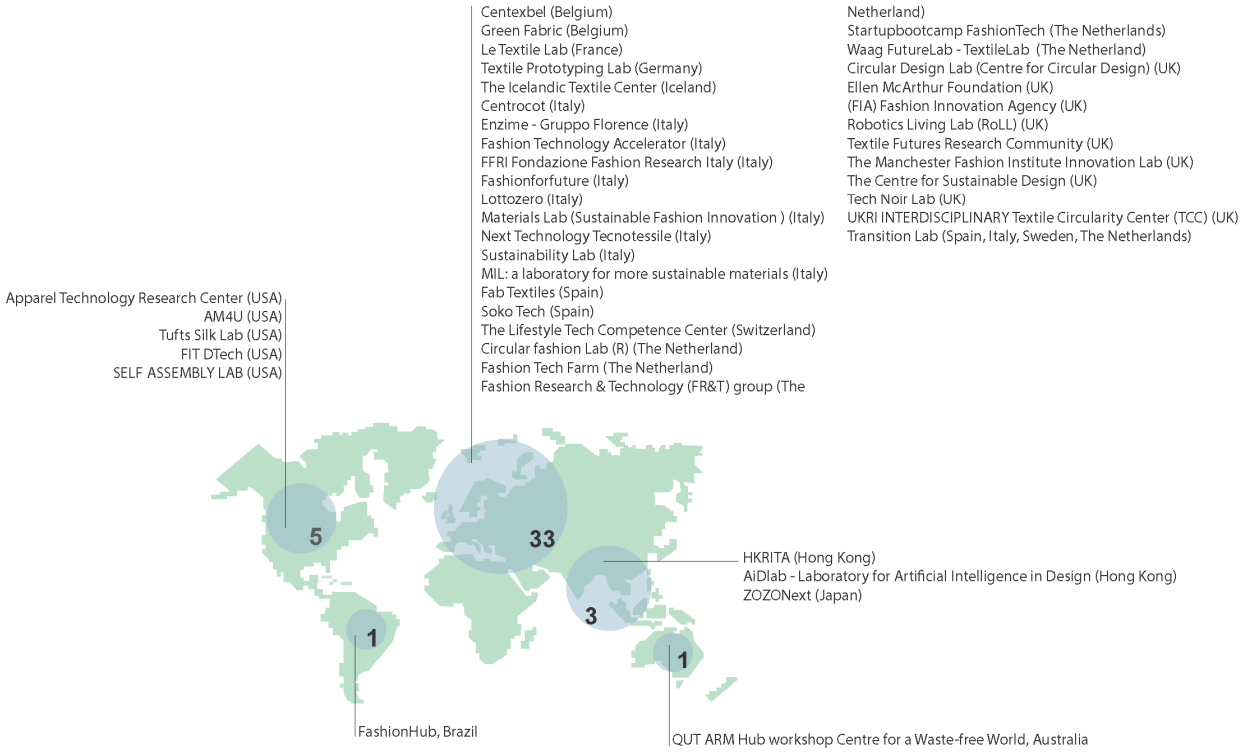

Figure 1. Map of the investigated initiatives.

4. Results of the Literature Review: Level of Adoption and Barriers of I4.0 from Fashion Companies toward Sustainability through Circularity

The systematic literature review aims to map the opportunities and benefits of a technological transition operated by fashion companies, understand the level of technological adoption, implementation, and integration by fashion companies, and identify the main barriers to embracing the digital transformation toward sustainability and circularity. We explored the current adoption, management, and readiness of I4.0's state-of-the-art technology in fashion firms to understand their attitudes, taking the perspective upstream in the supply chain at the design stage. The review shows the fashion industry's main digital and circular development issues and how to define and promote sustainable paradigmatic change from a design-driven perspective.

As discussed by Zahra et al. [56], most of the research on I4.0 technology adoption focused on codifying strategies that allowed fashion businesses to improve in the following ways:

- better reaction time or increased transparency [62],

- real-time market trend analytics for new product development [7],
- increased productivity [63],
- improved innovation capability [64,65],
- cost reduction [63,66],
- easy monitoring [67],
- faster product development process [68],
- increased access to global markets [69].

This perspective provides insights into the benefits achievable by fashion companies in boosting performance and remaining competitive in the global market by adopting I4.0 technologies. In 2021, companies spent almost 1.8% of their sales on tech-driven investments, and these numbers are expected to rise between 3 and 3.5 percent by 2030 [11]. Several studies discuss how the industry needs a newly digitized value chain model that integrates multiple internal processes and data sources, from the design stage to store and sale optimization [7,37,70–73]. According to a study by McKinsey [11], technology adoption could support fashion companies in addressing complex aspects of end-to-end processes, from a better understanding of consumer demand to allowing an integrated supply chain through digital technologies. This means establishing a process in which each phase, from the procurement of raw materials to production, quality control to packaging, retail to distribution, and eventual delivery, is data-interlinked, smart, and interconnected.

Despite this, the literature also highlights that the expected benefits have yet to be able to push fashion companies beyond the barriers that inhibit their digital transformation. Accordingly, we have revisited and reorganized the obstacles listed by Majumdar et al. [74] and Mosca and La Rosa [75] into five key variables (organizational, technological, business, cultural, and normative), grouping the initial set of 22 barriers based on their conceptual nuances and categorizing them according to the multifaceted system of different characteristics and performance objectives typical of I4.0 [76,77]. The organizational group encompasses fashion companies' organizational culture and architectural management [78,79]. The technological and manufacturing-related variables group refers to topics that range from training a skilled workforce to nurturing environments where it is possible to build new infrastructure based on IT [80,81]. The business group involves project management, budgeting, cost analysis, resource allocation, and risk management concerning the new paradigm of I4.0 [79]. The cultural group is concerned about adopting Industry 4.0 technologies in fashion production as it requires training employees in digital skills. The predominantly older workforce is reluctant to change, rendering the training process comparable to initiating a new profession. The evident generational divide may lead to differing work paces in teams, with older artisans passing on their expertise to younger, technology-savvy colleagues [75]. The normative group refers to framing new rules regarding the possible roadmap for transitioning traditional business functions into smart ones aided by I4.0 technologies [82] (Table 2).

Table 2. List of defined key variables (adapted from Majumdar et al. [74]).

ORGANIZATIONAL-RELATED VARIABLES	Lack of understanding and commitment from top management. Complex organizational and process changes. Time constraint. Lack of experience in organizational management. Fear of failure. Problems with coordination and collaboration.
BUSINESS-RELATED VARIABLES	High implementation cost. Lack of clear apprehension of benefits. Lack of risk management tools for investments. Lack of experience in budgeting.

TECHNOLOGICAL AND MANUFACTURING-RELATED VARIABLES	Employment disruption. Lack of internet coverage and IT facilities. Lack of ad hoc technologies designed to be integrated into the current/traditional fashion processes (developed for other sectors and applications). Seamless integration and compatibility issues. Inadequate maintenance support system. Lack of knowledge of manufacturing process operation systems. Poor R&D on I4.0 adoption.
CULTURAL VARIABLES	Lack of digital culture. Increased skill requirements for employees. Lack of trained staff.
NORMATIVE-RELATED VARIABLES	Lack of a methodical approach to implementation. Legal and contractual uncertainty. Lack of government support and policies.

The traditional fashion industries are gradually incorporating technologies into their workflows, but cultural and economic barriers and a shortage of skilled workers are delaying the pace [60,83,84]. Furthermore, limited studies are currently focusing on fashion-tech for sustainability and circularity, with only a few existing labs dedicated to investigating technologies in the fashion sector that will provide workers with knowledge about sustainable technologies and support companies in the digital and green transition [37,60,70]. These laboratories and research entities are strategic tools for supporting fashion companies during the green and digital transition [85]. From a design perspective, both opportunities and barriers act as possible insights for the transformation of fashion companies systemically and systematically, offering specific perspectives on integrating emerging technologies into their supply and value chain. Di Lodovico et al. [20] discussed how fashion groups proactively embrace open innovation methods, incorporating contests, corporate incubation, acceleration programs, and educational collaborations. Entrepreneurial innovation is fostered through initiatives led by academia-linked and independent incubators and accelerators. The driving force behind this transformative process comes from fashion, technology, and fashion-tech start-ups, implementing inventive solutions across different business models like B2B, B2C, B2B2C, and C2C. In this context, design could have a strategic role in driving this transformation by positioning itself at the center of decision-making for companies to drive technological change with a positive and purposeful scope of addressing holistic sustainability dimensions and circularity.

5. Cross-Case Study Analysis Results: Drafting a Taxonomy of Initiatives for Fashion Companies' Green and Digital Transition

The case study research aims to deconstruct the complex context of the fashion and technology research organization by understanding the current practices and modeling them according to a series of criteria (readiness, adoption, and implementation). This enables an understanding of how to create manageable steps that will help fashion companies in the textile and clothing sector achieve circularity and sustainability through technology. The analysis and coding of the case studies were conducted to understand the following aspects:

- Research areas and topics of interest for research initiatives;
- Research support toward sustainability and circularity;
- Entangled disciplinary domains involved in building efficient and practical support for the fashion industries;
- Nature of research initiatives and their management;

- Offered services to aid, support, and accompany the fashion industries in the twin transition;
- Configuration of physical structures, infrastructures, and technological assets.

