Closing the Loop: A Pilot Study on Circular Feedstock in the Fashion Industry

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Abstract
The fashion industry is among the most environmentally harmful sectors due to intensive resource consumption, overproduction, and waste generation. Circularity is emerging as a framework to rethink fashion systems, with materials acting both as environmental burdens and regenerative assets. This study is part of the PNRR-funded FasT4C project, which develops and tests a cradle-to-cradle, design-driven approach through Industry 4.0 technologies. FasT4C highlights the strategic role of process design in innovation across the Made in Italy value chain, from prototyping to end-of-life, supporting sustainable and circular processes. Focusing on the material dimension, the paper presents the pilot Sustainable Fabrication from Circular Feedstock, which investigates reintegration of textile waste into production using non-linear manufacturing methods, including technological and bio-based solutions. By reframing waste as a resource, the project promotes design-led sustainable practices and opens new pathways for resilient circular models in the fashion industry.

Keywords
Circular Feedstock
Fashion Industry
Transformation
Material-driven innovation
Textile Recycling
Non-standard Fabrication

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INTRODUCTION

The fashion industry, traditionally associated with creativity, cultural expression, and economic vitality, now stands as a critical contributor to some of the most pressing environmental challenges of our time. Driven by rapid globalization, the proliferation of fast fashion, and ever-shorter product lifecycles, the sector has evolved into a resource-intensive, waste-generating system with a disproportionately large ecological footprint (Surjit et al., 2024). Its current linear model — based on extractive production, mass consumption, and rapid disposal — is fundamentally incompatible with the principles of environmental sustainability and long-term resource stewardship. As such, the need for a systemic transformation in fashion is both urgent and necessary, with circular economy principles increasingly recognized as a viable and necessary framework for future development (D'Itria & Aus, 2023).

The environmental impacts of the fashion industry are multifaceted and extensive. According to the United Nations Climate Change - UNCC, fashion is responsible for approximately 10% of global greenhouse gas emissions — exceeding the combined emissions of international aviation and maritime shipping (UNCC, 2018). Additionally, the industry is the second-largest consumer of water globally. The production of a single cotton t-shirt can require up to 2,700 liters of water, a volume equivalent to nearly three years' worth of drinking water for one individual (EU, 2024). Textile dyeing processes contribute significantly to freshwater pollution, releasing toxic chemicals into water systems and endangering both ecological and human health, particularly in regions with lax environmental regulation (Mukherjee et al., 2024).

Synthetic fibers, especially polyester, now dominate the global fiber market, accounting for almost 60% of total fiber production (Textile Exchange, 2024). These materials are derived from fossil fuels, contribute to greenhouse gas emissions, and persist in the environment due to their non-biodegradable nature. Moreover, during laundering, synthetic garments release microplastics into aquatic environments, posing a long-term threat to marine biodiversity and entering the food chain. Waste generated by the fashion industry is similarly troubling: an estimated 92 million tonnes of textile waste are produced globally each year, with the vast majority ending up in landfills or incinerated. Less than 1% of discarded textiles are recycled into new garments, underscoring the limitations of the existing take-make-dispose paradigm (Tang, 2023; Juanga-Labayen et al., 2022).

The urgency for change is underscored by the results of these exploitations, such as ecological crises, including climate change, biodiversity loss, and resource scarcity. Fashion's environmental impact is no longer a peripheral concern, but it is central to global sustainability discourse. Increasing awareness among consumers, evolving regulatory frameworks, and the rising expectations of investors are intensifying pressure on the industry to reduce its ecological footprint and transition toward more sustainable business models. In this context, sustainability is not merely a reputational issue but a strategic imperative with direct implications for business resilience and competitiveness (Thorisdottir & Johannsdottir, 2020).

In the presented context, the circular economy is emerging as a transformative alternative to the prevailing linear model. Such an economic model offers a promising framework for restructuring the fashion system (D'Itria & Aus, 2023). In fashion, circularity aims to decouple economic activity from the consumption of finite resources by designing out waste, keeping

materials in use, and regenerating natural systems (Ellen MacArthur Foundation, 2023). Key strategies include designing for durability and recyclability, investing in closed-loop recycling technologies that allow fibers to be recovered and reintroduced into the production cycle.
Implementing circularity in fashion requires coordinated action across the entire value chain (Pal et al., 2019). Designers must integrate sustainability criteria from the earliest stages of product development, including material selection and end-of-life considerations. Brands and retailers need to develop reverse logistics infrastructures, traceable supply chains, and digital product passports to facilitate reuse, resale, and recycling. Consumers must be engaged and empowered to adopt more sustainable consumption behaviors, such as extending the lifespan of garments or participating in alternative ownership models. Moreover, policymakers must play a central role in creating enabling environments through regulatory instruments, economic incentives, and investment in sustainable innovation (D'Itria & Colombi, 2023).
Several pioneering companies and initiatives have begun to experiment with circular business models, including take-back schemes, clothing rental platforms, biodegradable textiles, and fiber-to-fiber recycling (Mishra et al., 2021). However, despite these promising developments, significant barriers remain to large-scale implementation. These include economic challenges, technical limitations, and cultural inertia (Dissanayake & Weerasinghe, 2022). Overcoming these barriers will require systemic thinking, cross-sector collaboration, and long-term investment in sustainable infrastructure and education.
The fashion industry stands at a pivotal crossroad. The transition to a circular fashion system represents not only an environmental imperative but also a significant opportunity for innovation, value creation, and long-term resilience. Accordingly, this paper aims to provide guidance for navigating this critical juncture by introducing and presenting the findings of the FasT4C – Fashion-Tech Design for Circularity project. By critically examining the environmental impacts of the sector and acknowledging the systemic nature of the required transformation, this work seeks to contribute to a deeper understanding of how the fashion industry can realign itself with the principles of ecological integrity, social equity, and economic sustainability.

