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Research

Materials selection and fashion design: strengthening reflections on fibre's nature in fibres and textiles selection

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Received: 31 December 2023 / Accepted: 24 May 2024
Published online: 03 August 2024

Abstract
Textile ecosystems are complex productive realities, in the eye of the cyclone when it comes sustainability-related analysis. Being characterised by very complex value-chains and interconnection of productive actors, textiles production and use represent one of the most crucial challenges for the circular and sustainable transition. Their deployment is esteemed to be in growing for the next years, therefore reflections on how to improve product and materials circularity in this sector is of increasing interest in research and industrial practice. In this contribution, authors will try to map the material properties that can influence textiles application in the fashion sector, focusing on the coupling of material selection activity and application of design strategies to anticipate at best the reflections upon textiles use and recirculation. Results of this activity are then shown and discussed to question the applicability of the reported data into a fashion design activity, to promote awareness and critical reflections upon materials use while designing new fashion goods.

1 Introduction

The textile ecosystem is composed by the textile, clothing, leather and footwear industries and is among the most globalized value chains. In Europe, it employs 2.2 million workers and is made up of 99.5% of small and medium-sized enterprises (SMEs) [1]. The textile production system has for years been in the eye of the cyclone for the change of production paradigm, with a tightening in recent times: in the Circular Economy Action Plan of 2022 [2] the textile sector, in the European context, was placed in fourth place for greater impact on the environment and climate change—after food, housing and mobility -, at third place for the use of water and soil and fifth place for the extraction of primary raw materials. Global textile production almost doubled between 2000 and 2015 [3] and, to exacerbate this scenario, it is estimated that the consumption of clothing—representing 81% of the EU's textile destination—and footwear should increase by 63% by 2030, from the current 62 million tonnes to 102 million tonnes in 2030 [4]. These negative impacts stem from the linear economy model that defines the sector along its value chain through the system of production, distribution, and use of clothing. This takes-make-dispose approach places excessive stress on natural resources and lacks long-term resilience [5].

To contain the negative impacts of this productive sector industry, government agencies and the scientific community are analysing and modeling the transformation of the current linear economic model into a circular one. The Fashion Systems, characterized as the combination of garments, shoes, or accessories that undergo design, purchase, production,

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and supply processes, are now influenced by new regulations [6]. These regulations emphasize concentrating on key activities occurring at the intersection of physical and digital practices in the design and sale of fashion garments.

First, promoting the design and use of fashion products responsibly and effectively in society as long as possible and in their most valuable form, then safely return to the biosphere when no longer in human use [7] is one of the strong inputs coming from regulations and studies. Globally, during the COP24 in Katowice (Poland) in December 2018, the Fashion Industry Charter for Climate Action [8] was issued, which provides the industry and its signatories with a clear path to zero net greenhouse gas emissions by 2050, the recycling of traditional closed-loop materials and the derivation of materials from regenerative or deforestation-free/land conversion crops and the phasing out of coal from owned sites and suppliers by 2030.

Secondly, promoting information exchange along all the productive value chain. The EU Strategy for Sustainable and Circular Textiles is a crucial step Europe has taken to address emerging sectoral issues and fulfill its commitments under the European Green Deal [2], the Circular Economy Action Plan, and the European Industrial Strategy [9]. The objective of this document is to speed up the resilience and competitiveness of textile ecosystems, regulate and introduce sustainable and circular textile products with improved design, production, and disposal, emphasizing the importance of implementing clean technologies in textile production systems. In this framework technologies ad the Digital Product Passport and the Digital Twins for Fashion garments take place.

Finally, empowering an aware use of materials and resources in the sector is mandatory. Another European action plan called the Sustainable Product Initiative[1] has announced pragmatic strategies to achieve the goals set in the field. Among these, the most revolutionary conceptually concerns a regulation on the eco-design of sustainable products: the Ecodesign for Sustainable Products Regulation (ESPR) [10] which will establish new requirements to make products more durable, reliable, reusable, repairable, to be renewed and recycled, as well as more energy efficient through the correct design, which according to the European Commission determines up to 80% of the environmental impact of the product life cycle [2].

In this framework, the design field is therefore of fundamental importance to promote the adoption of new circular design strategies and consumption systems [11], and Designers are the first ones responsible for designing products. And in this product-oriented perspective, materials used for the design of fashion garments play an important role in the transition pathway for circular product design [12]. Therefore, the question is to understand if fashion designers are ready to embed reflections of materials environmental properties into their design activity.

If the technical language and breadth of the available studies concerning limitations and guidelines for certain materials use in the fashion industry make it difficult for designers to directly understand and use their results, a "short circuit" in the transition may occur [13]. The purpose of this study is therefore to understand and highlight environmental-related material information and propose a framework to help designers in embedding these technical data into their creative activity.

2 Literature review

Integrating environmental requirements into product design for sustainable fashion is nowadays mandatory to achieve performance objectives in the fashion system [14]. The development of new design strategies is possible through the understanding of the environmental damage that the fashion industry and its products cause. In this perspective, a huge amount of proposals, plans, methodologies and scenarios have been produced in literature to frame and accomplish transitional objectives.