5.1. Deepening the Research Areas and Topics of Interest for Research Initiatives

The compared initiatives exhibit a diverse composition in their vocation, encompassing fashion, clothing, and textiles, but have in common that they are actively working to enhance responsibility through technology support or adoption. Their efforts extend beyond the design phase, encompassing business management and technological aspects. The analysis of the cases allowed us to understand the main research areas of those research entities, therefore understanding the significant topics of interest for fashion companies. Based on the recurrence of these topics, we were able to categorize four main research areas (Figure 2):

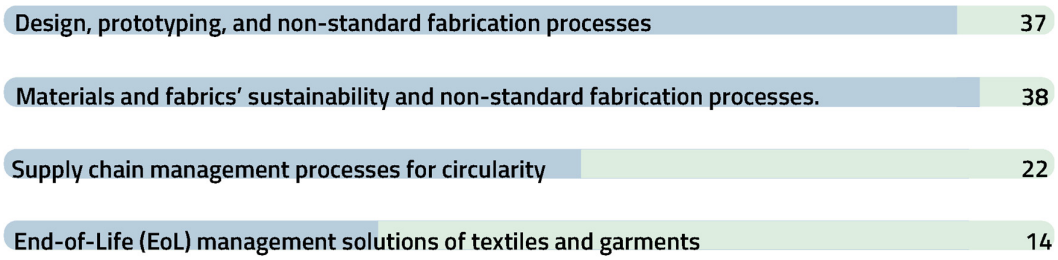

Figure 2. Research areas and topics of interest for research initiatives.

- Design, prototyping, and non-standard fabrication processes. Digital and virtual fashion design strategies, from research to sampling processes, are implemented to encompass enhanced human–machine/computer interactions and new, advanced design creative processes for fashion operator 4.0. This involves understanding digital software and hardware compatibility, limitations, and opportunities to enhance traditional and innovative design and pattern-making workflows. Additionally, it explores the potential of reverse engineering from body scanning, investigates the possibilities of AI in collaborative research and co-design approaches, and applies generative digital tools to promote circularity in the fashion industry.
- Materials and fabrics' sustainability and non-standard fabrication processes. The research shows a critical need for monitoring material-related information throughout the entire value chain. This necessitates the establishment of a shared methodology and language to facilitate the exchange of information regarding materials. Evaluating the limitations hindering the introduction of innovative technologies within the network of small and medium-sized enterprises (SMEs) is crucial. Understanding the constraints associated with adopting existing technologies for tracking activities and fostering transparency among SMEs is essential for creating synergies within the supply chain. For example, when analyzing the management of textile/leather waste, it is necessary to inventory the companies, categorize them, define KPIs, and identify bottlenecks and strategies in order to improve the sustainability and circularity of the sector.
- Supply chain management processes for circularity. Fostering models that facilitate decision-making in the design and performance measurement of circular supply chains involving the integration of traceability systems, smart technologies, and solutions to empower the management of (reverse) material and product flow both pre- and post-consumption. These models aim to enhance supply chain operations' efficiency, transparency, and sustainability by leveraging advanced technologies for monitoring, tracking, and optimizing the flow of materials and products throughout their lifecycle.

- End-of-life (EoL) management solutions for textiles and garments. In this direction, industrial and urban textile waste collection systems are rethought in relation to the European directive and the national legislation: an estimate of the textile waste produced per person, strengths and weaknesses of the supply chain in the treatment processes of collected and processed textiles, and correct management of synthetic fabric and microfiber release in the production and recycling phases.

These four research tracks represent the focus of the operation of research centers/labs (Figure 3). They are found in perfect alignment with the CE framework, which defines how innovation can occur by designing and creating products to safeguard resources, maintaining materials in a closed loop at their highest value, reimagining the linear fashion supply chain, and considering the management of processed waste to transform it positively [2].

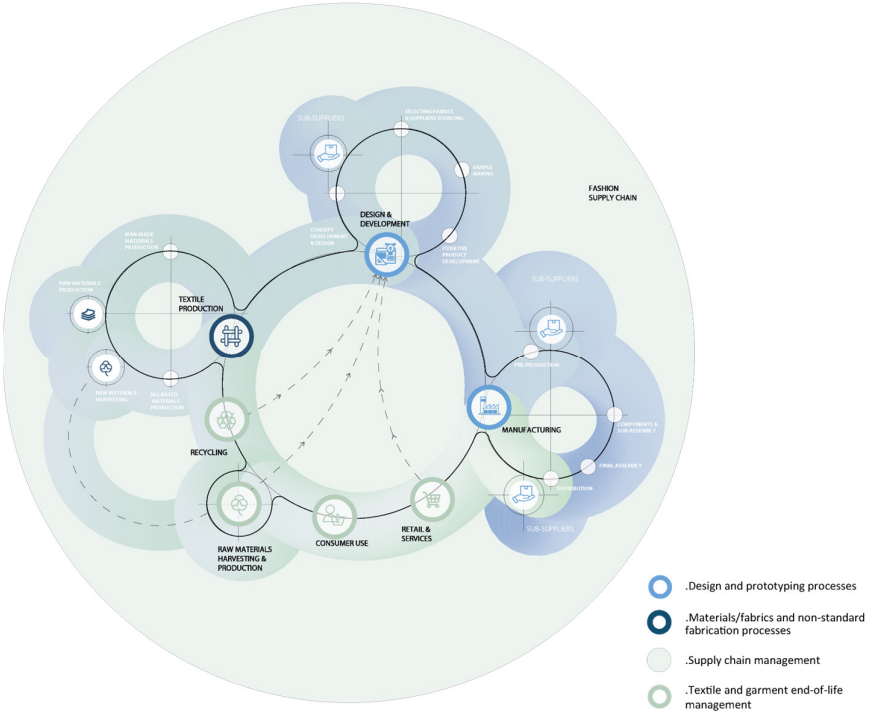

Figure 3. Systematization of the research areas and topics of interest for research initiatives.

5.2. Understanding Research Support for Sustainability and Circularity

All the mapped entities address sustainability and circularity within their supportive activities. They actively embrace stakeholders' evolving sustainability expectations, proactively addressing them through the strategic integration of circular practices. Their digital-driven approach fosters ideas that align with human preferences and technological feasibility, showcasing a dedicated commitment to sustainable innovation. Also, they play a crucial role in contributing to innovation and facilitating a sustainable transformation in the fashion industry by adopting different research and operational methods that enhance the fundamental pillars of sustainability [42]: environment, economy, society, and culture (Figure 4).

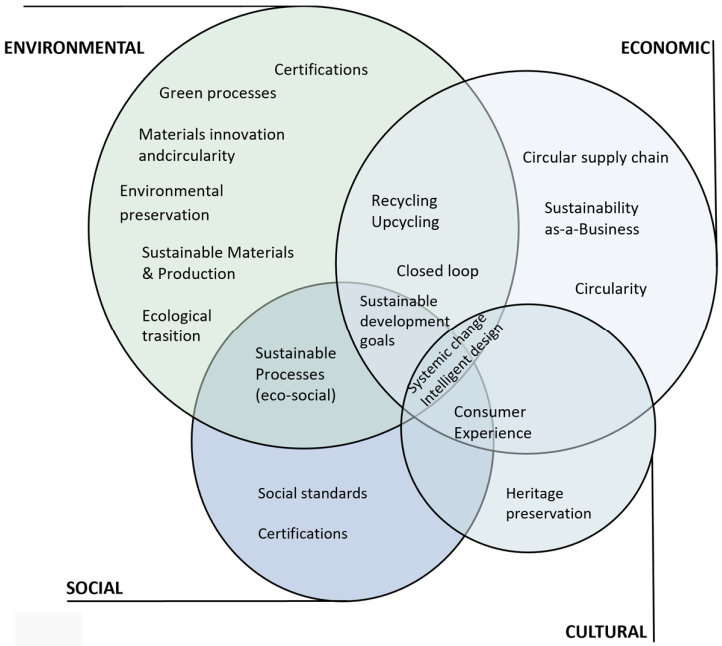

Figure 4. Sustainability areas and topics of interest for research initiatives.

Figure 4 depicts these instances, focusing on enhancing environmental practices to reduce greenhouse emissions during operations [86]. They adopt sustainable materials and production methods, contributing to the eco-friendly transformation of the clothing industry and the development of innovative materials [75]. Additionally, they invest in the innovation of eco-labels, sustainability certifications, and materials to optimize the positive impacts on production, consumption, and circularity, thus promoting environmental preservation [87].

From an economic standpoint, these cases emphasize organizational circularity in decision-making processes and performance improvement [22]. They invest in digital solutions for circular supply chains, facilitating data and material flow exchange [13]. Initiatives promoting "sustainability as a business" are undertaken to enhance the fashion industry's competitiveness through sustainable strategies [86].

Initiatives engaging with the social dimension prioritize certifications and adherence to social standards, addressing social concerns transparently through digital means [13]. Those focused on cultural aspects prioritize digitization for cultural heritage preservation [88]. Some cases operate at the convergence of these areas.

At the core of these pillars, there are instances of actively pursuing sustainable development goals through digital mediums. This involves building resilient infrastructure, promoting inclusive and sustainable industrialization, fostering innovation, ensuring sustainable consumption and production patterns, and taking immediate action against climate change and its repercussions [89].

At the intersection of environment and society, some initiatives invest in processes preserving ecologies and societies via sustainable technologies impacting manufacturing for both people and planet preservation [37]. In the overlap of environment and economy, practices related to recycling, upcycling, and closed-loop fashion supply chains address operational and managerial aspects, promoting sustainability [90]. Socio-cultural and economic considerations involve informing consumers about the social and environmental impacts of textiles/clothing, enabling conscientious purchasing decisions [91]. Lastly, the convergence of environmental and socio-economic aspects aims for systemic change and intelligent design, creating a new model that enhances environmental, economic, and social sustainability while promoting responsible design by adopting digital solutions [92].