INTRODUCING THE FAST4C PROJECT

FasT4C is a design-led research and innovation project that aims to foster circularity and sustainability in the Fashion, Textile, and Clothing (FTC) sector through the development and testing of an integrated cradle-to-cradle model (Casciani & D'Itria, 2024). The project is situated within the broader framework of MICS – Made in Italy Circolare e Sostenibile, part of the Italian Ministry of University and Research's Extended Partnerships initiative funded through the EU's NextGenerationEU programme under the National Recovery and Resilience Plan (PNRR). It addresses the urgent need for a radical transformation of the FTC sector by integrating advanced digital technologies with regenerative design approaches, guided by the principles of Industry 4.0 and the emerging paradigm of Industry 5.0.
At the core of FasT4C lies a conceptual and operational model articulated into two interdependent and mutually reinforcing dimensions: the blue and the green **Fig. 1**.

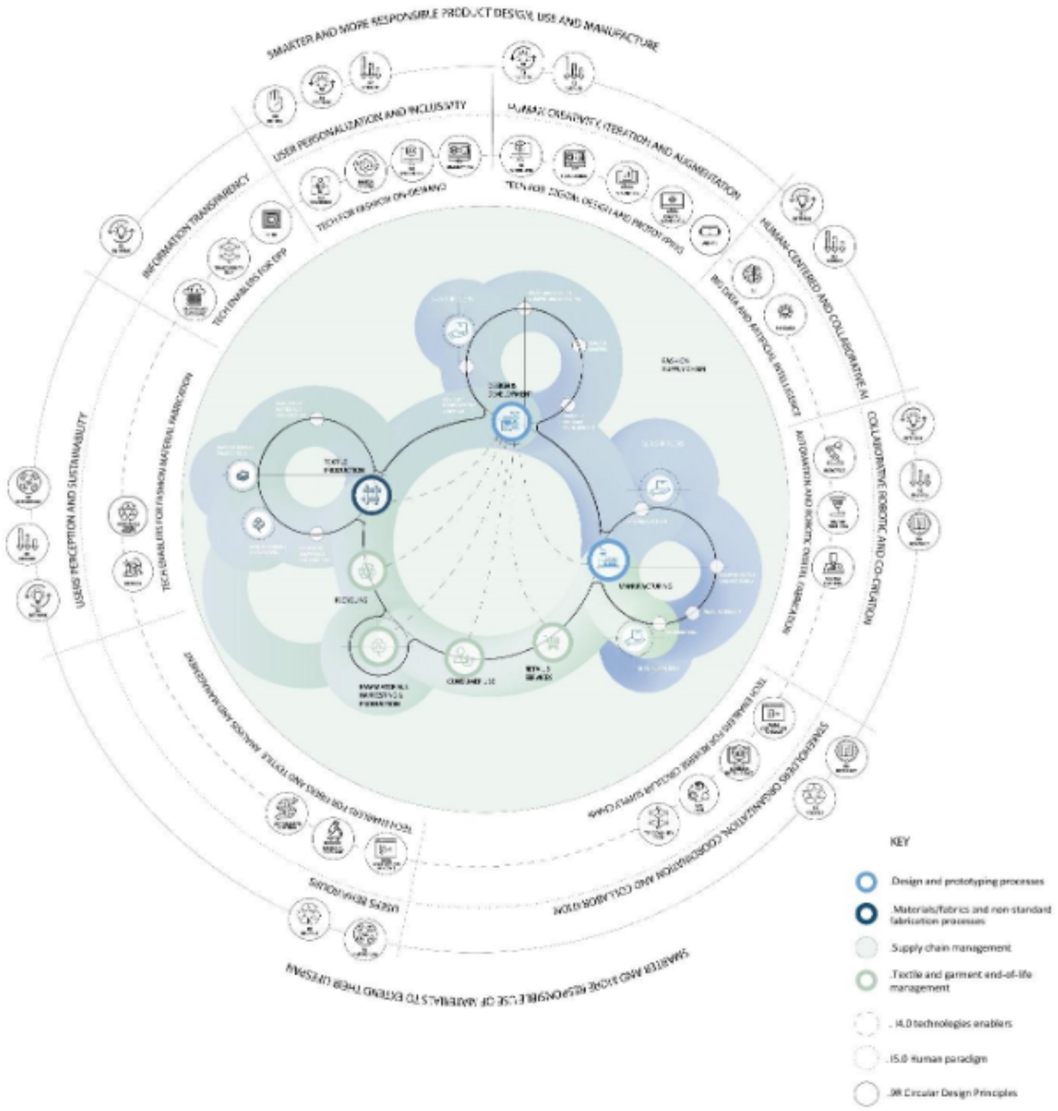

Fig. 1
FasT4C Model: a design-driven perspective of environmental and digital innovation of the FTC sector (Credits: Daria Casciani & Erminia D'Itria).