From very punctual and product-driven methodologies (such as the Ecodesign ones [15]) to broad and systemic design studies, a complex world of guidelines, strategies and tactics has been explored in literature, and when it comes to materials [16] the discourse gets even more interesting. Being at the basis of every physical artifact, materials play a significant role in the systemic transition towards circular products design [17, 18]. Materials in fact can be analysed at least on three different levels [19]: technically, sensorially and environmentally. In fashion design, the term "material" gains even more complexity [20] since it may refer to the chemical constituents of the single fibre, to yarns or even textiles and solid components of fashion garments.

[1] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en

According to European Commission [21], eight main building blocks should be followed to pursue an effective transition in the Textile, Clothing, Leather and Footwear Industries (TCLF): Creating a Sustainable competitiveness, Follow regulations and public Governance, Consider Social dimension in the transition, encourage R&I, Techniques and Technological Solutions, Empower infrastructures, work on Skills, Invest and fund innovative projects and practices and support EU strategic autonomy. In this framework, physical and digital attributes of textiles for fashion garments must be efficiently analysed throughout the design process to ensure efficient resources prolonged life at the end of the value chain. For doing this, authors envisioned in three main research tools the necessary basin of information to anticipate in the design phase some reflections concerning fibre's materials and their reverberation throughout all the production pathways. These tools will be analysed in depth in the following paragraphs and are respectively LCA-based methods for the fashion industry, Textiles Digital Twins Technology and Digital Product Passport for Textiles.

2.1 LCA-based methods for fashion industry

A widespread tool for assessing the environmental impact of products is the Life Cycle Assessment (LCA) [22]. Based on the analysis of LCA studies in the literature, it is possible to define areas in which it is possible to intervene during the garments design phase to limit the environmental impacts of new fashion and textile products, related to fiber's material choices.

The LCA method proposes the division into five phases [14]:

- Pre-production
- Production
- Distribution
- Use
- End of life

As shown in Fig. 1, it is possible to see that the environmental impacts of a fashion product are distributed unevenly within these phases of life, and focus on the first two phases: pre-production and production (collected in a single phase), and use.

The environmental impact in the pre-production and production phase includes the extraction of the raw material and its processing, the production of semi-finished products (yarns and fabrics), the finishing processes up to the packaging of the final product. All these phases and the associated environmental impacts are strongly influenced by the nature of the raw material [14].

To bring out the most relevant issues at this stage we have collected the most significant environmental impact categories: climate change, water use and consumption, human toxicity, and primary energy demand. These parameters are defined by the European Commission [24] as follows:

- *Climate change*: this indicator refers to the increase in global average temperatures because of greenhouse gas (GHG) emissions, in this case, to the supply and processing of raw material. The parameter "climate change" is measured in kilograms of equivalent carbon dioxide (kg CO_2 eq.) and corresponds to the impact of all greenhouse gases emitted, translated into the amount of CO_2 needed to produce that same impact.
- *Water use and consumption*: the withdrawal of water resources from lakes, rivers or aquifers can contribute to the exhaustion of available water. This impact category considers the availability or scarcity of water in the regions where the activity takes place if this information is available. The associated environmental impact is expressed in cubic meters (m^3 eq.) of water consumption concerning local water scarcity.
- *Human toxicity*: this indicator refers to the potential impacts on human health caused by the absorption of substances through air, water, and soil. The direct effects of products on humans are currently not measured. The unit of measure of the category is UTCh, which stands for "Comparative Toxic Unit for human".
- *Primary energy demand*: primary energy demand means the amount of energy coming from all the different sources, both renewable and non-renewable, necessary to acquire and transform the raw material, in this case into textile fibers.

These categories together account for about 55% of the total impact.

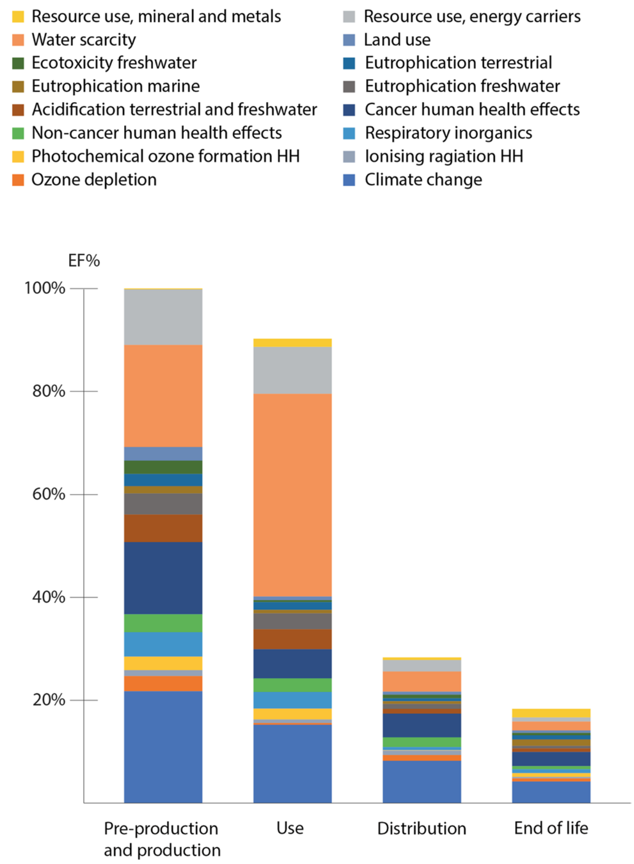

Fig. 1 Overall results that could be obtained by performing an LCA on a clothing product. Reworking of the author by Vezzoli et al. (2022)