5.3. Involving Entangled Disciplinary Domains

From the data analysis emerged a heterogeneous picture of knowledge and disciplinary fields involved in such initiatives, ranging from design, engineering, and science as the main three domains out of four of creative exploration that are coherent with the research area of interest as highlighted in the previous section (Figure 5). The role of each domain is to maximize the creative and innovative potential of research and development, where the arts and humanities focus on human behaviors and perceptions, science converts information into knowledge, engineering solves empirical problems, and design, like a collector and a central element, takes the solutions to maximize function and enhance the human experience [93] (Figure 5).

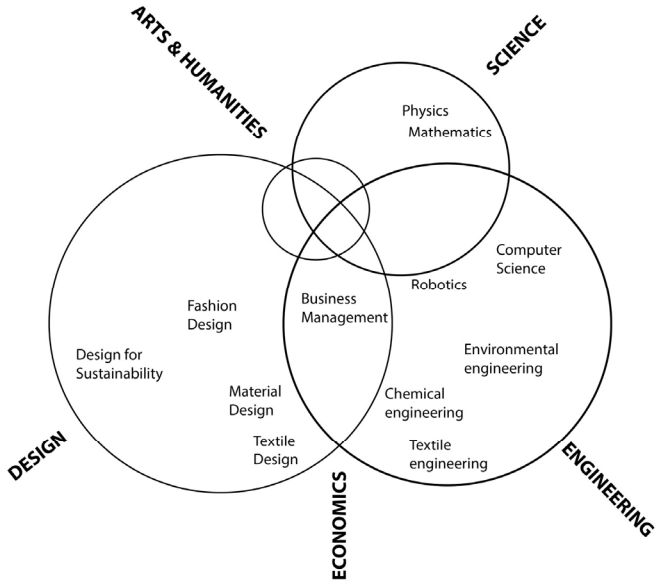

Figure 5. Disciplines involved in the investigated initiatives.

The integration of knowledge from these different disciplines is crucial in framing and navigating the complex problems of the fashion-tech paradigm. By combining insights from various fields, a more comprehensive and holistic understanding of the issues at hand can be achieved, which aligns with the sustainability understanding [94]. This interdisciplinary approach synthesizes diverse perspectives, methodologies, and expertise, contributing to more effective problem-solving and innovative solutions. It encourages collaboration and the breaking down of traditional silos, fostering a richer and more nuanced exploration of challenges and opportunities within the identified paths, from design and creation to EoL management [95]. Research initiatives address technological, sustainability, and circularity challenges from a multi-disciplinary perspective and have been applied toward various goals [96].

5.4. Understanding the Nature of Research Initiatives and Their Management

The data showed that these initiatives often operate in heterogeneous settings, navigating the divide between the academic and industrial and public and private spheres. Some mapped initiatives develop hybrid solutions that straddle these two dimensions by connecting actors and systems from both categories. This collaborative and integrative approach is essential for effectively addressing the complex and interconnected challenges associated with achieving sustainability and circularity in the diverse sectors of the fashion industry through technology adoption, integration, and implementation.

Regarding private entities, research labs (7%) can be identified as company units conducting research into a specific disciplinary domain toward developing new ideas, technologies, and solutions that can contribute to the company's competitiveness and growth. The private research centers (20%) have a more complex organization and structure, aiming to explore broader research scopes. Structured as a networked infrastructure, they typically involve professionals and staff from multiple units or departments, bringing together experts with diverse disciplinary backgrounds. Other types of private entities are Fablabs (12%), which are small-scale workshops whose mission is to empower individuals by providing education, community, and workforce toward innovation, design-thinking, entrepreneurship, problem-solving, and change-making, together with open and equitable access to digital fabrication tools, equipment, and technology [97,98]. They are generally open to collaboration with companies and the public to facilitate the diffusion, dissemination, and adoption of technologies within the industry.

In the public domain, the public research labs (2%) are units like the private ones that receive financial support from public sources, such as government grants or subsidies, driven by the overarching mission to contribute to the public interest. While they may adopt business-oriented models for efficiency and effectiveness, their primary goal is to generate knowledge, promote innovation, and address societal challenges to benefit the broader community. Universities are involved as labs (14%), which are single initiatives operating within the academic structures for research conducted for educational, scientific, or experimental purposes, and centers (26%) that are formally structured in between different units/departments within the same university, very rarely involving different universities. Their establishment is driven by the objective of advancing interdisciplinary knowledge through collaborative research, training, communication, and dissemination.

At the intersection of the public and private sectors, we find research labs (5%) stemming from the collaboration between these two dimensions. They typically involve partnerships or joint initiatives between public institutions, such as government agencies or research organizations, and private sector entities, including businesses or industry players. The purpose of such collaboration is often to leverage the strengths and resources of both sectors to address shared challenges, foster innovation, and promote the mutual exchange of knowledge and expertise. Competence centers (2%) are entities aiming at knowledge organization and transfer, and they vary depending on the focus area, scope, domain, and socio-economic framework. Typically, their mission is training, knowledge transfer, interdisciplinarity, standardization, and collaboration among different institutions or departments. Competence centers serve as hubs for specialized expertise and skills to support fashion companies in transitioning toward a digital and green future [99]. Finally, incubators/accelerators (12%) are programs specifically designed to help startups refine their business plans and navigate challenges from the idea stage through the growth stage. These programs typically cater to multiple early-stage startups representing diverse disciplines. Incubators play a crucial role in regional economic development and are often funded through public sources and private grants. In comparison, accelerators operate in shorter and more intensive timeframes.

Despite the fact that 13% of the investigated entities operate primarily within their internal boundaries, indicating an internally focused approach, a significant majority work by setting up partnerships, nurturing external collaborations, and emphasizing a more open and collaborative orientation. These data highlight the importance of external partnerships for most initiatives, potentially involving cooperation with: (i) HEIs (21%) to permit organizations to enhance the quality and relevance of their operations, cultivate and fortify their networks of collaborators, nurture their ability to collaborate and internationalize through the sharing of ideas, and develop new practices and methodologies related to fashion-tech, digitalization, and ecosystem innovation; (ii) companies (27%) to improve and develop assets that will lead to a long-term competitive advantage on the market by providing the field expertise and market requirements; and (iii) other initiatives (NGOs, stakeholders, tech providers, or players outside their structure) to foster a

comprehensive approach to growth and advancement, where the pursuit of new knowledge is coupled with efforts to enhance or create assets, contributing to the overall progress and development of fashion and technologies (hardware and software). Also, the nature of these partnerships can vary based on each initiative's specific goals and objectives (Figure 6).

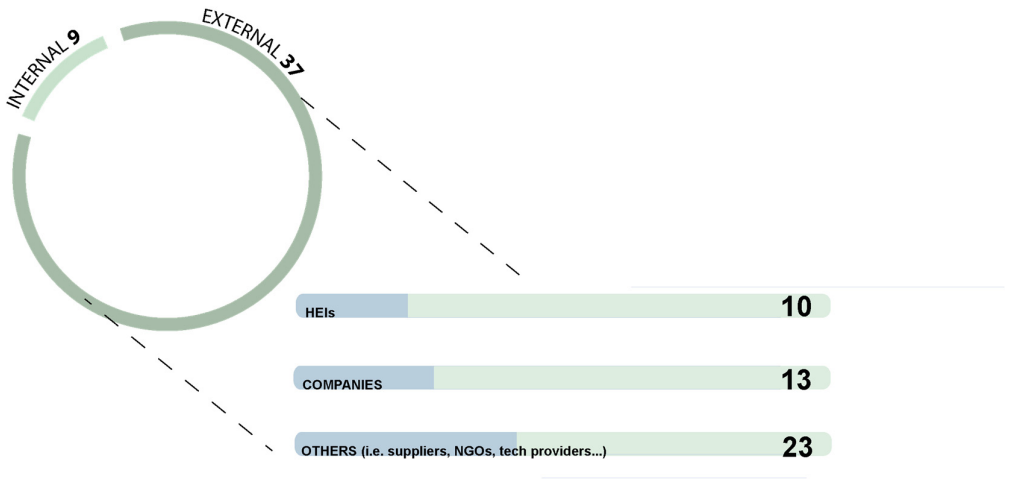

Figure 6. Partnership and involved actors.

5.5. Mapping Offered Services for the Green and Digital Transition of Fashion Companies

When engaging in research-driven practices, the initiatives focus on two methods: basic research (5%) and applied research (21%). Basic research is conducted with the primary purpose of advancing theoretical knowledge. This type of research is traditionally fundamental to university missions and often aligns with their commitment to the pursuit of knowledge and academic excellence.

Applied research is an original investigation conducted to acquire new knowledge but directed toward a specific practical aim or objective. Unlike basic research, which seeks to expand theoretical understanding without an immediate practical goal, applied research focuses on addressing particular issues or solving practical problems related to technology implementation and innovative circular solutions in the fashion industry. Applied research outcomes are intended to have direct applications in technology development, policy formulation, and problem-solving in real fashion industry contexts [100].

