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# Design e valorizzazione sostenibile di scarti e sottoprodotti agro-industriali per la circolarità del settore tessile | Design and Sustainable Valorization of Agro-Industrial Waste and By-Products for the Circularity of the Textile Sector

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## Abstract

The theoretical debate on design is intertwined with and fueled by the various theories and approaches that have developed since the second half of the twentieth century in the economic and industrial fields, among which the concept of the Circular Economy has emerged. In a linear economy, what is normally considered waste or by-product becomes a resource whose value is to be retained. In the domain of design, this corresponds to a progressive broadening of perspective from the level of the individual product to the design of the complex system in which it is embedded and the adoption of new strategies, including "closing the loop." In this sense, the agro-industrial sector represents fertile ground for sustainable, design-driven innovation, partly due to the significant amount of waste generated annually at all stages of the supply chain. The sustainable valorization of such biomass represents an alternative feedstock for the recovery of high-value substances and materials, potentially increasing the level of circularity in various application sectors characterized by high consumption of non-renewable resources, such as the textile sector. Through the critical selection and comparative analysis of three case studies, this research aims to define the changed role of design in the current scenario and the nature of interactions between the designer and other relevant actors in the transition towards circular production and consumption models, particularly exploring the theme of valorizing agro-industrial waste and by-products for applications in the textile sector.

**Keywords:** Circular Design; Waste and by-products valorization; Circular Economy; Textile Field; Case studies; Design research

## Introduction

In the course of the second half of the twentieth century, the theoretical debate on sustainable design evolved through a progressive broadening of perspective from the level of individual products to "insular" and "systemic" dimensions (Adams et al., 2016). This shift led to considering the attribute "sustainable" not as a property of individual elements within a system, but as a property of the entire system and a dynamic condition that requires the adoption of organic and non-linear thinking (system thinking) (Hjorth & Bagheri, 2006).

The transition of the design discipline through different definitions and terminologies represents a progressive broadening of the perspective on design theory and practice, as well as an attempt to engage with the complexity that a "sustainable" approach to design implies (Madge, 1997). However, according to van Dam et al. (2019), the varied terminology developed by research over the years (e.g., "green design", "ecodesign", "design for sustainability") often presents overlapping concepts and can be counterproductive by generating a fragmentation of knowledge that leads to a dispersion of relevant results. Instead, it is proposed to connect these similar research strands so that the design discipline can consolidate knowledge and make advancements in sustainability and circularity.

The concepts of system thinking and circularity are borrowed from theories developed in the economic and industrial fields and both have been well-established in economic systems for several decades, drawing inspiration from ideas on human and agricultural metabolism dating back to the eighteenth century (Reike et al., 2017). However, they have gained popularity more recently due to the widespread adoption of the concept of the Circular Economy (Ekins et al., 2019). Today, one of the most widely accepted definitions of the Circular Economy is that developed by the Ellen MacArthur Foundation:

> *«A circular economy is an industrial system that is restorative or regenerative by intention and design. [...] It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models» (Ellen MacArthur Foundation, 2013).*

The Circular Economy presents itself as an alternative model to the dominant "take-make-dispose" paradigm, through the adoption of five fundamental principles: (1) Design out waste; (2) Build resilience through diversity; (3) Rely on energy from renewable sources; (4) Think in systems; and (5) Waste is food (Ellen MacArthur Foundation, 2013).

Ekins et al. (2019) identify the three main purposes of the transition to a circular economy as the slowing down of the depletion of natural resources, the reduction of environmental damage caused by the extraction and transformation of virgin materials, and the reduction of pollution related to the transformation, use, and disposal of materials. This can be achieved through the adoption of new business models integrated within a systemic perspective on resource use, aimed at making utilization more efficient, increasing overall value, and extending the lifecycle of materials.

In the theoretical debate on design, some researchers have questioned the changing role of design in the contemporary context and have proposed adopting the term "Circular Design" to indicate an area of sustainable design whose objectives intertwine with those of the Circular Economy (e.g., Moreno et al., 2016; Medkova & Fifield, 2016; van Dam et al., 2019). Although Circular Design builds on established approaches, Asif et al. (2021) suggest that it differs from sustainable design and ecodesign practices, which predominantly move from a linear economy perspective. According to den Hollander et al. (2017), the role of the (circular) designer is to facilitate the transition from a linear to a circular economy and to make decisions aimed at preventing and reversing product obsolescence.