Fig. 2 European Commission 2022 EU Strategy for Sustainable and Circular Textiles, author re-elaboration

A material selection process focused on the main categories of environmental impact of the process that takes place at this stage can positively affect the environmental performance of the final product.

The use phase of the product is the second in terms of environmental impact (Fig. 2).

This is due to garment care processes, namely the type and frequency of washing, drying, and ironing [25–27]. Following the analysis of the literature we examined how different materials with their properties can discourage the frequency of such actions and encourage, among these, less impactful practices. In this phase, three problems that could be influenced by the material of which the garment is composed emerged: frequency of washing, type of washing, release of microplastics, frequency of ironing and durability.

To reduce the frequency of washing, the two properties to consider are stain resistance and odor resistance. Both may be intrinsically associated with the nature of the fibre, but it has emerged from the literature that the structure of the semi-finished product can also change its performance [28]. The first property is affected by the fiber moisture recovery, the tendency to accumulate static electricity and the circular section of the fiber; the second one is affected by the ability of the fiber or semi-finished product to absorb water.

About washing, today's literature does not document the direct relationship between the fiber's nature and wet or dry washing. The only releases are about probability: for example, it was found that clothing made of silk, wool and wool mixtures are three times more likely to be dry-cleaned than cotton or synthetic garments and their blends [29]. Dry-cleaning practice is less favored due to the use of chemical solvents that are hazardous to human health and the environment [30, 31] and increased energy consumption.

The release of microplastics is associated with synthetic garments, but the quality of the fibre, the structure of the yarns and that of the fabrics can allow a more or less great release of microfibers [32].

The concept of durability is not directly associated with that of sustainability, but it is related to the type of product that is considered: the plastic bag, for example, designed to be used a few times before being disposed of, finds in the biodegradability of the materials the characteristic closest to the principles of sustainability [33]. According to the Waste & Resources Action Programme (WRAP) [34] report, increasing garment durability is the "single greatest opportunity" to reduce the environmental impacts of greenhouse gas (GHG) emissions, water demand and waste production: extending the life of clothing by nine months could reduce the carbon footprint, water and waste from 20 to 30%. In addition, if the wearing frequency of a garment doubled, greenhouse gas emissions would decrease by about 44%, compared to the number of emissions generated by the production of a new garment. By cross-checking the standardized ISO tests used to assess the physical durability of materials, we have collected the properties that can be considered in the material selection phase for a durable garment: abrasion resistance, tensile strength, pilling resistance, light resistance, color fastness and dimensional stability.

The environmental impact associated with the end-of-life phase is closely linked to the issue of waste disposal. The Ellen MacArthur Foundation has estimated that the equivalent of a fabric-filled garbage truck is either dumped or incinerated every second [3].

The European Commission is now considering the EPR (Extended Product Responsability) as a regulatory measure to promote sustainable textiles and the treatment of textile waste following the waste hierarchy [35].

Currently available options for the disposal of clothing products are closed-loop recycling (or fiber-to-fiber), open-loop recycling (an option that usually sees the transformation of clothing items into upholstery for furniture products or insulating materials) incineration (with or without energy recovery), and landfill. Despite the range of options available, fashion waste is mainly landfilled or incinerated [3].

The analysis of the environmental impact of fashion products has resulted in the definition of applicable strategies during garments design phase, to enhance the product's circularity and environmental sustainability. In Table 1, a summary of strategies compiled by the European Union TwinRevolution [23] project is here presented.

2.2 Textiles digital twins

The intertwin of circular and digital strategies can support the transformation of the textile industry [36] and consequently have positive consequences in the fashion garments value chain.

Creating digital twins (DTs) for fashion garments design and prototyping represents a tangible opportunity in terms of coupling sustainable transformation with the digital one [37]. Defined as a virtual copy of any physical entity with real time data exchange [38], DT technology enables professionals in simulating e.g. processes, employ models, and life of digitalised physical artifacts. Exploiting probabilistic simulations, this technology can significantly contribute to information mapping throughout all the product life cycle. Therefore, decision-making processes [39] in the design activity can be strongly reinforced by DT technologies in terms of simulation and control of the decision made at the design stage throughout the whole product life cycle, such as material selection. In this perspective, DT may help, e.g., in material waste reduction, production optimisation and information mapping to allow material recovery at the garment's end of life.