Additionally, consultancy activities (20%) support diverse players in achieving complex yet attainable circular goals within the fashion industry. Organizations can make rapid strides toward establishing a more sustainable and environmentally friendly fashion sector by supporting them in scaling innovative green solutions, envisioning new design approaches, and leveraging digital mediums to enhance industry performances. The collaboration and efforts of these various stakeholders are instrumental in driving positive change and promoting a CE in the fashion industry.

Dissemination (14%) and communication (16%) activities are crucial in fostering innovation in the fashion ecosystem and engaging stakeholders. Dissemination aims to make the results available to the scientific community, policymakers, and industry using scientific language that prioritizes accuracy. This is focused on sharing information with specific audiences that can benefit from the research findings. On the other hand, communication activities are geared towards increasing the public visibility of the project and its results. This involves using accessible language to make the information understandable to a broader audience beyond the scientific community, policymakers, and industry stakeholders. Some mapped entities offer educational and training activities (15%) with the scope of transmitting knowledge and skills, encompassing the intellectual and practical

aspects of fashion-tech, and developing sustainable and circular innovations for the fashion industry. This kind of service benefits the internal community of researchers and students of all levels since it is one of the main goals of academia. Still, it could also be delivered to professionals who need to update their CVs and upskill for the current tech-green challenges.

Incubation or acceleration services are offered to help ideas grow from an early stage to a company that can stand independently. Their operations include offering office space, performing administrative functions, providing education and mentorship, offering access to investors and capital, and fostering idea generation.

Finally, the technology demonstration (5%) activities involve prototyping preliminary versions or rough examples of the conceivable product or system. Demonstrations are used to showcase the potential applications, feasibility, performance, and methods of advanced technological ideas. Demonstrations are valuable for testing and developing solutions based on proof-of-concept. They are conceived as small exercises to understand the potential of an incomplete idea, prototypes, and the visible, tangible, and functional manifestation of the concept, showing how to develop it through working models toward pilots. Demonstrations are mainly adopted for validated learnings that engage companies, investors, partners, or potential customers and serve as a tool to convince stakeholders of the merit and feasibility of the idea. They can also be tested on ordinary users to gather feedback and insights for further refinement.

5.6. Investigating the Configuration of Physical Structures, Infrastructures, and Technological Assets

The infrastructures of the analyzed entities encompass the physical and technological components constituting laboratory spaces, devices, and facilities crucial for scientific research, experimentation, and analysis. We found that the existing infrastructures that can support work dynamics are common but can have different configurations. The data showed that most mapped initiatives have a unified and located model (36%). This means the lab or center facility is physically located in a specific place and operates as a single-unit organization. This implies that the facility is a dedicated space with its infrastructure, resources, and staff in a particular location.

Another typology is the distributed and networked structural setting (6%), a dynamic and collaborative system where not a single unit within a single organization operates independently. Instead, depending on the case and need, different partners within the same network have the flexibility to utilize various facilities belonging to the partnership. This suggests a networked approach where resources, expertise, and facilities are shared among partners based on specific requirements and circumstances. Such a dynamic system encourages efficient collaboration, resource optimization, and a more adaptable response to diverse needs within the network. It reflects a model of interconnected and collaborative operations that leverages the strengths of multiple partners for mutual benefit.

The study also identified a minority of cases using a meta-laboratory (3%), which refers to an overarching laboratory that coordinates, facilitates, or oversees the activities of multiple individual laboratories or research entities. The emphasis is on collaboration and interdisciplinary efforts, where experts from various fields come together to work on shared goals or projects. The meta-laboratory concept promotes synergy, resource sharing, and a more comprehensive approach to research by uniting the strengths and expertise of different research units or laboratories. It also refers to a pop-up approach to lab structures that are highly adaptable and can be easily transported from one location to another. These structures are designed to be flexible in terms of their configuration and use, allowing them to be set up or taken down quickly and moved to different locations as needed.

Finally, flexible and portable structures (1%) are particularly beneficial when mobility and rapid deployment are essential, such as for temporary research projects, field studies, or events.

In terms of technological assets, most of the initiatives propose technologies that refer to digital design, 3D modeling and rendering, and digital prototyping, complementing the traditional paper-based and hand-sketching processes with virtual simulation of both aesthetics and functionalities, thus enabling a digital transition of creative processes toward a reduction in sampling. 3D body scanning is used to capture natural bodies, including anthropometric measurements, for the definition of parametric digital clothing design toward more personalized and on-demand design and manufacturing processes. Augmented and virtual reality support visualizing garments for simulation, consumption, and experience purposes. Digital fabrication technologies based on 3D and 4D printing, digital cutting, and embroidery are proposed to create highly complex novel products and re-engineer prototyping and manufacturing processes toward lean, on-demand, and resource-efficient ones.

All these technologies are rarely applied in a systematic and interoperable way by fashion companies. When supported by research, they tend to push the boundaries of actual applications more systematically toward socio-environmental goals. An example is the application of these technologies to design and implement digital garments as digital twins and develop their subsequent re-materialization through digital fabrication. Through the analysis, evaluation, testing, and validation of new design, prototyping, and manufacturing processes aided by digital technologies, the research allows the identification of problems and opportunities that are codified in supportive tools, both as customized software and hardware ones, to support fashion companies at product, process, service, and system levels.

On the side of materials and textiles, research entities are focusing on innovating manufacturing processes thanks to nano- and bio-technologies, thus directing the textile industry toward more responsible and sustainable selection, use, and production of fibers, yarns, and textiles used in the fashion and clothing industry. These technologies aim to transform the textile manufacturing phases, impacting the coloration and dyeing, weaving, and finishing processes toward reducing resource depletion and using more bio-based materials to limit the amount of used and wasted resources. In addition, much research supports the definition and testing of textile recycling processes and the upcycling of textile resources within the scope of a CE.

More research is focused on extensive data management and transparency through technologies enabling the digital product passport, such as RFID tags, blockchain, and non-fungible tokens, enabling tracking of products, processes, and systems, and aiding data-informed decisions during the design and manufacturing stages. Further research on artificial intelligence focuses on supporting creative processes in the research and design phases to understand, analyze, and define new patterns and correlations through extensive source data sets on fashion artifacts. Testing and analyzing the interaction of humans and AI collaborating through the co-generation of new data, information, and knowledge offers new impulses in the fashion industry's research, design, and decision-making processes. Fewer but essential for sustainability scopes are the research entities focusing on e-textiles that are working on the sustainable integration of the electronic components on garments, thus impacting product, process, and system design in fashion companies.

Finally, a small but interesting group of research entities is equipped with technologies that can systematically simulate the supply chain configuration, allow tracking data inside the system, and envision, test, and validate reverse logistics. Those digital tools based on software and data collection management support fashion companies in entering CE models, calculating the impact of different choices, and structuring how all the stakeholders can collaborate toward more lean and integrated operations (Figure 7).

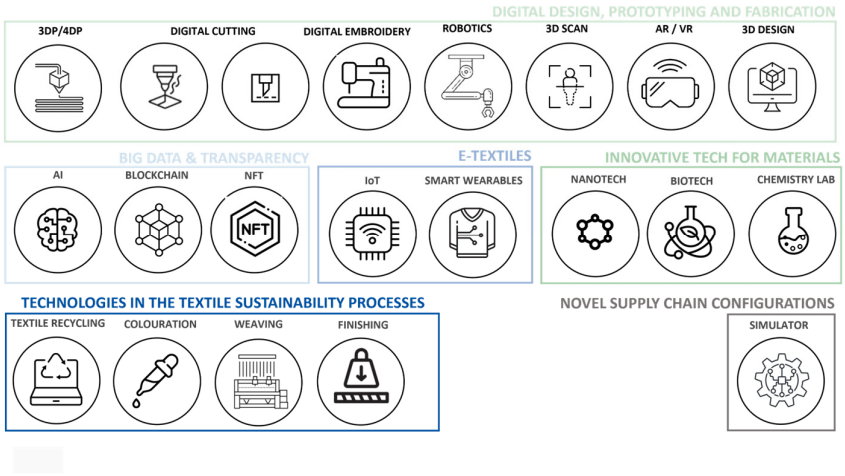

Figure 7. Technologies employed by research initiatives.

6. Discussion

This paper outlines a framework related to the barriers and opportunities of technologies of I4.0 and the values of I5.0 for a positive transition of the fashion industry toward more sustainable approaches and solutions and more valuable activities to reach the circular economic principles through a design-driven perspective and business innovation aided by technologies. In addition to this, it provides a comprehensive overview of the current state of various initiatives, entities, and organizations dedicated to boosting, enhancing, supporting, and enabling fashion-tech innovation within the complex fashion ecosystem to instill circularity for a sustainable industry transformation. The paper explains the correspondence between the barriers-related framework and the multiple services offered by research entities and initiatives to overcome mainly the technological, organizational, and socio-cultural variables that limit the transformation. Through communication, dissemination, and education services, the research entities try to withdraw the dominant culture of the industry, showing resistance to change due to low socio-cultural readiness and poor digital and technological literacy and skills. In addition, applicable research and consultancies are essential at a managerial and technological level to provide examples, information, and knowledge on technological choices, better control business risks, and understand the necessity of interoperability and customization of technologies specific to the sector.

The key findings from the examined case studies provide a profitable understanding and vision of specific topics of interest and research areas emerging as important or missing from the actual research initiatives. In particular, the identified four research areas cover the supply and value chain of textile and clothing fashion sectors, encompassing:

- The upstream processes developed through cutting-edge digital and virtual fashion design techniques are integrated across the entire research and sampling workflow. This facilitates a deeper understanding of improved interactions between humans and machines/computers, fosters innovative design processes, and addresses environmental considerations, ultimately progressing toward the era of fashion operator 4.0. Also, it is crucial to continuously monitor material-related data across the entire value chain to develop a unified methodology and language to streamline the exchange of material information among stakeholders to adopt or recover resources at the design stage.
- The downstream processes include developing strategies formulated to enhance the sustainability and circularity of the sector, aiming to optimize waste management practices, and promoting environmentally conscious approaches within the industry.