The analysis of the literature on the topic highlights an attempt by research to systematize principles, guidelines, and strategies for the circular design of solutions within the context of the circular economy. Various studies have sought to synthesize the contribution of design to the transition towards a circular economy by systematically identifying "Design for X" (DfX) approaches (Aguiar et al., 2021; Sassanelli, 2019; den Hollander et al., 2017; Moreno et al., 2016; De los Rios and Charnley, 2016). The various strategies identified in the literature can be traced back to four fundamental approaches to circular innovation: narrow, slow, close, regenerate (Konietzko et al., 2019). "Narrow" refers to reducing resource use, both in terms of materials and energy, throughout the entire product life cycle; "slow" aims to extend the life cycle of products, components, and materials; "close" means retaining the value of what is typically considered waste or by-product in a linear economy; and "regenerate" refers to minimizing the use of toxic substances and increasing the use of renewable materials and energy in a circular economy. Konietzko et al. (2019) have added the "inform" strategy to these four strategies to emphasize the importance of new technologies in supporting the circular economy. Each of the four strategies can be applied through three dimensions and scales of intervention (product, business, ecosystem) (Konietzko et al., 2019).

A comprehensive taxonomy that investigates the transition from sustainability-oriented design (DfX approaches) to Circular Design, synthesizing existing strategies into new categories, is provided by Moreno et al. (2016). Building on the previous taxonomy by De los Rios and Charnley (2016), the authors map design strategies that support the circular economy. These are articulated into: (a) design for resource conservation; (b) design for slowing resource loops; and (c) whole systems design, which in turn include five circular design strategies: (a1) design for circular supplies; (a2) design for resource conservation; (b1) design for long life use of products; (b2) design for multiple cycles; and (c1) design for systems change.

In the design domain, the "closing the loop" strategy is equivalent to retaining the value of what is normally considered waste or by-product in a linear economy. Bocken et al. (2016) identify two strategies for doing this: the first, usually at the product level, is "extending resource value", which involves collecting discarded materials and resources to transform them into new forms of value, potentially more appealing to the user while reducing material and final product costs; the second, at the ecosystem level, is a process-oriented solution that involves transforming the outputs of one process into feedstock for another process or production line (industrial symbiosis).

Large volumes of waste can be generated at different levels of the value chain, from the resource extraction phase to the production phase (production waste), to the consumption phase (post-consumption waste). Resource recovery pathways vary depending on the life cycle stage at which there is a need to recover resource value and the type of waste (Singh & Ordoñez, 2015). In general, materials and products can be recovered to serve the same purpose or new functions, within the same value chain, in different value chains, or to activate entirely new and/or innovative value chains.

Despite the abundance in literature of practical case studies of waste and by-product valorization for the design of innovative products and processes in various application areas, there are no significant methodological references to guide design activities (Karana et al., 2013). In this regard, there is a need to create a link between academic research and practice to activate new synergies within the context of the Circular Economy.

In the Systemic Design approach, the valorization of waste and by-products is a fundamental theme and is addressed through renewed attention to the local dimension. The outputs of production processes are elevated from their status as waste and considered resources to activate new production processes and industrial systems that generate economic and territorial development. In this context, the new role assumed by the designer is to outline and program the flow of matter that moves from one system to another in a continuous metabolism, organize and optimize all parts within an ecosystem so that they evolve coherently with each other, and accompany and manage the mutual dialogue among the various actors at all stages of project development on this new cultural ground (Bistagnino, 2011).

The systemic design methodology starts from a "holistic diagnosis", characterized by a phase of literature and field research to define and map all the components that define the scenario, considering both the surrounding context and the flow of energy and matter that characterizes the system. Through this collection of complex data, it is possible to highlight criticalities and potentialities and gather guidelines for the definition of new systems. The systemic project is based on the development of a system in which the relationships between processes and actors, optimized material and energy flows, and valorized outputs as resources are designed (Battistoni et al., 2019). The result is an autopoietic system, capable of self-organizing and continuously redefining itself based on the relationships (system organization) that exist between the elements that compose it (system structure) and based on the reciprocities that regulate the relationship with the surrounding environment (Bistagnino, 2011).