Some software (e.g. Clo3D, Daz3D ecc…) already started to embed partial information oriented to the DT technology. But when it comes to materials in fashion, the main aspects that are managed by designers concern the technical and hedonic features of prime matter, not having a proper control of how their decision may affect the whole production pathway.

However, some studies say *"Future studies can explore (1) how the DT processresulted in a smaller environmental footprint, (2) accurately mea-sured how much material, water, and dye treatments were saved,and (3) how it compares to the additional carbon footprint associ-ated with digital technologies in general, such as energy to runequipment, cloud storage, and so forth."* [38]

2.3 Digital product passport for textiles

The European Commission proposed the Ecodesign for Sustainable Products Regulation on March 30, 2022, as part of the EU Green Deal framework. By 2030, Digital Product Passports (DPP) will be mandatory for textiles sold in Europe to promote environmentally sustainable and circular products.A DPP is a digital record that contains information about a

Table 1 Summary of circular strategies in the textile sector [23]

Strategies	Description	Best practices
Ecodesign	Ecodesign takes environmental aspects into account at all stages of the product development process and strives for products that have the lowest possible environmental impact throughout the product's life cycle, where economic aspects are also considered	* Ensure maximum product lifetime; * Use recycled materials * Ensure production sustainability
Material Innovation	Innovation in materials, replacing fossil supplies with biobased and recycled content	* Substitution of fossil materials with biobased and recycled materials
Refurbishing	The process of repairing or restoring a garment though which the garment is given a new life	* Repair of clothing * Garment alterations
Recycling	Clothing recycling where clothes are processed and new fibres are obtained	* Use of technologies for easy recycling of clothing materials * Use of digital passports * Improving waste sorting
Change in the distribution model	To look at textiles in a new way not only in terms of sales	* Offer textile lease/rental business models

product's entire lifecycle, including product identifiers, material composition, performance, environmental and social data.

The European Commission (EC) defines a 'product passport' as a product-specific data set, which can be electronically accessed through a data carrier to "electronically register,process and share product-related information amongst supply chain businesses, authorities and consumers" [40].

The DPP would provide information on the origin, composition, and repair and disassembly possibilities of a product, including how the various components can be recycled or disposed of at end of life. This information can enable the upscaling of circular economy strategies such as predictive maintenance, repair, remanufacturing and recycling. It also informs consumers and other stakeholders of the sustainability characteristics of products and materials.

In a designer's perspective, being aware of the information contained and mapped through the DPP tool would significantly help in anticipating actions for disassembly, reuse, recycle, upcyle and other circular practices intervening by design on the idealization and definition of textiles fashion garments. This anticipation and control can even more easily be linked to the reflections concerning fibres material choices.

The European Commission proposes DPPs as a secure and standardized way of sharing product information across the entire value chain. The data can be accessed via physical identifiers such as QR codes, NFC tags or RFID chips. DPPs can promote sustainability by increasing transparency, improving durability, enhancing recyclability, and reducing waste.

3 Methodology

The objective of this study is to conduct a critical analysis of the life cycle assessment (LCA) of fashion products to identify the most significant environmental impact parameters. Based on the literature analysis, the study aims to extract information that can be translated into design features that are easily manageable by designers. This contribution mainly focuses on the asset of material innovation. The 'fibre's nature' refers to the physical element that makes up the raw material of the textile industry. This work will demonstrate that the extraction and processing of the raw material has the greatest environmental impact. The processes, properties, and end-of-life risks may vary depending on the fibre's nature.

The shift towards new circular and sustainable practices in textile ecosystems is not solely dependent on the type of fibre In-depth analysis of fibre characteristics can provide valuable information to enhance textile design and production, contributing to increased awareness in decision-making and industrial applications. Based on our literature review, we have classified and tabulated the materials as described below.

According to the Materials Market report of Textile Exchange [41], synthetic fibres (polyester, polyamide, polypropylene, acrylic, and elastane) make up about 65% of the global fibre market, vegetable fibres (cotton, linen, hemp, and other fibres) account for about 27%, man-made cellulosic fibres (viscose, acetate, lyocell, modal, and cupro) make up about 6.3%, and animal fibres (sheep wool, down, silk, and other animal fibres) account for about 1.6%. These fibres will be referred to as 'traditional fibres' as they are the established reference points for the fashion industry.

We have focused solely on the analysis of this type of material. However, we acknowledge the importance of other categories such as 'preferred fibers'—materials that have better environmental and/or social sustainability results than traditional ones—and neo-materials—innovative material solutions that are still underutilised but have promising environmental performance and unique characteristics that can expand the fashion design vision to new clothing concepts and design paradigms. These categories may be considered for future studies.

The geographical location of production for each selected traditional material is provided to indicate where the material is produced and to which the values of the environmental impacts of production refer. It is important to note that the environmental impact of marketed fibres is not solely dependent on the type of fibre, but also on the location and method of production [42]. The environmental impact of fibre production can be greatly influenced by geographical context, including scale, energy sources, chemical suppliers, and waste management [43]. Therefore, the same fibre produced in two different locations may have different environmental performance.

The materials were then categorized into two groups based on the origin of the raw material: virgin raw material and raw material from recycling processes.