- Along the supply chain, promoting models that support decision-making in designing and assessing circular supply chains involves integrating traceability systems, intelligent technologies, and solutions. This empowerment aids in managing the (reverse) flow of materials and products before and after consumption, enhancing overall efficiency and sustainability.

This study allows us to define the current typical and best features of research initiatives supporting the fashion sector's adoption, integration, and implementation of technologies toward positive and responsible innovations. Starting from these insights helps in formulating the features of a trailblazing laboratory model, the Circular Fashion-Tech Lab, encompassing winning examples and best practices by enhancing the following features:

- Experimentation and collaboration: the importance of the laboratory approach should be emphasized because its role is crucial in supporting experimentation and promoting openness within the fashion industry, thus innovation;
- Resilience and transformability: future research entities should become flexible and able to change if adverse conditions appear. Current research entities still underexplore this configuration, showing mostly traditional, static, and unified models;
- Modularity and redundancy: technological equipment and knowledge should be supported by agile and equitable management of actual and prospective organizations and reprogrammable partnerships taking part in the laboratory;
- Interdisciplinarity and anti-disciplinarity: strategic exchanges among different domains foster intersections and convergences among diverse sources of innovation and creativity. Design could facilitate this as a mediator between the arts and humanity, technology, and science;
- Humanizing technology through design: a boost of art and humanities inside the discussion of the fashion-tech transformation of the fashion industry is required to include some deeper reflection on the impact of technologies on users, processes, and sustainability through the inclusion of psychology, ethics, and philosophy;
- Sustaining innovation through company engagement: collaborations with companies are identified as critical. The real integration of research into fashion companies is viewed as a catalyst for positive partnerships, leading to the generation of new knowledge and the cultivation of novel forms of competitive advantages;
- On life education: the pivotal role of an educational perspective within this system is to fight and break down socio-cultural barriers by shaping the skills and talents necessary outside (for current students of the HEIs) and inside fashion companies (for the current professional and unskilled workforce) for their transition.

These features, combined together, help set a series of guidelines for designing a Circular Fashion-Tech Lab dedicated to basic and applied research grounded on scientific methodologies and education and dissemination activities, aiming to catalyze transformative change in the fashion industry toward sustainability and circularity. The focus will be on using the identified research paths and features for prototyping new processes within the fashion supply and value chain, mainly aimed at achieving circularity and sustainability through the adoption of I4.0 technologies. Testing and building radical ideas will position the lab as a space for testing and building concepts that have the potential to revolutionize current practices, with a specific focus on addressing unsustainable practices, fostering circular contexts and ecosystems, and involving fashion, fashion-tech, and tech companies in collaborative initiatives to create a new era of intelligent, circular, and environmentally sustainable factories. This seeks to achieve its objectives through collective endeavors that harness technological advancements—setting industrial ecosystems

based on fashion-tech solutions, envisioning solutions designed to address circularity challenges by fostering horizontal discourse, bringing diverse perspectives into problem framing, and encouraging collaborative innovation to address the complexity inherent in sustainable practices effectively.

7. Conclusions, Limitations, and Future Research Directions

This study adopts an iterative approach to identify barriers and opportunities and codify exemplary cases from academia and industry that depict a context where it is necessary to align with the technological paradigm through a design-driven and holistic approach to fashion sustainability and CE principles. This process is centered on modeling research paths and characteristics already operational within the framework of I4.0 in the fashion industry toward defining a new laboratory model that aids fashion companies in the twin transition.

We would like to draw attention to a few limitations of this study that may reduce the generalizability of the results. In particular, by conducting a systematic review of the grey literature for the case studies, we recognize that sources could have moderate credibility due to a tendency to report positive information and implications [101]. In addition, it needs to be more attainable to quantitatively and qualitatively derive conclusions about the success factors and challenges experienced by the supportive initiatives selected as case studies. Thus, to mitigate the potentially biased image of the case studies emerging from the grey literature, the results have been discussed by reflecting critically on the more simplistic ones. In addition, data about the practical achievements of supporting initiatives leading the tech-green transition of the fashion industries should be retrieved using different investigation methodologies, such as surveys and interviews with both stakeholders.

Recognizing the data's limited scope, this work does not aim to suggest new theories but rather contributes to the existing ones by interpreting and codifying the available data. We recognize that the selected cases should represent the primary types within each typology rather than being exhaustive. Even if the case studies span an international dimension, we acknowledge that they are context-dependent, referring to specific geo-cultural backgrounds and periods connected to specific technological trends. Therefore, the inclusion of these real-world examples was carefully examined, and their functionality was extrapolated to effectively represent the current research directions and central aspects of research initiatives supporting the evolution of fashion industries related to textiles and clothing. The limitation of time–culture dependency in the selected examples translates into the crucial imperative of creating supporting initiatives that are resilient and flexible to guide a future-proof transformation of fashion companies. It is necessary to establish initiatives that can change and transform themselves, interpreting the Zeitgeist related to the sector along with the pragmatic needs of fashion companies and strategically guiding the transformation through visionary research topics.

The article's comprehensive overview encourages interdisciplinary discussion and studies among fashion researchers, professionals, and companies. Drawing from the findings, we provide prospective research pathways to accelerate the transition of fashion companies toward sustainability and innovation, which might capture the interest of practitioners and scholars alike. Further research direction and critical reflections, driving the creation of a Circular Fashion-Tech Lab, could focus on the following aspects:

- Envision resilient futures for the company's fashion-tech evolution through scenario development by designing possible overarching strategies for different potential futures that integrate the complexity of the fashion ecosystem and current times through methods, tools, and tactics of sensemaking and anticipation.
- Consider the holistic approach of sustainability, encompassing the economic, environmental, social, and cultural dimensions and how they interrelate and condition each other. The research could shift the focus from ecological to cultural and social

sustainability, which seems the least investigated of the current research initiatives but requires further attention, especially in how technologies impact human activities, processes, and practices, thus influencing the cultural heritage of the sector.

- Criticize the tech-driven approach by applying a design-driven approach that focuses on positive and responsible innovation, where choices and practices influence the entire fashion value and supply chain along their different phases, from prototypes and production processes to sales and communication strategies, product use, and the end of their life cycle. Thus, design becomes a powerful guiding tool and a strategic asset toward meaningful perspectives that can orient innovation trajectories.
- Examine the role of digital technologies as key enablers through demonstrations within the lab that are useful to understand how digital technologies contribute to the holistic transformation of the fashion industry at the level of products, processes, and systems, considering insights and lessons learned from earlier research and cases.
- Understand deeply the obstacles and challenges associated with adopting, integrating, and implementing technology into fashion processes while the sector navigates the absence of a rooted digital culture. This should imply exploring the motivations of organizations that have yet to embrace or integrate digital practices and mindsets into their daily operations and finding a scalable and feasible solution to actuate change.
- Release design-driven open innovation aided by technologies toward diverse actors, including academia, industry, governments, and individuals. Emphasize open innovation's dynamic and multi-disciplinary aspects as a process that transcends closed and static behaviors, fostering knowledge and practices of co-creation and collaboration across different spheres and disciplines.
- Engage fashion companies into and out of laboratory settings, trying to understand the winning collaborative patterns with industrial partners to accelerate the diffusion and scale-up of research processes into feasible solutions that speed the transformation toward a more digital, sustainable, and human-centric fashion ecosystem.

These research paths can provide valuable and resilient insights into the complex dynamics of open innovation sustainably and circularly in the supply chain, offering a nuanced understanding of the actors involved, obstacles faced, the role of digital technologies, and the impact of collaborative innovation models. By actively incorporating these considerations, future research and industry ecosystems can become powerful catalysts for positive change, aligning with EU policies, promoting sustainable practices, and fostering innovation in the fashion sector.