One of the most explored areas by Systemic Design is the agri-food sector, which is particularly suited to this approach and has great potential in the context of the Circular Economy, also due to the large amount of waste produced by the supply chain (Fiore et al., 2020). According to Eurostat data, in 2016 the total agri-food waste produced in the European Union (EU28) amounted to 400 million tons, with the most significant category (about 22%) being organic waste of animal and plant origin, amounting to about 87 million tons. Of these, the agricultural production phase is responsible for 20% (17 million tons); the industrial transformation for 28% (24 million tons); the consumption phase for 38% (33 million tons); and services account for the remaining 14%, with about 13 million tons (Intesa San Paolo, 2016).

In this regard, the potential for valorizing biomass (a general term applicable to all materials of plant and animal origin) obtained from inedible food waste and agricultural waste has been highlighted as an alternative feedstock to non-renewable resources and a potential resource for recovering high-value substances and materials. Possible uses of plant-based biomass include traditional applications, such as livestock feed and fertilizers, and other uses, such as the design and production of innovative bio-based products (Sherwood, 2020). This can contribute to the establishment of a "circular bioeconomy", which is based on the sustainable and efficient valorization of biomass in integrated and multi-output production chains (e.g., biorefineries), also using residues and waste and optimizing the value of biomass over time through cascading processes (Stegmann & Junginger, 2020).

Within this context, the present study aims to explore the role and contribution of design in activating sustainable valorization processes for waste and by-products from the agri-food supply chain, with particular reference to applications in the textile sector and through the adoption of an interdisciplinary and collaborative approach. By exploring this topic, the intersection between design, the circular economy, and innovation in the textile field is investigated, and the contribution of design in the sector's transition towards a circular production and consumption model is studied, addressing the following specific objectives: a) Explore the sustainable innovation landscape in the textile field, with reference to the specific area of valorization of agri-food waste and by-products, by mapping the main areas of innovation; b) Explore the contribution of design and the new skills required for the designer in pursuing circularity strategies through the selection and analysis of application case studies; c) Explore the role of interdisciplinarity and collaboration between design research, academia, and industry based on the selected case studies.

## Circularity in the textile field

The potential valorization of biomass derived from agricultural and industrial waste and by-products represents an alternative feedstock and a potential source for the recovery of high-value substances and materials that can be applied in other sectors. Beyond the traditional applications summarized in the "5F" (Koopmans & Koppejan, 1997), possible uses include the design and production of materials, products, and innovative solutions through a cascading valorization approach that optimizes the value of biomass over time, defining usage scenarios in other production sectors characterized by high consumption of non-renewable resources, such as the textile sector, potentially of higher value.

The global textile industry is responsible for a significant environmental impact along the entire value chain, with substantial greenhouse gas emissions, significant consumption and pollution of water resources, and increasing waste production, with negative consequences on ecosystem quality and human health (Quantis, 2018). This scenario is exacerbated by the rise of a production and consumption model characterized by fast production cycles and early disposal of textile products, known as "fast fashion". The linear "take-make-dispose" model that characterizes the current textile industry consumes considerable amounts of resources. It is estimated that the sector annually uses about 98 million tons of non-renewable resources (Ellen MacArthur Foundation, 2017) across different production stages.

At the institutional level, the urgency to transform the textile sector into a sustainable and circular perspective has been recently addressed through the publication of the European Union Strategy for Sustainable and Circular Textiles, in March 2022. This strategy outlines a common framework for the textile sector, integrating existing regulations with new initiatives and legislative proposals, aiming to establish, by 2030, a circular textile ecosystem in which incineration and landfill disposal are minimized (European Commission, 2022). Among the key actions announced is the introduction of mandatory eco-design requirements for textiles and footwear, to be implemented by 2024 through the regulation known as the Ecodesign for Sustainable Products Regulation, with the objective of ensuring that textile products are fit for circularity, using secondary raw materials and limiting the presence of hazardous chemicals (European Commission, 2022). The adoption of the Ecodesign for Sustainable Products Regulation highlights not only the value attributed to the design process in achieving circularity but also the consolidation of a preventive approach to environmental impact and waste at the upstream of the supply chain, as a preferable option compared to downstream interventions aimed at increasing textile waste recyclability.