The two categories were divided into bio-based, fossil-based, and inorganic raw materials. This division helps the designer understand the renewability of the resources used, allowing for the selection of materials that do not rely on fossil extraction whenever possible.

We then searched the literature for the cradle-to-gate environmental impacts of these fibres by analysing the impact categories mentioned in Sect. 2.1: climate change (kg CO2 eq./kg), water use and consumption (m^3 eq./kg), human toxicity (UTCh/kg) and primary energy requirement (MJ/kg). The report 'Environmental impact of textile fibers' by Mistra Future Fashion [43] was used as a starting point. It contains a table at the end of the document that presents environmental impact data for animal fibres, vegetable fibres, regenerated fibres, and synthetic fibres. These data was collected, in turn, from peer-reviewed journal articles, reports, and databases. The Mistra Future Fashion paper's available data has been compiled into a database that includes the minimum and maximum values of the environmental impacts of fibers proposed in the literature, broken down by production continent. This associates each material with a numerical range indicating the environmental impact of the different categories of greatest interest.

The collection of these data was implemented in the analysis of the literature cited in the paper and, in the case of missing data, through additional literature searches by the authors. In the case of Life Cycle Assessments with data of our interest expressed through units of measurement other than those we established for compiling the database, where possible, we converted this numerical information using the conversion tables proposed by Dong et al. [44], which proposes conversion factors between results expressed according to different LCA methods and distinguishes them into high-correlation, low-correlation, and uncorrelatable factors.

We then analyzed the materials from the perspective of properties relevant to environmental impact in the use phase through both white literature (e.g. from the publications of Humphries [45], Johnston and Hallett [46] and Baugh [47]) and gray literature (e.g. from the publications of Bunsell et al. [48], Hosseini Ravandi and Valizadeh [49] and Sinclair [50]). The material properties we researched are those reviewed in Sect. 2.1. For each category of material, we indicated:

- Possible release of microplastics;
- Intrinsic properties of fibre durability:
- Abrasion resistance, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Dimensional stability, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Lightfastness, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Colorfastness, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Tensile strength, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Resistance to pilling, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Ease of removal of the pilling, expressed by means of qualitative indicators ("easy removal" or "difficult removal");
- Intrinsic properties of fibre maintenance:
- Stain resistance, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Crease resistance, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Odours resistance, expressed by qualitative scale (1 = bad, 2 = poor, 3 = decent, 4 = good, 5 = excellent);
- Drying speed, expressed by means of quality indicators ("slow drying", "moderate drying" or "fast drying");
- Compatible type of washing, indicated for each category of material according to the most commonly indicated type ("wet", "dry" or "hand"). Today's literature does not closely document the relationship between fashion materials and the three washing practices, but clothing made of silk, wool and wool blends are three times more likely to be dry-cleaned than cotton or synthetic garments and their mixtures [29].

Regarding the end-of-life environmental impact, potentially compatible EOL options have been indicated for each material. The selection of recyclable materials, from fibre to fibre, does not guarantee the recycling of the garment during disposal. The responsibility for this lies with the designer and/or the brand. They can achieve this through the collection of used clothing and collaboration with companies specialising in recycling technologies. However, the use of recyclable materials does provide the possibility for recycling. The end-of-life options include closed-loop recycling, open-loop recycling, incineration with energy recovery, biodegradation, and landfill. The association between a material and its compatible end-of-life option is determined by considering the raw material and the existing facilities that process textile waste. This does not always make the association between the two parameters true, but it allows the designer to be aware of the possibility of a certain end-of-life option for the chosen material. The designer and brand should ensure, through their suppliers, that the end-of-life option is feasible.

As stated earlier, not all factors that affect the environmental impact of a fashion product and are under the control of the designer are related to the inherent nature of the available materials. Table 1 provides some representative examples.

However, the parameters selected in the previous subsection to characterise materials, such as cradle-to-gate production impacts, durability properties, and maintenance, can also be applied to circularity strategies, such as designing durable garments. Certain strategies are contingent on the selection of fashion materials, while others, such as those aimed at mitigating impacts during distribution, are not influenced by material choice and cannot be presented in the same manner.

The literature (e.g. the publications of Vezzoli et al. [14], Cobbing and Vicaire [32], and Ellen MacArthur Foundation [3]) provides a sample of strategies applicable in the fashion industry or already implemented by some brands. These strategies are presented as case studies that align with the three pillars of the circular economy: eliminate waste and pollution, circulate products and materials (at their highest value) and regenerate nature [51]. The three principles were recontextualised and repurposed within the scope of the current study, resulting in the formulation of three new tenets: 'optimisation of resource use', 'product longevity', and 'waste valorisation'. An analysis was then conducted to translate these principles into overarching strategies or adaptable guidelines applicable across various domains.

The strategies have been categorised based on their scope of application: design-related circularity, component selection-related circularity, materials-related circularity, and business strategies for circularity.