Drawing inspiration from Luciano Floridi's philosophical framework (2020), this model conceptualizes the blue and green dimensions not merely as technological and ecological domains, but as complementary forces in shaping a more sustainable, inclusive, and human-centered innovation ecosystem. The blue dimension concentrates on digital innovation and technological reconfiguration of value chains, while the green dimension addresses ecological regeneration and end-of-life management, together supporting a systemic transition from a linear to a circular model of production and consumption.
The blue dimension unfolds across three primary research tracks: Design and Prototyping Processes, Supply Chain Management, and Materials and Non-Standard Fabrication. These tracks are underpinned by the use of Industry 4.0 technologies such as digital fabrication, collaborative robotics, artificial intelligence, blockchain, and data analytics. The first track, Design and Prototyping, explores virtual and generative design methods—including 3D modeling, digital prototyping, and body scanning—with the aim of enabling waste-free and made-to-measure production, design for disassembly, and on-demand manufacturing. The second track, Supply Chain Management, focuses on developing decision-support systems, reverse logistics models, and traceability frameworks. This includes the integration of blockchain-based Digital Product Passports (DPPs), allowing for transparent and data-rich lifecycle monitoring that supports circular practices across all stages of the

supply chain. The third track, Materials and Non-Standard Fabrication, investigates advanced manufacturing processes such as additive manufacturing, 3D filament printing, and hybrid techniques that facilitate modular design, repairability, and component reuse—strategies that extend product lifespans and reduce environmental impact.

Complementing the blue dimension, the green dimension addresses the fourth research track: Textile and Garment End-of-Life Management, a domain that is increasingly recognized as critical to achieving circularity within the FTC sector. Rather than treating textile waste as a technical or logistical issue alone, this dimension adopts a systemic perspective, analyzing the textile waste ecosystem through the creation of material inventories, actor mapping, and waste stream categorization (Sandvik & Stubbs, 2019). Importantly, the green dimension supports the formulation of design-led strategies that do not merely aim to optimize the current production model but challenge and expand its boundaries. While conventional approaches to end-of-life management often focus on recycling and material recovery within narrowly defined circular loops, this dimension promotes a more expansive and regenerative view. It reconceptualizes textile waste as a resource of potential, shifting the paradigm from linear disposal to material transformation. By doing so, it opens up alternative pathways for value creation—particularly in the context of non-standard and regenerative fabrication processes. Specifically, textile waste is reframed as both a raw resources for the creation of textile-like materials for fashion and a biological support for the development of novel materials through biofabrication (Pollini & Rognoli, 2024). This includes leveraging emerging biotechnologies and the capabilities of living organisms—such as fungi, algae, and bacteria—to grow or transform waste into new material forms. These approaches reflect the principles of regenerative design, where biological and technical systems are integrated to restore rather than merely sustain material cycles. In contrast to traditional recycling, which often leads to quality loss (downcycling), regenerative fabrication aims to upgrade or re-contextualize materials within new ecological and design frameworks. This shift aligns closely with contemporary debates around circular and regenerative economies, which advocate not only for closing material loops but also for enhancing the resilience, adaptability, and ecological embeddedness of production systems (Andreucci et al., 2021). By framing waste as a generative input rather than a terminal output, the green dimension challenges ingrained perceptions of end-of-life discard and repositions it as a site of innovation, experimentation, and value redefinition (Papamichael et al., 2022). In doing so, it contributes to the emergence of a next-generation material culture—one that is locally sourced, biologically informed, and systemically integrated into broader sustainability goals (Zieker, 2024).

Together, the blue and green dimensions support a twin transition—both digital and ecological—towards a more resilient and inclusive FTC sector. This vision aligns with the principles of Industry 5.0, which emphasize ethical, human-centered innovation, and the enhancement of social and environmental well-being alongside economic growth. In this context, technological innovation is not an end in itself but serves as a strategic enabler of sustainability goals (Jabeen & Goli, 2025). The FasT4C model promotes cross-disciplinary collaboration, co-design practices, and the development of open digital tools that foster transparency, traceability, and systemic innovation. It encourages new forms of coordination across supply

chain actors and supports the emergence of distributed production networks that are adaptable, regenerative, and context-sensitive.
To operationalize its theoretical framework, FasT4C is developing a series of pilot demonstrators and establishing the Circular Fashion-Tech Lab—an open, hybrid infrastructure that supports experimentation, prototyping, and validation of circular strategies across the FTC sector. These pilots engage industrial partners, SMEs, and designers in real-world applications of circular practices, enabling the transition from lab-scale research to scalable, market-ready solutions. The lab also serves as a training and knowledge-sharing platform for professionals, researchers, and students, fostering a new generation of design practitioners equipped to drive the circular transition.
Ultimately, FasT4C positions design as a strategic driver of sustainable transformation within the FTC sector. By integrating the technological innovation of the blue dimension with the regenerative logic of the green, the project envisions a systemic shift toward models of production and consumption that are circular, repairable, and ecologically embedded. Within this framework, the present contribution focuses on the pilot project "Sustainable Fabrication from Circular Feedstock", which operationalizes the green dimension by reframing waste as a generative and multi-dimensional resource.