In pursuing a circular economy and a genuinely sustainable approach, the first objective should be to reduce as much as possible the introduction of virgin raw materials into the value chain. This can be achieved firstly through the maximization of textile use and the extension of the material or product's life through repair or reuse. Secondly, it can be done by replacing non-renewable resources with feedstock from recycled materials, recirculating already available materials without depleting new resources, provided that this can be done through eco-sustainable processes (Ellen MacArthur Foundation, 2017). However, adopting this strategy is currently insufficient to meet the need for virgin materials. Where recycled feedstock materials are unavailable, the choice should fall on materials obtained from renewable feedstocks produced with a circular and regenerative approach. Additionally, transitioning to production processes that require fewer resource inputs, are energy-efficient, based on renewable energy, and generate less waste can further contribute to reducing the need for non-renewable inputs (Laudes Foundation, 2021).

In this regard, the recovery of agro-industrial waste as secondary raw materials and new inputs that can be integrated into the textile supply chain represents an opportunity not yet fully explored, to which design can substantially contribute through its approaches, tools, and visions.

This “cross-fertilization” approach responds to modern challenges and the need for innovation, involving an increasing number of sectors and increasingly specialized skills (Cappellieri, 2006). Conti (2012) defines cross-fertilization as an interdisciplinary phenomenon concerning the relationship and contiguity between different areas of human knowledge, affecting the boundaries and research areas created between one disciplinary area and another. It is precisely in these “border territories” that dynamics of knowledge transfer between sectors are activated, facilitating the emergence of significant processes of transversal innovation (Conti, 2012).

In the textile sector, the last decade has seen the development of numerous materials, products, and solutions based on the sustainable valorization of agro-industrial waste and by-products. The current innovation landscape is rapidly and continuously evolving, leveraging concerted action by designers, academic research, and industry (Laudes Foundation, 2021). In Fig. 1 a mapping of the state of the art is provided, illustrating the main areas of sustainable innovation based on the valorization of agro-industrial waste and by-products, related to the following themes:

• Processes: this area of innovation includes the development of production processes that are more energy-efficient and resource-efficient, with a lower impact on ecosystems. It also encompasses the refinement of advanced technologies for textile recycling and waste management. In the realm of waste valorization, the literature presents various examples of utilizing agricultural waste and by-products for the treatment of textile wastewater, particularly as adsorbents for the removal of dye residues from water (e.g., Amalina et al., 2022; Al-Gheethi et al., 2022; Gül & Bayazit, 2020).

• Textile Materials: to mitigate the demand for virgin raw materials, the use of alternative and renewable sources for the production of materials such as fibers, yarns, and fabrics represents a viable strategy. Numerous solutions already available on the market are based on the valorization of agro-industrial outputs as feedstock for obtaining natural, artificial, and synthetic fibers.

• Products for textile treatment, dyeing and finishing: this includes the development of more sustainable alternatives to products for pre-treatment, dyeing and finishing of textiles, with the primary objective of reducing or eliminating the use of chemicals that are potentially harmful to humans and the environment. Examples of bio-based products include natural dyes, bio-mordants or products that confer functional properties (e.g., water repellency, stain resistance).

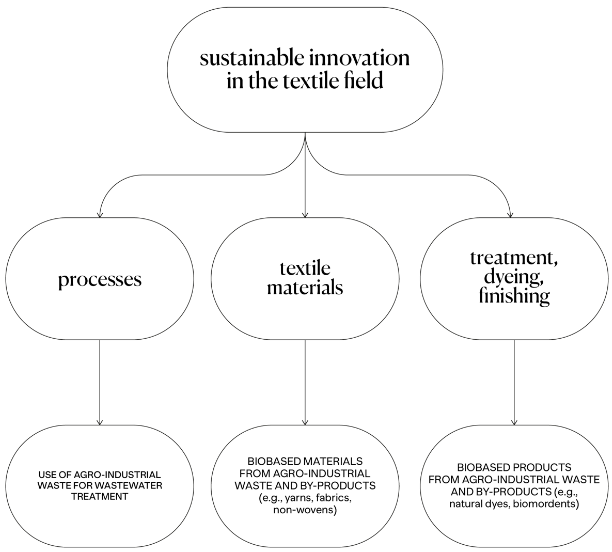



**Figure 1. Sustainable innovation in the textile sector through the valorization of agricultural and industrial waste and by-products. Source: own elaboration, 2024**

## Methodology

Within the framework of sustainable innovation, and with the aim of exploring the role and contribution of design in activating sustainable valorization processes for agro-industrial waste and by-products, thereby managing and directing resource flows toward the textile sector, the use of case studies has been deemed useful for delineating general considerations about the examined context (Eisenhardt, 1989). The selection of cases was conducted by distinguishing two different contexts for literature review: an academic context and a practical context (Romani et al., 2021). In the first case, academic databases, journal articles, and book chapters were considered; in the second case, the research was conducted through the analysis of design websites and blogs, including successful case studies implemented by the industry.