Author Contributions: The paper is the result of common research and findings. Nevertheless, E.D. edited Sections 2–3 and D.C. edited Sections 4–5. Both authors contributed to Sections 1 and 6 and the whole document editing. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out within the MICS (Made in Italy—Circular and Sustainable) Extended Partnership and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3—D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Name	Research Area									Typology of Mapped Initiatives (University Research Lab/Center, Private Research Lab/Center, Public/Private Research Lab/Center, Fablab, Incubator/Accelerator, Competence Center)
	Design, Prototyping, and Non-Standard Fabrication Processes	Materials and Fabrics' Sustainability and Non-Standard Fabrication Processes	Supply Chain Management Processes for Circularity	End-of-Life (EoL) Management Solutions of Textiles and Garments	Research Lab_ Fashion Oriented	Research Lab _ General	Year (Fundation)	Country	Contact	
Fashion Tech Farm	✓	✓			✓		2019	The Netherland	https://fashiontechfarm.com/ (accessed on 28 February 2024)	incubator/accelerator
Sustainability Lab	✓	✓	✓		✓		2016	Italy	https://www.sdabocconi.it/it/faculty-ricerche/ricerca/new-value-knowledge-platform/sustainability-lab/osservatori/monitor-for-circular-fashion (accessed on 28 February 2024)	university research center
Fashion Research and Technology (FR&T) group	✓	✓			✓		2020	The Netherland	https://www.amsterdamuas.com/kc-fdmci/shared-content/research-groups/fashion-research--technology/fashion-research-technology.html (accessed on 28 February 2024)	university research lab

ZOZONext	✓	✓			✓		2021	Japan	https://zozonext.com/ (accessed on 28 February 2024)	private research lab
Fashion Technology Accelerator	✓	✓	✓	✓	✓		2012	Italy	https://www.ftaccelerator.it/ (accessed on 28 February 2024)	incubator/accelerator
Startupbootcamp FashionTech	✓	✓	✓	✓	✓		2010	The Netherland	https://www.sbcfashiontech.com/ (accessed on 28 February 2024)	incubator/accelerator
The Lifestyle Tech Competence Center	✓	✓			✓	✓		Switzerland	https://lifestyletechcompetencecenter.com/about/ (accessed on 28 February 2024)	incubator/accelerator
Textile Futures Research Community	✓	✓		✓	✓		2012	UK	https://www.arts.ac.uk/colleges/central-saint-martins/research-at-csm/textile-futures-research-community (accessed on 28 February 2024)	university research lab
The Manchester Fashion Institute Innovation Lab	✓	✓			✓		unknown	UK	https://fashioninstitute.mmu.ac.uk/research-and-knowledge-exchange/fashion-technology/ (accessed on 28 February 2024)	university research lab
Robotics Living Lab (RoLL)	✓	✓			✓		2023	UK	https://www.mmu.ac.uk/news-and-events/news/story/?id=16033 (accessed on 28 February 2024)	university research lab
FFRI Fondazione Fashion Research Italy		✓			✓		2015	Italy	https://www.ffri.it/ (accessed on 28 February 2024)	private research lab

The Centre for Sustainable Design	✓	✓			✓	✓	1995	UK	https://cfsd.org.uk/ (accessed on 28 February 2024)	university research center
Apparel Technology Research Center	✓	✓	✓		✓			US	https://www.cpp.edu/agri/apparel-technology-research-center/index.shtml (accessed on 28 February 2024)	university research lab
AM4U	✓	✓	✓	✓	✓		1996	US	https://am4u.com/ (accessed on 28 February 2024)	private research center
Tech Noir Lab	✓	✓			✓		2016	UK	https://technoirlab.com/new-page (accessed on 28 February 2024)	private research center
Circular fashion Lab (R)	✓	✓	✓	✓	✓		2019	The Netherland	https://www.wur.nl/en/research-results/projects-and-programmes/circular-fashion-lab.htm (accessed on 28 February 2024)	university research center
Tufts Silk Lab		✓			✓	✓		US	https://silklab.engineering.tufts.edu/ (accessed on 28 February 2024)	university research center
Centexbel		✓	✓	✓	✓		1950	Belgium	https://www.centexbel.be/en (accessed on 28 February 2024)	competence center
Materials Lab (Sustainable Fashion Innovation)		✓			✓			Italy	https://sustainablefashioninnovation.org/portfolio/materials-lab/ (accessed on 28 February 2024)	private research center
Enzime—Gruppo Florence	✓	✓	✓		✓		2020	Italy	https://www.gruppoflorence.it/ (accessed on 28 February 2024)	private research center

Circular Design Lab (Centre for Circular Design)	✓		✓		✓		2017	UK	https://www.circulardesign.org.uk/circular-design-lab/ (accessed on 28 February 2024)	university research lab
FIT DTech	✓				✓			US	https://dtech.fitnyc.edu/webflow/index.html (accessed on 28 February 2024)	university research center
Soko Tech	✓	✓			✓	✓		Spain	https://www.soko.tech/labs/ (accessed on 28 February 2024)	private research center
HKRITA	✓	✓	✓	✓	✓		2006	Hong Kong	https://www.hkrita.com/ (accessed on 28 February 2024)	university research center
Ellen McArthur Foundation	✓	✓	✓		✓	✓		Uk	https://www.ellenmacarthurfoundation.org/ (accessed on 28 February 2024)	private research center
Waag FutureLab—TextileLab	✓	✓	✓		✓		1994	Amsterdam, Netherland	https://waag.org/en/project/textilelab-amsterdam/ (accessed on 28 February 2024)	fablab
MIL: a laboratory for more sustainable materials	✓	✓			✓		2013	Milan, Italy	https://www.kering.com/it/news/mil-a-laboratory-for-more-sustainable-materials/ (accessed on 28 February 2024)	private research lab
UKRI INTERDISCIPLINARY Textile Circularity Center (TCC)	✓	✓	✓	✓	✓			UK	https://textilescircularity.rca.ac.uk/ (accessed on 28 February 2024)	university research center
Transition Lab	✓	✓	✓	✓	✓		2021	European (Spain, Italy, Sweden, The Netherlands)	https://transitionsproject.eu/ (accessed on 28 February 2024)	university research center

Fashionforfuture	2 3	✓	✓		✓	2023	Italy	https://www.fashionforfuture.it/en/ (accessed on 28 February 2024)	private research center
Green Fabric	✓	✓	✓		✓	2019	Belgium	https://greenfabric.be/ (accessed on 28 February 2024)	fablab
Lottozero	✓	✓	✓		✓	2012	Italy	https://www.lottozero.org/laboratory (accessed on 28 February 2024)	private research center
Textile Prototyping Lab	✓	✓	✓		✓	2017	Germany	https://www.textileprototypinglab.com/ (accessed on 28 February 2024)	public research center
Le Textile Lab	✓	✓	✓		✓		France	https://letextilelab.com/exploration/projets/ (accessed on 28 February 2024)	fablab
Fab Textiles	✓	✓			✓	2013	Spain	https://fabtextiles.org/ (accessed on 28 February 2024)	fablab
QUT ARM Hub workshop Centre for a Waste-free World			✓	✓	✓	2022	Australia	https://armhub.com.au/addressing-textile-supply-chain-through-technological-innovation/ https://research.qut.edu.au/textiler/research/robotics-to-help-sort-and-disassemble-clothing/ (accessed on 28 February 2024)	university research center
Fashionhub	✓	✓	✓		✓	no data	Brazil	https://fashionhub.com.br/ (accessed on 28 February 2024)	incubator/accelerator
AiDlab—Laboratory for Artificial Intelligence in Design	✓			✓	✓	2021	Hong Kong	https://www.aidlab.hk/en/ (accessed on 28 February 2024)	university research center

The Icelandic Textile Center, TextileLab	✓	✓			✓		2021	Iceland	https://www.textilmidstod.is/is (accessed on 28 February 2024)	fablab
(FIA) Fashion Innovation Agency	✓		✓	✓	✓		2013	UK	https://www.fialondon.com/about-the-fashion-innovation-agency/ (accessed on 28 February 2024)	private research center
SELF ASSEMBLY LAB	✓	✓				✓	2019	USA	https://selfassemblylab.mit.edu/ (accessed on 28 February 2024)	university research center
Next Technology Tecnotessile	✓	✓		✓	✓			Italy	https://www.tecnotex.it/ (accessed on 28 February 2024)	Public/private reserach lab
Centrocot	✓	✓		✓	✓			Italy	https://www.centrocot.it/ (accessed on 28 February 2024)	Public/private reserach lab