PILOT MODEL PRESENTATION AND ANALYSIS (The entire paragraph has been proofread in English)

The Sustainable Fabrication from Circular Feedstock pilot project represents a collaborative initiative led by experts from the Design and Chemistry Departments of Politecnico di Milano (POLIMI), in partnership with engineering specialists from Politecnico di Torino (POLITO). This interdisciplinary effort integrates sustainable fashion design, material innovation, and advanced recycling processes within the broader FASt4C ecosystem, specifically under the Materials/Fabrics and Non-Standard Fabrication Processes tracks of the Circular Fashion-Tech Lab framework. The

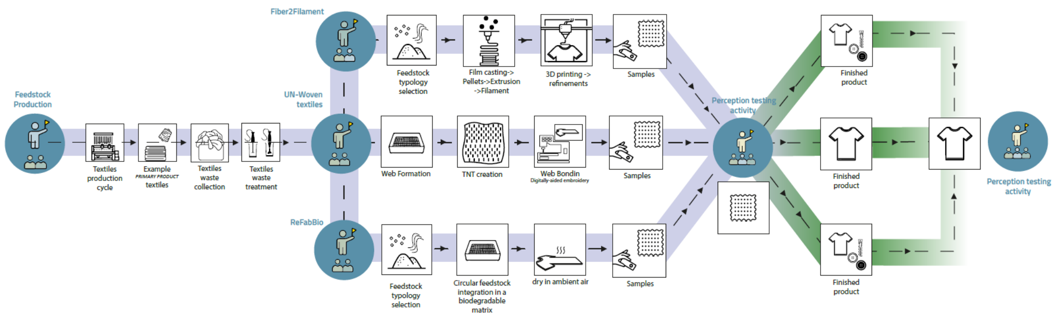

Fig. 2
FasT4C Sustainable Fabrication from Circular Feedstock Pilot Model. (Credits: Erminia D'Itria).

primary objective of the pilot is to investigate and promote sustainability and circularity within the fashion industry through the implementation of innovative recycling strategies targeting textile waste. This aim is pursued through three distinct experimental pathways, each dedicated to transforming discarded textiles into novel, high-value materials that can be reintroduced into fashion production cycles **Fig. 2.**

The first experimental pathway focuses on the development of composite filaments designed for Additive Manufacturing (AM) technologies. By converting textile waste into filaments suitable for 3D printing, this approach

seeks to exploit the precision and customization capabilities of AM to enable the creation of sustainable fashion components. This strategy not only extends the lifecycle of textile materials but also reduces reliance on virgin resources.
The second pathway investigates the use of biomaterials as renewable and biodegradable feedstocks. This line of research prioritizes the sourcing of materials that inherently support circular economy principles by providing environmentally benign alternatives derived from renewable resources. The incorporation of biomaterials aligns with efforts to replace traditional synthetic polymers with sustainable counterparts, thereby improving the ecological performance of fashion products. The third pathway explores the fabrication of textile-like materials from recycled fibers, processed through digital embroidery techniques. This innovative approach combines traditional textile aesthetics with advanced fabrication technologies, enabling the production of customized, sustainable materials that retain the tactile and visual qualities required by the fashion sector. Digital embroidery functions as a versatile method for material manipulation, facilitating the creation of intricate designs from recycled feedstock.
Across all pathways, the resulting materials undergo rigorous evaluation of their physical, mechanical, and sensory properties to determine their suitability for diverse fashion applications. These assessments ensure that sustainability objectives are balanced with performance requirements, ultimately supporting the development of market-ready sustainable fashion products.
Overall, this pilot project exemplifies a comprehensive, interdisciplinary approach to textile waste valorization, implementing innovative recycling methodologies to advance circular economy principles.

FIBER2FILAMENT

The recycling of textile waste into 3D-printable filaments aligns with circular economy principles by valorizing low-value materials and reducing environmental impact. Reinforced 3D printing materials enable the fabrication of complex geometries with enhanced mechanical performance compared to non-reinforced alternatives. By integrating fibers into polymer matrices, material stiffness and other key properties can be improved through the careful control of fiber content, orientation, and adhesion with the matrix (Rajak et al., 2019). Traditionally, carbon, glass, and aramid fibers are employed to reinforce polymers due to their stability and ability to increase stiffness; however, natural fibers are garnering growing attention in the literature (Pervaiz et al., 2021). Fibers such as cotton, linen, kenaf, and hemp show strong potential for the development of 3D-printable and biodegradable composite materials (Siddiqui et al., 2024).
A promising approach for producing reinforced composites for additive manufacturing lies in transforming waste textiles into reinforcement components for 3D-printing filaments (Rithika & Sudha, 2024). This strategy generates dual benefits: it contributes to waste reduction while simultaneously supplying sustainable materials for 3D printing (e.g., Candal et al., 2020; Cisneros-Lopez et al., 2019).
Textile waste—including pre-consumer offcuts and post-consumer garments—poses an increasingly significant environmental challenge. Globally, inefficient sorting processes and the prevalence of mixed-material

fabrics hinder effective recycling and lead to high volumes of landfill disposal or incineration. Mechanical recycling of textile waste allows recovery of fibers through cutting and shredding garments into short fiber forms. While this method is effective for natural materials, synthetic and blended textiles often require additional sorting or compatibilization strategies (Proto et al., 2000; Türemen & Demir, 2017). The recovered fibers—particularly those derived from pre-consumer waste—are typically heterogeneous in nature and geometry and may be considered for reinforcement in 3D-printable filaments; however, appropriate treatments are required. After sorting and cleaning according to dominant fiber type, mechanical shearing is necessary to produce dry, short fiber bales.