The criteria for selecting the case studies were based on the previously outlined theoretical framework, including only examples of innovation that integrated design, the valorization of agro-industrial waste and the textile sector, while excluding the valorization of other types of waste (e.g., pre- or post-consumer textile waste). Only case studies where the designer was involved in the development of the project or solution were considered. Additionally, in order to present the most recent developments in sustainable innovation in this specific area of research, the selection was limited to case studies conducted between 2014 and 2024.

Based on these criteria, three valorization cases were selected and examined, deemed exemplary of three distinct approaches: one derived from industrial research (EarthArt), one stemming from collaboration between

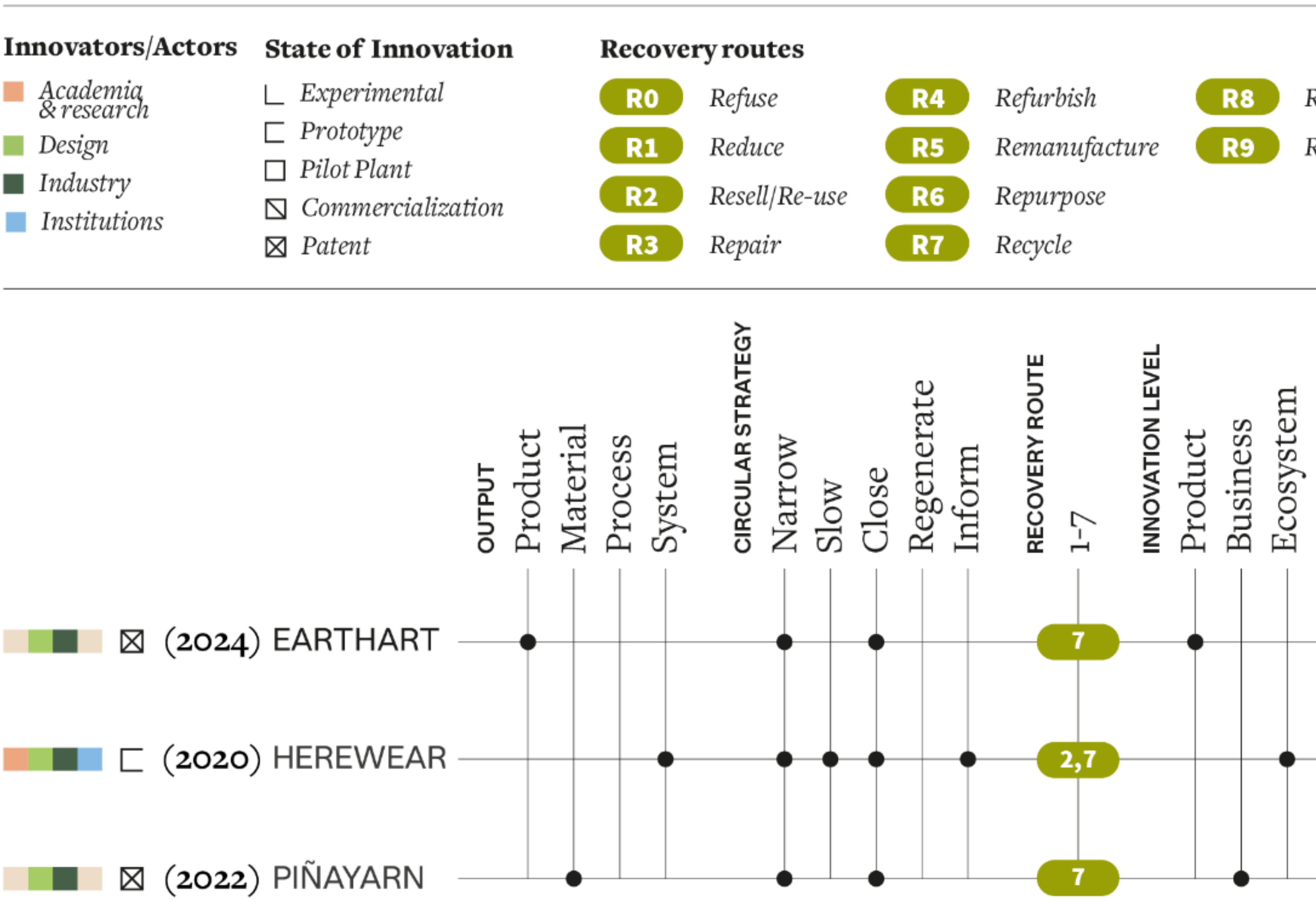
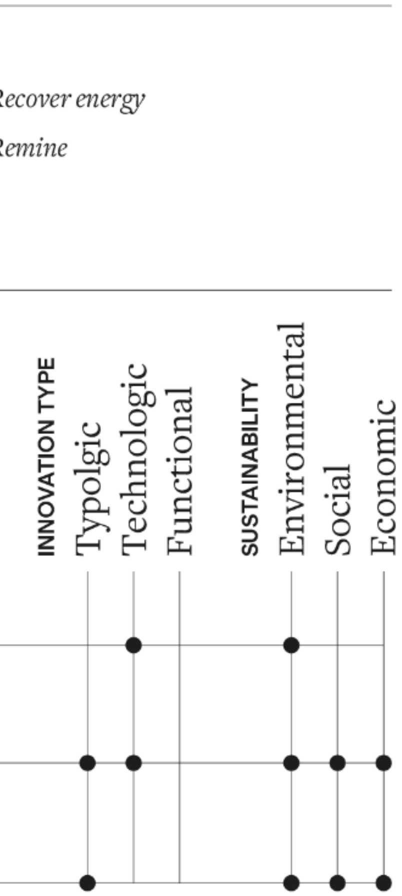