Design-related circularity strategies provide guidelines for the design chapter and offer methods to enhance material performance. One strategy in this category involves using specific textile structures to enhance the fabric's abrasion resistance. The finished product's properties can be affected by the textile structure of its constituent material [41]. Therefore, to achieve the design goal of increasing the garment's longevity, it is advisable to avoid textile structures that allow for greater mobility of threads and yarns, such as knitted structures.

A second example of this type of strategy is pattern-placing. Another strategy that can be used is pattern-placing. This technique can be applied to all types of weave materials and involves pre-determining the placement of the pattern on the fabric to minimize waste. This strategy has the potential to bring benefits of circularity in both resource optimization and waste valorisation (by reusing off-cuts) as well as potentially increasing the longevity of garments (by using off-cuts as reinforcements at high wear points).

The strategies for achieving circularity through component selection involve adopting a holistic approach to garment circularity. This includes selecting certified suppliers and using standard accessories that ensure spare parts availability.

4 Results

The authors constructed a database to enter the information that emerged from the literature review and characterization of traditional materials. An illustrative excerpt of the Excel table is given in Table 2.

In this database, the authors collected data on 25 different materials, including variants that differ in location of production: 10 plant fibers, 3 animal fibers, 3 man-made cellulocic fibers, and 9 synthetic fibers. Among these, we included four materials: two types of generic organic cotton (from global and European production), one case study of recycled cotton (RPure from the company Recover), and one case study of recycled wool (MWool from the company Manteco). These materials are defined as 'preferred materials', a concept developed by Textile Exchange [52] to refer to fibers or materials that result in better environmental and/or social sustainability outcomes and impacts than traditional ones. This definition encompasses traditional fibres that differ from conventionally produced counterparts through responsible cultivation, the use of organic matter to produce synthetic fibres, the use of recycled raw materials, and the control and certification of sourcing methods. It is important to note that while this definition includes a wide variety of materials, their actual environmental performance is not always clear and can vary from case to case.

The data table has been divided into sections. The first section includes the industrial information of the material, such as the level of industrialization (to implement the database with the inclusion of neo-materials), the manufacturer and website (of specific materials), and the geographical location of production. The second section provides information on the origin of the raw materials, which are divided into 'virgin raw materials' and 'recycled raw materials.' The latter are further divided into 'biobased,' 'fossil-based,' and 'inorganic.' For each category, the percentage of raw material in the reference material and its specific origin can be indicated. The section also includes a subsection on 'certification' for specific case studies aimed at implementing the database. The third section presents data on the environmental impact of cradle-to-gate production, categorised according to the environmental impact categories mentioned in the previous sub-sections. The numerical data is presented as both a range and a mean value, with a colour scale used to highlight the highest and lowest values. The fourth section provides details on the environmental impact of the material in use, including the release of microplastics, durability properties, and maintenance properties, which were previously investigated. The fifth section discusses the environmental impact at the end-of-life stage and identifies the options compatible with each material, which were explored earlier in this article.

Table 2 Extract of the database produced by the authors for the characterization of traditional fashion materials

Material	Material type				Industrial information			
	Traditional material	Preferred	Neo-materials		Level of industrialization	Manufacturer	Web site	Geographical location of production
	X	X	X	Family				
Cotton (CO)	X					–		Asia

Origin of raw material											Environmental impact in production							
Virgin					Recycled					*Certifications*	Global warming potential (GWP100)		Water use and consumption		Human ecotoxicity (carcinogenic + non-carcinogenic)		Primary energy demand (PED)	
Bio-based		Fossil-based		Inorganic	Bio-based		Fossil-based		Inorganic		Measure ($kgCO_2eq./kg$)		Measure ($m^3eq./kg$)		Measure ($CTUh/10^{-7}kg$)		Measure (MJ/kg)	
X	Source	X	Source	X	X	Source	X	Source	X		Variation range	Average	Variation range	Average	Variation range	Average	Variation range	Average
100%	–										– 0.71 to +3.88	**+1.50**	+0.34 to +1.48	**+0.91**	+1.60 to +8.83	**+5.22**	+66.2 to +78.3	**+72.25**

Environmental impact in the use phase													End-of-life environmental impact						Common applications
Microplastic release	Durability properties							Maintenance properties					Recyclability			Energy recovery	Biodegradability	Landfill as only option	
X	Abrasion resistance	Dimensional stability	Lightfastness	Colourfastness	Tensile strength	Pilling resistance	Pilling removal	Stain resistance	Crease resistance	Odour resistance	Drying speed	Compatible washing	*Closed-loop*		*Open-loop*				
													X	Recycling technology	X	X	X	X	
	Decent	Low	Low	Low	Good	Low	Easy	Low	Low	Excellent	Slow	Wet cleaning	X	Mechanical-Chemical	X	X	X	Avoidable	Ready-to-wear clothing, outdoor clothing, jeans, shirts, underwear

The authors have added the most common applications for each material (e.g. ready-to-wear, outdoor, jeans, shirts, underwear, etc.) to facilitate and draw more critical attention to the material selection phase for designers.