Additional chemical or physical surface treatments may be employed to improve interfacial adhesion, such as the use of silane coupling agents or maleic anhydride-grafted PLA (Calabia et al., 2013). To ensure homogeneous dispersion and controlled fiber geometry, sieving is generally required before mixing the fibers with thermoplastic resins (e.g., PLA, rPET). At this stage, 3D-printable filaments can be produced by extruding the compound into formats compatible with AM machines; filament diameters of 1.75 mm and 2.85 mm are commonly used in FDM systems (Candal et al., 2020; Yu et al., 2024). A central challenge in fiber-reinforced composites is the limited adhesion between hydrophilic fibers and hydrophobic polymer matrices. Addressing this issue can yield improved tensile strength, stiffness, and reduced moisture sensitivity in the final filaments.

The advantages of producing 3D-printing materials to upcycle textile waste are well-documented across numerous case studies. Rashwan et al. (2023) investigated the conversion of PET into flexible filaments via pelletisation, incorporating a chain extender, toughening agent, and impact modifiers before extrusion. These modifications enabled the production of filaments with robust mechanical integrity suitable for FDM applications in functional prototyping. Charoen et al. (2022) developed PLA-based filaments containing 10–30% recycled cotton fibers. Increasing fiber content resulted in higher melt viscosity, tensile modulus, and glass transition temperature, alongside improved water absorption, while preserving filament consistency and printability up to 30 % fiber loading. Apostolopoulou-Kalkavoura et al. (2024) demonstrated the transformation of post-consumer polycotton into cellulose nanocomposites suitable for FDM. The resulting filaments retained printability and enabled lightweight, flexible printed parts with applications in filtration and protection systems. Additionally, the UK-based company Fishy Filaments extracts nylon from end-of-life fishing nets to produce engineering-grade filaments and SLS powders. These materials, approved by manufacturers such as Ford and Mercedes-Benz, exhibit high tensile strength and impact resistance, serving as a benchmark for successful resource recovery and industrial circularity.

Nonetheless, textile waste is typically characterised by heterogeneous fiber lengths, fineness, and contamination. Despite the potential of this approach, several uncertainties must be addressed. Mixing fibers from diverse sources is a critical point of investigation, as it may mitigate performance variability. Insufficient or uneven fiber dispersion within the polymer matrix can result in fiber agglomeration and nozzle clogging in FDM printers; thus, adequate compounding and pellet realisation can improve dispersion and filament quality. Natural fibers tend to absorb moisture, leading to hydrolysis during extrusion, making pre-drying and the use of moisture scavengers (e.g., molecular sieves) advisable. Fiber inclusion also alters polymer viscosity and

melt rheology, impacting printing temperature and flow behaviour. Differential scanning calorimetry (DSC) and rheological analysis are required to optimise extrusion parameters and ensure melt stability (Candal et al., 2020; Yu et al., 2024).
Nevertheless, the utilisation of textile waste in filament production contributes to landfill diversion and reduces carbon emissions associated with polymer manufacturing. Locally sourced materials and on-site fabrication minimise transport-related impacts. Furthermore, high-value applications in sectors such as automotive, technical filtration, and fashion prototyping enhance economic feasibility, reinforcing the establishment of a closed-loop ecosystem.
Potential initial applications of the resulting filaments include:
• Functional prototyping, such as printed components for mechanical testing, sensor housings, or robotics, replacing the use of virgin materials.
• Fashion-tech accessories, such as sustainable jewellery, eyewear, or footwear prototypes, offering customisation and minimal production waste.
The conversion of textile waste into 3D-printable filaments offers a multifaceted strategy to address both plastic pollution and fast-fashion waste. Laboratory- and pilot-scale studies (e.g., Charoen et al., 2022) confirm the technical feasibility of producing composite filaments based on PLA, PET, TPU, polycotton, and nylon. Compatibilisers such as silanes, grafted polymers, and nanocellulose play a crucial role in performance enhancement.

Fig. 3
Fiber2filament process – Cotton starter, filament extrusion, and sample printing.
Credits: Flavia Papile.

Although case studies demonstrate feasibility at both maker/hobbyist and industrial scales, challenges persist in standardising and scaling production processes, ensuring consistent feedstock quality and property repeatability, and optimising rheological behaviour. Through the integration of technological innovation, sustainable sourcing, and supportive policy frameworks, textile-to-filament upcycling has the potential to progress from an academic innovation to a widely adopted industrial standard—opening a new chapter in additive manufacturing and sustainable materials. Accordingly, within the project, several experiments have been initiated on fiber-reinforced polymers derived from pre-consumer textile waste, with the aim of upcycling commonly used textile materials (e.g., polycotton) **Fig. 3**.

FIBRAframe introduces an innovative research trajectory within the field of circular textile systems, exploring the potential of digitally assisted industrial embroidery as a core tool for sustainable material fabrication. Rather than treating embroidery as a decorative finishing process, the research repositions it as a structural and operational technique capable of actively defining, stabilising, and assembling components derived from circular feedstock. The primary aim is to demonstrate how a conventional tool—traditionally associated with garment embellishment—can be repurposed as a generative instrument within a fabrication workflow that prioritises material efficiency, process legibility, and zero-waste outcomes. This approach aligns with the broader call for systemic innovation in fashion and textile production, where sustainability is increasingly recognised as a challenge involving not only material selection but also infrastructural, procedural, and epistemological dimensions.