**Figure 2. Overview of the three case studies selected. Source: own elaboration, 2024**

research centers and academia (Herewear) and one resulting from the entrepreneurial initiative of a designer (Piñayarn).

The three case studies were first schematically framed, indicating the main stakeholders involved—designers, research centers and academia, companies or industrial clusters and institutions. The nature of the innovation was studied and categorized into three types: “technological”, “typological” or “functional”. Additionally, the state of the innovation was identified, indicating whether the project is in the experimental, prototype, pilot, commercialization phase or includes a patented solution. The sustainability aspect was also examined, categorized into three dimensions: environmental, social and economic. The analysis of the output describes the type of output obtained. The type “R” imperative adopted is also indicated by adopting the waste management hierarchy suggested by Reike et al. (2017).




Subsequently, the three case studies were further examined using the method suggested by De los Rios & Charnley (2016) and based on the Multilevel Design Model (MDM) proposed by Joore and Brezet (2015). This model was developed as a tool for analyzing the innovation system, useful for determining potential contributions of design in terms of both tangible and intangible results (De los Rios & Charnley, 2016). The analysis is conducted considering the following four dimensions: “reflection” describes the characteristics of the initial context in which the case study is embedded; “analysis” describes the objectives and requirements that support the transition towards a circular model; “synthesis” lists and describes the solutions developed through design; “experimentation” describes how the produced solutions respond to and contribute to the implementation of the Circular Economy. Finally, for each case study, the role of design was highlighted and translated into skills and competences using the evidence obtained from the case studies and cross-referencing the design requirements in each scenario with the existing theoretical framework concerning Design for X (DfX) strategies (De los Rios & Charnley, 2016).

## Results: Analysis of CE Strategies

The collection of case studies presented in this research does not aim to be a systematic and exhaustive compilation of all solutions developed within the area of interest. Instead, it is a critical selection of valorization projects with textile applications where design has played a key role. The three selected case studies—EarthArt, Herewear, and Piñayarn—are schematically presented in the infographic in Fig. 2 and subsequently analyzed according to the previously described methodology [Tables 1-3].