Additionally, the authors have associated compatible circularity strategies with each material based on their characteristics. In the 'Strategies' section, the authors compiled alphanumeric codes that correspond to specific strategies identified in the literature. These strategies were collected in another Excel sheet (see example in Table 3). They can be identified by an alphanumeric code of the format Xnn, where X represents the letter that indicates the type of strategy. Strategies related to circularity in the design phase are denoted by D, those related to component selection by S, those related to materials by M, and business strategies for circularity by B. Each strategy is accompanied by a description and an indication of the benefit that can be achieved if applied, including resource use optimization, product longevity, and waste valorization.

5 Discussion

This work presents an overview of the characteristics related to the nature of the fiber that the authors have identified as factors that can influence the final product;s impact. It provides guidance for designers during material decision-making. However, some considerations pertain to the final output, represented by an Excel file, which could benefit from improved usability for designers. Design-oriented tools typically use graphical information structures, such as maps, infographics, and fact sheets, to optimize consulting and enable rapid consultation during the design phase [13]. Additionally, simple data collection may result in a list of numbers and ranges of values.

This study considered 25 materials, 21 of which are traditional and 4 of which are preferred materials.

The implementation of the file by adding preferred materials or neo-materials can help the designer to implement a material selection resulting from a wider analysis. In fact, the use of materials belonging to these two categories is not a guarantee of sustainable fashion products, especially when used without critical participation. This implies that, during the material selection of a specific project, it is essential to choose the material (be it traditional, preferred or neo-material) the characteristics of which are consistent and compatible with the sustainability objectives that are to be imparted to the final product. For this reason, the role of other material categories, and especially of neo-materials for fashion, is not (and should not be) to replace traditional materials, but to expand the opportunities available and inspire new design paradigms.

After the data collection activity, it is important to highlight the strategies for circularity and the opportunities offered by the data collection. This is because timely information on a specific material property is not sufficient to determine the sustainability impact of a product.

We have collected from the literature a total of 63 strategies of circularity that we divided according to the scope of application in: 24 strategies for circularity related to the design phase, 12 strategies for circularity related to the selection of components, 17 material-related circularity strategies, and 10 business strategies for circularity. The list of strategies represents the state of the art on what have been until now (considering the limits of research) the reflections on the problems of the sector. Their proposal aimed to generate reflective input and creative stimulus for new solutions and strategies.

A collection of design strategies collected to material properties has been implemented in the database to envision a concrete relationship between design strategies and specific material use as already shown in Table 3.

At the same time, the opportunity to consult and analyze individual material properties can be important during the material selection activity in design projects. During the material selection phase, the designer can consider the collection of strategies for circularity related to the material, of which an extract is provided in Table 4. In this way, the awareness and sensitivity of the designer in the practice of choosing materials can increase. Because of the new regulations coming in the sector (e.g. DPP), it becomes essential to be aware of and keep under control the origin of the material and any processes that alter its nature.

The importance of this last step has been further explored by the authors in order to prototype a first, practical and visual tool for designers to test the efficiency of the proposed results. To respond to the specific need to move from the individual property of the material to a wider reflection on the use and selection of fabrics, in the thesis work CircularMAT [53] was presented a first attempt of tool to support the work of designers. CircularMAT is a tool developed by the authors that collects and overlaps the materials used in the fashion industry and design strategies compatible with the concept of circular economy. The purpose of the tool is to provide practical support to material selection to direct fashion projects—which rarely focus on reducing environmental impacts—towards the circular and sustainable model that the European Union asks the industry. Circular MAT wants to generate reflections in the

Table 3 Extract from the table in which the authors have collected the strategies for the circularity in view of the acquisition of a circular economic model by the fashion industry

Strategies for circularity related to the design phase					
Code	Strategy	Description	Benefits		
			Resources use	Product longevity	Waste valorization
D1	Monomaterial product	Use of a single material for the entire product			X
D2	Early end of life design	Anticipation of the product's potential end-of-life during its design and facilitation of the process			X
D3	Design of easy to disassemble components	Use of reversible connections between parts (e.g., avoid high-tension seams, avoid rivets, etc.)		X	X
D4	Elimination of unnecessary treatments	Prefer natural fiber colors and replace polluting functional treatments with fiber blends	X		X
D5	Use of functional textile structure	Use of knitted or woven textile structures to enhance material performance and/or avoid blends	X	X	X

Table 4 Extract from the table in which the authors have collected material selection strategies related to the material properties in view of the acquisition of a circular economic model by the fashion industry

Strategies for circularity related to materials					
Code	Strategy	Description	Benefits		
			Resources use	Product longevity	Waste valorization
M1	Selection of efficiently recyclable materials	Selection of materials whose recycling technology produces the highest material valorization. given the difficulties of fiber-to-fiber recycling, it is necessary to negotiate agreements with specific recycling companies and ensure the recovery of end-of-life products (B10)	X		X
M2	Selection of certified materials and suppliers	Prefer certified materials and suppliers by third-party organizations regarding environmental impact and ethics			X
M3	Selection of renewable materials	Prefer renewable raw materials (and quickly renewable ones) to avoid depletion of fossil sources	X		
M4	Selection of recycled materials	Prefer raw materials recycled to avoid the extraction of virgin material and to encourage circularity	X		X
M5	Selection of water-efficient materials	Prefer raw materials that minimize water consumption for cultivation or fiber production	X		
M6	Selection of less energy-intensive materials	Prefer raw material that minimizes energy use in the production phase	X		

user to support a conscious design, without limiting its creativity. This is a first prototyping tool containing scientific literature and belonging to areas unrelated to fashion designers (e.g. textile engineering, chemical and material engineering, etc.) transformed into an intuitive visual language.