FIBRAframe addresses this complexity by advancing a hybrid methodology that integrates technical experimentation with critical process design. The research began with an extensive review of current literature, industry practices, and ongoing European research initiatives in circular design, digital fabrication, and sustainable material innovation. This preliminary investigation underscored a significant gap: digital manufacturing technologies—despite their widespread availability in the textile sector—are seldom leveraged beyond their traditional functions. In particular, embroidery machines, which are ubiquitous in industrial and semi-industrial contexts, are rarely explored for their capacity to manipulate structure or define functional zones within material systems.

Building on this insight, the project reframes the embroidery machine as a device capable of generating frameworks that capture and stabilise regenerated fibers—such as those obtained from garnetted textile waste—by stitching them into precise, load-bearing geometries. These stitched zones are not ornamental; they are inherently functional, facilitating the physical containment of otherwise unstable fibers to provide shape, structural integrity, and modularity to the resulting textile elements. This approach constitutes a methodological inversion: instead of imposing structure externally through additional materials or binding agents, structural integrity emerges internally from the digital embroidery process itself Fig. 4.

The implications of this shift are both technical and conceptual. From a technical perspective, the process allows high levels of control over stitch distribution and density, enabling the production of lightweight, structurally coherent textile modules with minimal material input. Conceptually, it challenges dominant hierarchies in textile manufacturing that segregate decorative and functional operations, proposing instead their convergence in a framework where expressivity and engineering co-evolve.

The fabrication workflow developed within FIBRAframe integrates loose, fleece-like fibers—typically deemed unsuitable for reuse due to their instability—into a substrate through localised stitched reinforcement. By digitally programming embroidery machines to define precise zones and patterns, fibers can be selectively encapsulated within a semi-rigid matrix, transforming them into usable elements for garment or accessory construction. The process is designed to be iterative and adaptable, with parameters such as stitch tension, pattern density, and thread composition adjusted according to the behaviour of the underlying material. The method

has been successfully applied across a range of circular substrates, including denim, felted wool blends, recycled fleece, and mixed-fiber compositions, demonstrating scalability and versatility across material typologies. Experimental prototypes produced using this technique exhibit strong dimensional stability and mechanical resistance, while maintaining a soft tactile quality suitable for both fashion and interior applications. Importantly, the embroidery frame not only defines the geometry and structure of the textile module but also facilitates handling, transportation, and integration within broader assemblies, positioning it as a viable alternative to conventional cut-and-sew or composite fabrication methods.
In parallel, the project integrates waste recovery practices by introducing a system for collecting and reintegrating fibers that fall outside the stitched zones. Rather than being discarded, these residual materials are dissolved in water and reintroduced into the garnetting process, creating a closed-loop cycle with minimal material loss. This reinforces the project's commitment to circularity, extending beyond the product level to encompass the fabrication system as a whole.