EarthArt is a family of denim fabrics born from the industrial partnership between Nature Coatings and Soorty Enterprises, characterized by the use of bio-based dye derived from agro-industrial waste instead of synthetic dyes. The environmental impact of denim is primarily linked to the intensive cultivation of traditional cotton, which requires large amounts of water, pesticides, and fertilizers, and the release of microfibers into the ecosystem. Despite denim being derived from a natural fiber, it is extensively treated with chemicals such as synthetic dyes and other additives to enhance the durability and performance of the fabric, leading Athey et al. (2020) to define it as “anthropogenically modified cellulose”. In response to these challenges, Soorty Enterprises is dedicated to producing denim with a strong focus on sustainable innovation, frequently collaborating with other manufacturers and research centers to reduce the environmental impact of production processes through the integration of circular design principles and the experimentation and use of cutting-edge technologies. The project partner, Nature Coatings, specializes in producing bio-based dyes and textile finishes obtained from waste. Specifically, the BioBlack TX dye is based on transforming wood waste from Forest Steward Council (FSC)-certified forests into bio-based black pigments, which offer high colorfastness and are cost-competitive with synthetic alternatives derived from non-renewable resources. Additionally, according to a carbon footprint analysis conducted by Accend, BioBlack TX has an 85% lower carbon footprint compared to petroleum-derived alternatives (Nature Coatings, n.d.).


**Figure 3. EarthArt denim dyed with BioBlack TX. Source: Nature Coatings [@naturecoatings]. (2024, January 10). https://www.instagram.com/p/C16kyHRofhu/?igsh=MTJhbDRyODlhY3A1MA=**

*Table 1. EarthArt System analysis. Source: own elaboration, 2024*

| | **REFLECTION Initial state** | **ANALYSIS Requirements and targets** | **SYNTHESIS Developments** | **EXPERIMENTATION Implementation of Circular Economy** |
|---|---|---|---|---|
| **SOCIETAL SYSTEM Contextual Landscape** | Denim accounts for 35% of the global cotton production, associated with the use of pesticides, fertilizers and high water consumption. Synthetic dyes contribute to the severe impact | Need to establish a new supply chain for denim by eliminating the use of synthetic dyes and harmful chemicals detrimental to human health and the environment | Industrial collaboration for the development of denim characterized by dyeing/finishing obtained from the valorization of agro-industrial waste | Generation of environmental benefits and benefits for the stakeholders involved in the creation of a circular value chain |
| **SOCIO TECHNICAL SYSTEM System innovations and market** | Transforming the denim process sustainably may not be economically viable and advantageous from a commercial standpoint | Overcoming hurdles to commercialization and fostering the development of a competitive product | Partnership among various industrial actors for the collaborative development of a sustainable process for denim production: cost optimization and reduction of innovation lead times | Activation of a circular system based on the reorganization of the production chain through stakeholder collaboration |
| **PRODUCT-SERVICE SYSTEM Business and process innovation** | The dyeing and finishing phase represent one of the most impactful stages in terms of water consumption and pollution, as well as greenhouse gas emissions | Developing a more sustainable process for denim production | Production and dyeing process with reduced impact in terms of water, energy, and chemicals used. Possibility to adapt BioBlack TX to the "warp dyeing" technique, commonly used for indigo dyeing | Integration of bio-based feedstock into the denim production process through a collaborative approach with other actors |
| **PRODUCT-TECHNOLOGY Product innovation** | Denim fibers are non-biodegradable due to the dyes and treatments applied | Developing a denim fabric that is more sustainable and free from harmful chemicals | Development of a denim collection with certified yarns and obtained through a low-impact process, using BioBlack TX dye derived from FSC-certified wood waste, free from carcinogenic PAHs, and with a negative carbon footprint | Utilization of agro-industrial waste in a circular perspective for the sustainable transformation of denim products |

Herewear aims to establish a European-level ecosystem for the production of circular textiles from bio-based resources. Initiated in 2020, the research project is funded by the European Horizon 2020 program and is carried out by a consortium of stakeholders including research centers, universities, companies and manufacturers. The project is based on three pillars: the integration of circular principles into the textile production chain, the use of bio-based sources for textile production and the pursuit of circularity through the valorization of the local dimension. Herewear's contribution covers the entire textile value chain [Fig. 4], from the production of yarns obtained from various types of agro-industrial waste (agricultural biomass, algae and forestry) to fabric production and the development of clothing prototypes. The process involves the development and testing of emerging technologies for wet spinning and the extrusion of cellulose from waste streams and biocompatible polyesters on a semi-industrial scale. Additionally, yarn and fabric production include the development of bio-based dyes, finishes and printing techniques. The use and end-of-life phases are investigated through the identification of innovative solutions in repair, reuse and recycling. The project includes the development of digital tools and software for designers and companies to facilitate the integration of circular design principles into the production process. The concept of locality is promoted as a tool for activating an "open-loop" circular system and is developed through the construction of a network of local actors based on the ability to build innovative processes and development projects for the territory (Herewear, n.d.).