References

1. Niinimäki, K.; Peters, G.; Dahlbo, H.; Perry, P.; Rissanen, T.; Gwilt, A. The environmental price of fast fashion. *Nat. Rev. Earth Environ.* **2020**, *1*, 189–200.
2. A New Textiles Economy: Redesigning Fashion's Future. Available online: https://www.ellenmacarthurfoundation.org/a-new-textiles-economy (accessed on 29 February 2024).
3. Hur, E.; Cassidy, T. Perceptions and attitudes towards sustainable fashion design: Challenges and opportunities for implementing sustainability in fashion. *Int. J. Fashion Des. Technol. Educ*. **2019**, *12*, 208–217.
4. Fletcher, K. Slow fashion: An invitation for systems change. *Fashion Pract*. **2010**, *2*, 259–265.
5. Schwab, K. *The Fourth Industrial Revolution*, 1st ed.; Crown Business: New York, NY, USA, 2017.
6. Bertola, P.; Teunissen, J. Fashion 4.0. Innovating fashion industry through digital transformation. *Res. J. Text. Appar.* **2018**, *22*, 352–369.
7. Behr, O. Fashion 4.0—Digital innovation in the fashion industry. *J. Technol. Innov. Manag*. **2018**, *2*, 1–9.
8. Küsters, D.; Praß, N.; Gloy, Y.S. Textile learning factory 4.0—Preparing Germany's textile industry for the digital future. *Procedia Manuf*. **2017**, *9*, 214–221.
9. Gökalp, E.; Gökalp, M.O.; Eren, P.E. Industry 4.0 revolution in clothing and apparel factories: Apparel 4.0. *Industry* **2018**, *4*, 169–183.
10. Jimeno-Morenilla, A.; Azariadis, P.; Molina-Carmona, R.; Kyratzi, S.; Moulianitis, V. Technology enablers for the implementation of Industry 4.0 to traditional manufacturing sectors: A review. *Comput. Ind.* **2021**, *125*, 103390.
11. State of Fashion Technology Report 2022. Available online: https://www.mckinsey.com/industries/retail/our-insights/state-of-fashion-technology-report-2022 (accessed on 29 February 2024).
12. Colombi, C.; D'Itria, E. Fashion Digital Transformation: Innovating Business Models toward Circular Economy and Sustainability. *Sustainability* **2023**, *15*, 4942.
13. Heim, H.; Hopper, C. Dress code: The digital transformation of the circular fashion supply chain. *Int. J. Fashion Des. Technol. Educ.* **2022**, *15*, 233–244.
14. Madsen, D.Ø. The emergence and rise of Industry 4.0 viewed through the lens of management fashion theory. *Adm. Sci.* **2019**, *9*, 71.
15. Bertola, P.; Colombi, C. Can fashion be sustainable? Trajectories of change in organizational, products and processes, and socio-cultural contexts. *Sustain. Sci. Pract. Policy* **2024**, *20*, 2312682.
16. The European Green Deal. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 29 February 2024).
17. The Green Deal Industrial Plan: Putting Europe's Net-Zero Industry in the Lead. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_510 (accessed on 29 February 2024).
18. Communication: A Green Deal Industrial Plan for the Net-Zero Age. Available online: https://commission.europa.eu/document/41514677-9598-4d89-a572-abe21cb037f4_en (accessed on 29 February 2024).
19. Jin, B.E.; Shin, D.C. The power of 4th industrial revolution in the fashion industry: What, why, and how has the industry changed? *Fashion Text.* **2021**, *8*, 31.
20. Di Lodovico, C.; Colombi, C.; Ana, R. Promoting Innovation Within the Fashion-tech Sector. The Role of Pan-European Projects. In Proceedings of the Global Fashion Conference, Warsaw, Poland, 21–22 October 2021.
21. Ghoreishi, M.; Happonen, A. The case of fabric and textile industry: The emerging role of digitalization, internet-of-Things and industry 4.0 for circularity. In *Proceedings of Sixth International Congress on Information and Communication Technology: ICICT 2021, London, Volume 3*; Springer: Singapore, 2021; pp. 189–200.
22. Khan, S.A.R.; Zia-ul-haq, H.M.; Umar, M.; Yu, Z. Digital technology and circular economy practices: A strategy to improve organizational performance. *Bus. Strat. Dev.* **2021**, *4*, 482–490.
23. Demir, S.; Paksoy, T.; Kochan, C.G. A Conceptual Framework for Industry 4.0: (How is it Started, How is it Evolving Over Time?). In *Logistics 4.0*, 1st ed.; Paksoy, T., Koçhan, C., Ali, S.S., Eds.; CRC Press: New York, NY, USA, 2020; pp. 1–14.
24. Nahavandi, S. Industry 5.0—A human-centric solution. *Sustainability* **2019**, *11*, 4371.
25. Möller, D.P.; Vakilzadian, H.; Haas, R.E. From Industry 4.0 towards Industry 5.0. In Proceedings of the IEEE International Conference on Electro Information Technology (eIT), Mankato, MN, USA, 19–21 May 2022.
26. Özdemir, V.; Hekim, N. Birth of industry 5.0: Making sense of big data with artificial intelligence,"the internet of things" and next-generation technology policy. *Omics A J. Integr. Biol.* **2018**, *22*, 65–76.
27. Romero, D.; Bernus, P.; Noran, O.; Stahre, J.; Fast-Berglund, Å. The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. In *IFIP Advances in Information and Communication Technology*; Springer: Cham, Swizerland, 2016; pp. 677–686.
28. Wang, B.; Zheng, P.; Yin, Y.; Shih, A.; Wang, L. Toward human-centric Smart Manufacturing: A human-cyber-physical systems (HCPS) perspective. *J. Manuf. Syst.* **2022**, *63*, 471–490.
29. Welfare, K.S.; Hallowell, M.R.; Shah, J.A.; Riek, L.D. Consider the human work experience when integrating robotics in the Workplace. In Proceedings of the 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI), Daegu, Korea, 11–14 March 2019.

30. Pathak, P.; Pal, P.R.; Shrivastava, M.; Ora, P. Fifth Revolution: Applied AI & Human Intelligence with Cyber Physical Systems. *Int. J. Eng. Adv. Technol.* **2019**, *8*, 23–27.
31. Ivanov, D. The industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives. *Int. J. Prod. Res.* **2022**, *61*, 1683–1695.
32. Industry 5.0—Towards a Sustainable, Human-Centric and Resilient European Industry. European Commission: Brussels, Belgium. Available online: https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/ (accessed on 29 February 2024).
33. Xu, X.; Lu, Y.; Vogel-Heuser, B.; Wang, L. Industry 4.0 and Industry 5.0—Inception, conception and perception. *J. Manuf. Syst.* **2021**, *61*, 530–535. https://doi.org/10.1016/j.jmsy.2021.10.006.
34. Ghobakhloo, M.; Iranmanesh, M.; Mubarak, M.F.; Mubarik, M.; Rejeb, A.; Nilashi, M. Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values. *Sustain. Prod. Consum.* **2022**, *33*, 716–737.
35. Davis, T.; Dunne, L.E.; Bigger, E. Risky business: Sustainable fashion through new technologies. In *Accelerating Sustainability in Fashion, Clothing and Textiles*, 1st ed.; Charter, M., Pan, B., Black, S., Eds.; Routledge: London, UK, 2023; pp. 377–392.
36. Hoque, M.A.; Rasiah, R.; Furuoka, F.; Kumar, S. Critical determinants and firm performance of sustainable technology adoption in the apparel industry: The stakeholder approach. *J. Fashion Mark. Manag.* **2023**, *27*, 182–200.
37. Casciani, D.; Chkanikova, O.; Pal, R. Exploring the nature of digital transformation in the fashion industry: Opportunities for supply chains, business models, and sustainability-oriented innovations. *Sustain. Sci. Pract. Policy* **2022**, *18*, 773–795.
38. Park-Poaps, H.; Rees, K. Stakeholder forces of socially responsible supply chain management orientation. *J. Bus. Ethics*, **2010**, *92*, 305–322.
39. D'Itria, E.; Aus, R. Circular fashion: Evolving practices in a changing industry. *Sustain. Sci. Pract. Policy* **2023**, *19*, 2220592.
40. Our Vision of a Circular Economy for Fashion. Available online: https://www.ellenmacarthurfoundation.org/our-vision-of-a-circular-economy-for-fashion (accessed on 29 February 2024).
41. Bocken, N.M.; Short, S.W.; Rana, P.; Evans, S. A literature and practice review to develop sustainable business model archetypes. *J. Clean. Prod.* **2014**, *65*, 42–56.
42. D'Itria, E. Driving Sustainability in Fashion through Design: Experimenting with the Role of Design in the Development of a Circular Fashion Supply Chain Model. Ph.D. Thesis, Politecnico di Milano, Milano, Italy, 2022; (Unpublished).
43. Rockström, J.; Richardson, K.; Steffen, W.; Mace, G. Planetary boundaries: Separating fact from fiction. A response to Montoya et al. *Trends Ecol. Evol.* **2018**, *33*, 233–234.
44. Kwatra, S.; Kumar, A.; Sharma, P. A critical review of studies related to construction and computation of Sustainable Development Indices. *Ecol. Indic.* **2020**, *112*, 106061.
45. Morseletto, P. Targets for a circular economy. *Resour. Conserv. Recycl.* **2020**, *153*, 104553.
46. Nobre, G.C.; Tavares, E. The quest for a circular economy final definition: A scientific perspective. *J. Clean. Prod.* **2021**, *314*, 127973.
47. Kirchherr, J.; Urbinati, A.; Hartley, K. Circular economy: A new research field? *J. Ind. Ecol.* **2023**, *27*, 1239–1251.
48. Schröder, P.; Lemille, A.; Desmond, P. Making the circular economy work for human development. *Resour. Conserv. Recycl.* **2020**, *156*, 104686.
49. Sterling, S. Education in Change. In *Education for Sustainability*, 1st ed.; Sterling, S., Huckle, J., Eds.; Routledge: London, UK, 2014; pp. 18–39.
50. Ghobakhloo, M.; Iranmanesh, M.; Grybauskas, A.; Vilkas, M.; Petraitė, M. Industry 4.0, innovation, and sustainable development: A systematic review and a roadmap to sustainable innovation. *Bus. Strategy Environ.* **2021**, *30*, 4237–4257.
51. Khanzode, A.G.; Sarma, P.R.S.; Mangla, S.K.; Yuan, H. Modeling the Industry 4.0 adoption for sustainable production in Micro, Small & Medium Enterprises. *J. Clean. Prod.* **2021**, *279*, 123489.
52. Lopes de Sousa Jabbour, A.B.; Jabbour, C.J.C.; Godinho Filho, M.; Roubaud, D. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. *Ann. Oper. Res.* **2018**, *270*, 273–286.
53. Drift for Transition—The Transition to Good Fashion. Available online: Drift.eur.nl/wp-content/uploads/2018/11/FINAL_report.pdf (accessed on 12 October 2023).
54. Priya, A. Case study methodology of qualitative research: Key attributes and navigating the conundrums in its application. *Sociol. Bull.* **2021**, *70*, 94–110.
55. Nixon, N.W.; Blakley, J. Fashion thinking: Towards an actionable methodology. *Fash. Pract.* **2012**, *4*, 153–175.
56. Zahra, S.A.; Liu, W.; Si, S. How digital technology promotes entrepreneurship in ecosystems. *Technovation* **2023**, *119*, 102457.
57. Vuksanović Herceg, I.; Kuč, V.; Mijušković, V.M.; Herceg, T. Challenges and driving forces for industry 4.0 implementation. *Sustainability* **2020**, *12*, 4208.
58. Hardabkhadze, I.; Bereznenko, S.; Kyselova, K.; Bilotska, L.; Vodzinska, O. Fashion Industry: Exploring the Stages of Digitalization, Innovative Potential and Prospects of Transformation into an Environmentally Sustainable Ecosystem. *East.-Eur. J. Enterp. Technol.* **2023**, *1*, 121.
59. Oesterreich, T.D.; Schuir, J.; Teuteberg, F. The emperor's new clothes or an enduring IT fashion? Analyzing the lifecycle of industry 4.0 through the lens of management fashion theory. *Sustainability* **2020**, *12*, 8828.
60. Govindan, K.; Kannan, D.; Jørgensen, T.B.; Nielsen, T.S. Supply Chain 4.0 performance measurement: A systematic literature review, framework development, and empirical evidence. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *164*, 102725.