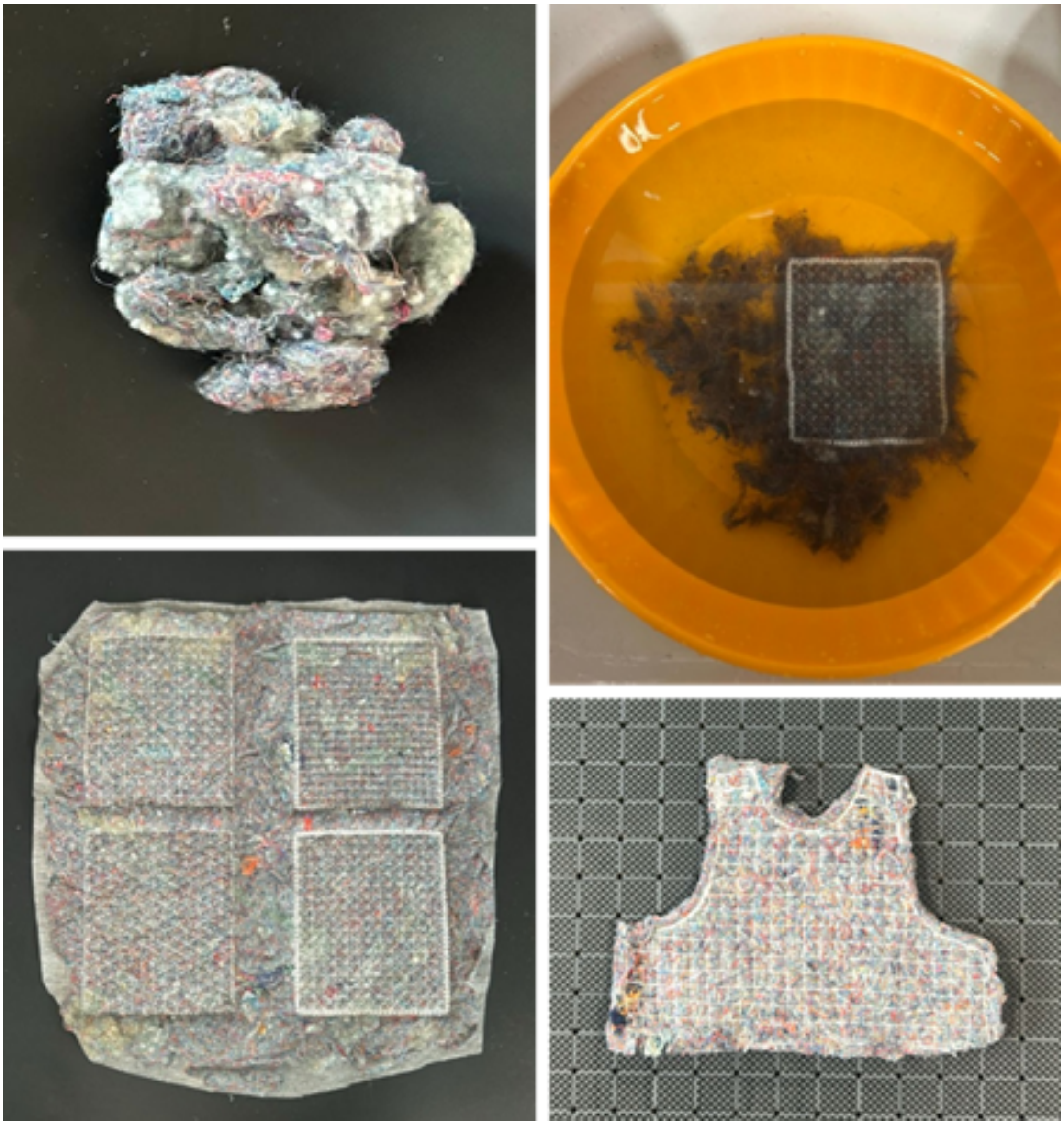

Fig. 4
FIBRAframe polycotton – starter with embroidered TNT and module sample
Credits: Erminia D'Itria.

Beyond its technical contribution, FIBRAframe also addresses the cultural and perceptual dimensions of textile design. The current phase of the research focuses on defining material attributes and exploring user perception of embroidery-based structures. A central line of inquiry concerns how the visible presence of the stitched framework—representing a trace of the fabrication process—influences cognitive and sensory responses to recycled materials. By making the process legible on the material surface, the stitched framework functions as a form of semiotic device, signalling intentionality, care, and transparency. In this context, the stitch acts simultaneously as structure and narrative: it communicates the origin of the material, its transformation, and its potential trajectory. The project hypothesises that such visibility may contribute to the revaluation of waste-derived materials, increasing their perceived value and desirability. This will be examined through qualitative testing, co-design sessions, and focus groups involving designers, material developers, and end-users. Early observations suggest that participants interpret the embroidery not simply as an aesthetic element, but as an indicator of sustainability and innovation—qualities increasingly prioritised in contemporary markets.
The goal of this phase is to generate data that inform the development of design guidelines and pattern libraries, enabling customisation of embroidery strategies according to both material performance and perceptual feedback. By positioning the stitch as a site of technical and cultural intervention, FIBRAframe supports the emergence of a new material language grounded in process transparency, circular logic, and digital craftsmanship.
In conclusion, FIBRAframe articulates a research-driven methodology for sustainable textile fabrication arising from the critical reappropriation of an existing tool. By reframing digitally assisted embroidery as a structural rather than decorative process, the project expands the possibility of working with unstable or non-standard materials in controlled, precise, and aesthetically meaningful ways. It demonstrates that innovation may emerge not solely through the invention of new tools but through the creative reinterpretation of existing ones, grounded in an awareness of their latent capacities. In doing so, it proposes a model for pursuing sustainability not only at the material level but within the very logic of fabrication itself—establishing processes that are efficient, expressive, and intrinsically regenerative.

REFABBIO

ReFabBio is a material–driven design research initiative situated at the intersection of textile waste recycling and biodesign. As part of the broader Textile Waste Recycling project, the initiative focuses on the development of innovative material prototypes by combining post- and pre-consumer textile fibers—especially wool, cotton, and polyester—with bioadhesives derived from bacterial cellulose (BC).
ReFabBio investigates how biological bonding agents can facilitate the regeneration of textile waste into context-specific, functional materials through experimental biofabrication methods (Guarino et al., 2024; Langella, 2024; Rognoli et al., 2022). The project aims to develop environmentally sustainable solutions for the fashion industry, with a particular focus on accessories such as garment labels, trims, and tags.
While significant progress has been made globally in textile recycling and upcycling, the integration of biofabricated materials—especially living

materials such as BC—into textile reuse remains largely unexplored within design practice. ReFabBio addresses this gap by examining the potential of BC produced via microbial fermentation (e.g., kombucha) as a bioadhesive for the creation of novel textile composites. The use of BC in this context opens new opportunities for sustainable design and production, offering both functional and experiential benefits.
The project contributes to this emerging field by exploring how BC may act not only as a binding agent but also as a mediator of sensory experience, material tactility, and perceived value. This line of inquiry aligns with the broader FAST4C framework, which promotes circular innovation from both technological and cultural standpoints. Building upon initial research conducted within the Biolab track of FAST4C—where BC was investigated as a base material—the project extends this work through cross-disciplinary collaboration among material researchers, biofabrication specialists, and textile designers **Fig. 5**.

Fig. 5
REFABbio - BIOCOMPOSITE SAMPLE FROM TEXTILE WASTE – TEXTILE WASTE COURSE & MATERIAL COOKBOOK.
Credits: Nicla Guarino & Ziqian Yu.

The materials development process involves transforming shredded textile fibers into cohesive, tactile samples through manually controlled fusion and moulding techniques. Pre- and post-consumer textile fibers are mechanically shredded and combined with BC-based bio-binders in varying proportions before being cast into silicone moulds under ambient conditions. This approach allows for precise variation in colour, form, thickness, and texture. A central research focus concerns the formulation of the BC binder itself. By adjusting the ratio of BC to water and incorporating additional natural agents, the team has identified a range of binder consistencies that significantly impact material properties such as drying time, flexibility, surface finish, and mechanical strength.