To assess the usefulness of the results obtained, we conducted a trial on the use of Circular MAT with 12 participants. The study participants consisted of fashion design students from Politecnico di Milano and similar institutions, as well as professionals working in the fashion industry. The trial aimed to record participants' interaction with Circular MAT and collect their impressions through a questionnaire to evaluate its compatibility with professional needs.

Each participant received an excerpt of the instrument, accompanied by a short presentation. The trial results indicate a positive response to the tool's usefulness and information. 92% of respondents stated they would use the tool, finding it more compatible with the fashion industry professional profile (1st place) and design students (2nd place).

The analysis of the responses revealed that 45% of the participants would use Circular MAT during the material selection phase, while 30% would potentially use it during the briefing phase to establish new design requirements that align with circularity principles.

Furthermore, participants indicated a preference for a digital tool in the future. This provides valuable insight for authors regarding the future development of Circular MAT.

6 Conclusions

In conclusion, this study aimed to conduct a critical analysis of the Life Cycle Assessment (LCA) of fashion products, with a focus on identifying the most significant environmental impact parameters. The primary objective was to extract translatable information from the literature that designers could easily incorporate into their decision-making processes. The designer, thanks to his characteristics of interdisciplinarity and horizontal vision, is a key figure to promote the transition to a circular economic model, abandoning the current linear model of the fashion industry. To shed light on the areas in which the designer can intervene, the government and industry objectives and the product of fashion and the characteristics that can determine its environmental impact throughout the life cycle have been analysed.

The study focused mainly on the category of traditional fibers with the aim of developing a new method of critical analysis of these materials in the selection and application in fashion projects. Traditional fibers, comprising synthetic, vegetable, manmade cellulosic, and animal fibers, were classified as the reference points for the fashion industry.

To achieve the objective of this study, the significance of the raw material known as the "nature of fibres" in the textile industry was highlighted. The research revealed that the extraction and processing of raw materials contribute significantly to the environmental impact, with variations based on the processes involved, properties, and end-of-life risks. Starting from this awareness—and not only—the materials sciences are developing new material alternatives, so-called preferred materials and neo-materials are making their way into the market. These categories present interesting peculiarities, but for productive issues they do not represent an immediate solution to the problems emerged: their availability is still limited and further scientific and technological advances are necessary for their improvement. For these reasons, the present study takes into consideration mainly and almost exclusively (with interest to implement the results also through the inclusion of preferred materials and neo-materials) the traditional materials. It will be the responsibility and merit of the designer, giving way to traditional materials (and not only) to participate in the transformation of the fashion industry, using them critically and consciously through the adoption of strategies of circularity. The application of such strategies to the benefit of a circular design corresponds to the consideration of several factors that emerged during this research.

Due to the importance of the raw material, the study meticulously categorized materials based on the origin of raw materials, distinguishing between virgin and recycled materials, further classified into bio-based, fossil-based, and inorganic categories.

The transition of textile ecosystems to circular and sustainable practices also requires considerations that go beyond the nature of fiber. Geographic factors, such as production location, were found to influence environmental impacts significantly. Similarly, the production processes related to each material affect its environmental impact. For this reason, environmental impact data for each material, expressed as cradle-to-gate production impacts, were collected from various sources and compiled into a comprehensive database.

Additionally, the study considered properties relevant to the environmental impact during the use phase, such as microplastic release and various durability and maintenance properties. The environmental impact at the end of the product life cycle was also addressed, presenting potential disposal options for each material.

The analysis extended beyond material characteristics to encompass circularity strategies, aligning with the principles of optimizing resource use, enhancing product longevity, and valorizing waste. The strategies were classified into design-related, selection of components, material-related, and business-related circularity strategies. The knowledge of all these circularity strategies is useful to the designer to have a vision of the range within which the industry can move.

In summary, the study aims to provide a database of essential information for stylists. The database, enriched with data on environmental impact, fibre properties, end-of-life options and circularity strategies, is materialised in a tool created with the practical purpose of supporting the decision-making process in material selection. Overall, this research aims to help bridge the gap between the scientific literature and the practical needs of the fashion industry in order to facilitate a more informed and sustainable approach to material selection.

Author contributions Conceptualization, M.M.; introduction and literature review, F.P.; methodology, M.M.; results and discussion, M.M. and F.P.; writing, M.M. and F.P.; supervision and final review B.D.C. All authors have read and agreed for the submission of this 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-GenerationEU (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 Data available on request. The data presented in this study are available on request from the corresponding author. Most data are contained within the article.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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