61. Baxter, P.; Jack, S. Qualitative case study methodology: Study design and implementation for novice researchers. *Qual. Rep.* **2008**, *13*, 544–559.
62. Theuer, H.; Pahl, M. MES–Industry 4.0-Ready| MES–Industrie 4.0-ready. *Product. Manag.* **2016**, *21*, 49–55.
63. Jamwal, A.; Agrawal, R.; Sharma, M.; Giallanza, A. Industry 4.0 technologies for manufacturing sustainability: A systematic review and future research directions. *Appl. Sci.* **2021**, *11*, 5725.
64. Morrar, R.; Arman, H.; Mousa, S. The fourth industrial revolution (Industry 4.0): A social innovation perspective. *Technol. Innov. Manag. Rev.* **2017**, *7*, 12–20.
65. Müller, J.M.; Kiel, D.; Voigt, K.I. What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. *Sustainability* **2018**, *10*, 247.
66. Preuveneers, D.; Ilie-Zudor, E. The intelligent industry of the future: A survey on emerging trends, research challenges and opportunities in Industry 4.0. *J. Ambient. Intell. Smart Environ.* **2017**, *9*, 287–298.
67. Wang, S.; Wan, J.; Li, D.; Zhang, C. Implementing smart factory of industrie 4.0: An outlook. *Int. J. Distrib. Sens. Netw.* **2016**, *12*, 3159805.
68. Maier, M.A.; Korbel, J.J.; Brem, A. Innovation in supply chains-solving the agency dilemma in supply networks by using industry 4.0 technologies. *Int. J. Commun. Netw. Distrib. Syst.* **2015**, *15*, 235–247.
69. Javaid, M., et al. Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustainable Operations and Computers*, **2022**, 3, 203-217.
70. Colombi, C.; Casciani, D. Fashion-Tech Alliance: Innovating professional digital competences and skills in the Fashion Industry. In Proceedings of the 15th International Technology, Education and Development Conference, Online Conference, 8–9 March 2021; pp. 7842–7852.
71. Chkanikova, O.; Pal, R.; Gustafsson, K.; Timour, F. Shaping the future of fashion-tech-business models, roles and skills aiding digital transformations. In Proceedings of the Global Fashion Conference 2021, Warsaw, Poland, 21–22 October, 2021.
72. Ranta, V.; Aarikka-Stenroos, L.; Väisänen, J.M. Digital technologies catalyzing business model innovation for circular economy—Multiple case study. *Resour. Conserv. Recycl.* **2021**, *164*, 105155.
73. Hermann, M.; Pentek, T.; Otto, B. Design principles for Industrie 4.0 scenarios: A literature review. *Tech. Univ. Dortm. Dortm.* **2015**, *45*, 1–15.
74. Majumdar, A.; Garg, H.; Jain, R. Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: Interpretive structural model and triple helix framework. *Comput. Ind.* **2021**, *125*, 103372.
75. Mosca, F.; La Rosa, E. 4.0 technology within fashion and luxury production. *Symphonya Emerg. Issues Manag.* **2019**, *2*, 82–94.
76. Nosalska, K.; Piątek, Z.M.; Mazurek, G.; Rządca, R. Industry 4.0: Coherent definition framework with technological and organizational interdependencies. *J. Manuf. Technol. Manag.* **2019**, *31*, 837–862.
77. Culot, G.; Orzes, G.; Sartor, M.; Nassimbeni, G. The future of manufacturing: A Delphi-based scenario analysis on Industry 4.0. *Technol. Forecast. Soc. Chang.* **2020**, *157*, 120092.
78. Raj, A.; Dwivedi, G.; Sharma, A.; de Sousa Jabbour, A.B.L.; Rajak, S. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *Int. J. Prod. Econ.* **2022**, *224*, 107546.
79. Müller, J.M. Business model innovation in small-and medium-sized enterprises: Strategies for industry 4.0 providers and users. *J. Manuf. Technol. Manag.* **2019**, *30*, 1127–1142.
80. Kamble, S.S.; Gunasekaran, A.; Sharma, R. Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. *Comput. Ind.* **2018**, *101*, 107–119.
81. Industry 4.0 after the Initial Hype Where Manufacturers Are Finding Value and How They Can Best Capture it. Available online: https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/getting%20the%20most%20out%20of%20industry%204%200/mckinsey_industry_40_2016.ashx (accessed on 29 February 2024).
82. Luthra, S.; Kumar, A.; Zavadskas, E.K.; Mangla, S.K.; Garza-Reyes, J.A. Industry 4.0 as an enabler of sustainability diffusion in supply chain: An analysis of influential strength of drivers in an emerging economy. *Int. J. Prod. Res.* **2020**, *58*, 1505–1521.
83. Abdualee, A. H. ; Mohammed, K. H. Digital transformation in design and the impact of modern tools and technologies. *Glob. Prosper.* **2024**, *4*.
84. Ponis, S.T.; Lada, C. Digital transformation in the Greek fashion industry: A survey. *Int. J. Fash. Des. Technol.* **2021**, *14*, 162–172.
85. Ortega-Gras, J.J.; Bueno-Delgado, M.V.; Cañavate-Cruzado, G.; Garrido-Lova, J. Twin transition through the implementation of industry 4.0 technologies: Desk-research analysis and practical use cases in Europe. *Sustainability* **2021**, *13*, 13601.
86. Konina, N.Y. Smart Digital Innovations in the Global Fashion Industry and a Climate Change Action Plan. In *Smart Green Innovations in Industry 4.0 for Climate Change Risk Management*; Popkova, E.G., Ed.; Springer International Publishing: Cham, Swizterland, 2023; pp. 255–263.
87. Islam, M.M.; Perry, P.; Gill, S. Mapping environmentally sustainable practices in textiles, apparel and fashion industries: A systematic literature review. *J. Fash. Mark. Manag. Int. J.* **2021**, *25*, 331–353.
88. Trček, D. Cultural heritage preservation by using blockchain technologies. *Herit. Sci.* **2022**, *10*, 6.
89. Akram, S.V.; Malik, P.K.; Singh, R.; Gehlot, A.; Juyal, A.; Ghafoor, K.Z.; Shrestha, S. Implementation of digitalized technologies for fashion industry 4.0: Opportunities and challenges. *Sci. Program.* **2022**, *2022*, 7523246.
90. Hu, W.; Lim, K.Y.H.; Cai, Y. Digital Twin and Industry 4.0 Enablers in Building and Construction: A Survey. *Buildings* **2022**, *12*, 2004.

91. Alves, L.; Sá, M.; Cruz, E.F.; Alves, T.; Alves, M.; Oliveira, J.; Santos, M.; Rosado da Cruz, A.M. A Traceability Platform for Monitoring Environmental and Social Sustainability in the Textile and Clothing Value Chain: Towards a Digital Passport for Textiles and Clothing. *Sustainability* **2023**, *16*, 82.
92. Stock, T.; Obenaus, M.; Kunz, S.; Kohl, H. Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential. *Process Saf. Environ. Prot.* **2018**, *118*, 254–267.
93. Oxman, N. The Age of Entanglement. JoDS. 2016. Available online: https://jods.mitpress.mit.edu/pub/ageofentanglement/release/1 (accessed on 29 February 2024).
94. Brown, S.; Vacca, F. Cultural sustainability in fashion: Reflections on craft and sustainable development models. *Sustain. Sci. Pract. Policy* **2022**, *18*, 590–600.
95. Kastenhofer, K.; Bechtold, U.; Wilfing, H. Sustaining sustainability science: The role of established inter-disciplines. *Ecol. Econ.* **2011**, *70*, 835–843.
96. McCrory, G.; Schäpke, N.; Holmén, J.; Holmberg, J. Sustainability-oriented labs in real-world contexts: An exploratory review. *J. Clean. Prod.* **2020**, *277*, 123202.
97. Kohtala, C. Making "making" critical: How sustainability is constituted in Fab lab ideology. *Des. J.* **2016**, *20*, 375–394.
98. Rayna, T.; Striukova, L. Fostering skills for the 21st Century: The role of Fab Labs and makerspaces. *Technol. Forecast. Soc. Chang.* **2021**, *164*, 120391.
99. How to Set up a Competence Centre for Innovation. A Short Guidance and Check List Developed by Procurement the Procure2innovate Project. Available online: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ca9385b0&appId=PPGMS (accessed on 29 February 2024).
100. Applied Research. Available online: https://uis.unesco.org/en/glossary-term/applied-research (accessed on 29 February 2024).
101. Adams, R.J.; Smart, P.; Huff, A.S. Shades of grey: Guidelines for working with the grey literature in systematic reviews for management and Organizational Studies. *Int. J. Manag. Rev.* **2016**, *19*, 432–454.