The resulting samples demonstrate notable variation in texture, weight, and visual character depending on the fiber type and binder composition employed. BC has shown high compatibility with a wide range of fiber types—

including natural fibers such as wool and silk, as well as synthetic fibers like polyester—with minimal adhesion or integration issues. This versatility provides promising opportunities for reprocessing mixed-content textile waste, which is typically challenging to address using conventional recycling techniques (Patti et al., 2020). The resulting materials are simultaneously soft and structurally stable, making them suitable for lightweight accessories requiring both shape retention and surface definition.

ReFabBio also critically engages with the constraints and potential of DIY-scale, non-industrial biofabrication. The labour-intensive process relies on manual techniques, which may lead to minor inconsistencies across samples, particularly with respect to adhesive distribution and drying uniformity. Nevertheless, this handcrafted dimension is integral to the project's experimental and educational ethos. Integrated into material design courses at Politecnico di Milano, ReFabBio functions as a pedagogical platform, introducing emerging designers to the aesthetic, technical, and regenerative potential of reclaimed textile fibers. As such, the project positions itself not only as a site of material innovation but also as a model for embedding circular principles into design education.

In its next phase, ReFabBio will expand its focus to include expressive and sensory evaluation. Alongside mechanical testing, the project will incorporate sensory assessments engaging designers and potential end users in direct interaction with material samples. ReFabBio hypothesises that tactile and visual engagement may enhance the perceived value of recycled materials and support a broader cultural shift toward the acceptance of waste-derived products.

By adopting a biofabrication-integrated approach to textile waste valorisation, ReFabBio strengthens the FAST4C pilot. Its material samples—composed entirely of reclaimed textile fibers combined with bacterial cellulose binders—represent a biodegradable and sustainable alternative for fashion accessory development. By prioritising tactility, biological processes, and educational engagement, ReFabBio advances a comprehensive vision of material regeneration within circular fashion systems.

CONCLUSIONS AND FUTURE SCOPE

This paper has examined the FAST4C pilot focused on Materials/Fabrics and Non-Standard Fabrication Processes, developed within a broader framework that combines environmental responsibility (green) and digital innovation (blue). As part of a design-driven, Industry 4.0-enabled research agenda, the pilot aims to reframe textile waste as a regenerative input within circular fashion systems.

A key outcome of the pilot was the integration of zero-waste design principles and bio-based functional materials into scalable workflows, while also monitoring the environmental impact of synthetic fiber release. These innovations contribute directly to the advancement of circular fashion practices by embedding sustainability at the material and process levels. The pilot thus exemplifies how design-driven innovation can generate systemic value across the fashion lifecycle.

To provide a clearer synthesis of the experimental pathways, Table I summarizes the three approaches—Fiber2Filament, FIBRAframe, and

ReFabBio—highlighting materials, processes, outputs, and the main criticalities alongside opportunities for future development.
The comparative analysis shows that while technical and scalability challenges persist—such as heterogeneous fiber quality, process variability, and cultural acceptance—each pathway opens up significant opportunities. Fiber2Filament demonstrates potential for localized production and integration into additive manufacturing markets; FIBRAframe introduces design innovation through modularity and visible process aesthetics; ReFabBio advances biofabrication and biodegradable product development, reinforcing the role of design education in circular practices.
Nevertheless, the pilot also revealed several limitations. Technical challenges in processing textile waste, inconsistencies in material quality, and limited scalability of certain fabrication techniques indicate the need for further research. Additionally, integrating advanced manufacturing tools and traceability systems remains difficult for small and medium enterprises (SMEs) with limited digital capacity.
Looking ahead, future work will expand this pilot to explore other material categories, deepen testing of bio-composites, and investigate the environmental performance of emerging fabrication methods. Particular attention will be given to the development of hybrid design–technology platforms capable of supporting industry adoption and policy alignment. The Circular Fashion-Tech Lab will continue to serve as a research and testing infrastructure for validating new approaches to material regeneration and circular innovation.
In conclusion, the FAST4C pilot demonstrates that circularity in fashion is not only a technical challenge but a design opportunity. By repositioning textile waste as a regenerative resource and strategically addressing criticalities and opportunities, it provides a compelling model for sustainable transformation in fashion and beyond.

Pathway	Materials	Processes	Outputs	Main Criticities	Opportunities
Fiber2Filament	Pre-consumer textile waste (cotton, polycotton)	Mechanical shredding, surface treatment, extrusion	3D-printable composite filaments for fashion-tech and prototyping	Heterogeneous fiber quality, moisture absorption, adhesion issues	Localised production, reduction of virgin polymer use, integration into additive manufacturing markets
FIBRAframe	Loose recycled fibers (denim, wool blends, fleece)	Digital embroidery for structural reinforcement	Textile modules with dimensional stability and aesthetic value	Process scalability, stitch density optimization, cultural acceptance	Design innovation through visible process aesthetics, modularity for circular fashion, educational applications
ReFabBio	Mixed textile fibers + bacterial cellulose	Bioadhesive formulation, moulding, drying	Biodegradable composites for accessories (labels, trims, tags)	Manual process variability, drying uniformity, limited industrial scalability	Advances in biofabrication, biodegradable product development, integration into sustainable design curricula

Tab. I
Summary of Experimental Pathways with Criticities and Opportunities

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