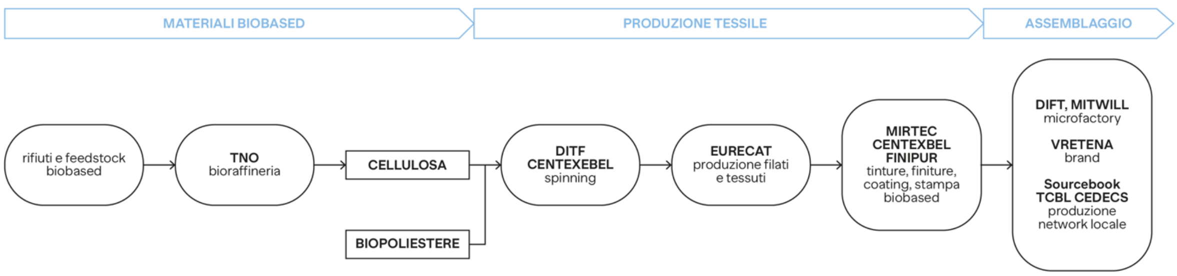



**Figure 4. Representation of the value chain proposed by the Herewear project. Source: adapted from Herewear, (2020) https://herewear.eu/**

*Table 2. Herewear System analysis. Source: own elaboration, 2024*

| | **REFLECTION Initial state** | **ANALYSIS Requirements and targets** | **SYNTHESIS Developments** | **EXPERIMENTATION Implementation of Circular Economy** |
|---|---|---|---|---|
| **SOCIETAL SYSTEM Contextual Landscape** | Fragmentation of the textile value chain as a barrier to circularity | Reorganization of the entire production ecosystem according to circular principles | Utilization of a systemic approach to create "open loop" local systems through collaboration among stakeholders | Practical application of circular principles; promotion of territorial development with benefits for all stakeholders |
| **SOCIO TECHNICAL SYSTEM System innovations and market** | Economic and technological barriers to the development of commercially viable solutions | Development and market introduction of sustainable solutions through collaboration among various stakeholders and interdisciplinary approaches | Development of local networks where production entities collaborate for raw material sourcing, cost optimization, and innovation time reduction | Activation of a circular system based on the reorganization of production chains; importance of collaboration among stakeholders for the production of sustainable innovation |
| **PRODUCT-SERVICE SYSTEM Business and process innovation** | Technological obstacles to integrating waste into the textile chain or adapting existing technologies | Development of technologies for integrating waste into the textile chain or adapting existing technologies | Experimentation with new production processes based on bio-based sources and collaboration with other actors; development of tools for designers and companies to facilitate the integration of circular principles into the process | Promotion of collaboration with other companies and stakeholders in a systemic perspective. Importance of design for the application of circular principles |
| **PRODUCT-TECHNOLOGY Product innovation** | Significant consumption of non-renewable resources and linearity of the textile chain | Development of innovative bio-based and circular materials for a reduction in environmental burden | Interception of waste streams at the local level and development of bio-based yarns, fabrics and garments | Application of circular principles throughout the product lifecycle, including end-of-life considerations |

Piñayarn [Fig. 5] is a yarn produced by the company Ananas Anam, founded by textile designer Carmen Hijosa. The material is obtained from the recovery of pineapple leaves, which represent a by-product of pineapple harvesting (Ananas comosus). The valorization process takes place in the Philippines, where pineapple cultivation is of fundamental importance, generating additional sources of income for farmers and creating job opportunities in rural communities (Ananas-anam, 2024). Furthermore, the reuse of residues prevents improper waste management, such as the burning of leaves, a practice widely used in Southeast Asia (Laudes Foundation, 2021). It is estimated that the production of Piñayarn avoids the release of approximately 6 kg of CO2 for every kg of yarn produced (Ananas-anam, n.d.). The fiber production process does not include the use of chemicals and utilizes an enzymatic pretreatment. The remaining process is mechanical. The dry-spinning technology used to obtain the yarn does not require the use of water and chemicals. The resulting material is defined as "100% bio-based, biodegradable, and compostable" and exhibits good mechanical and performance characteristics, with high tensile strength, high absorbency and dyeability. The use of the material in blends with other fibers allows for further performance enhancement. The traceability of the material is also ensured through a certificate of origin (Ananas-anam, n.d.).

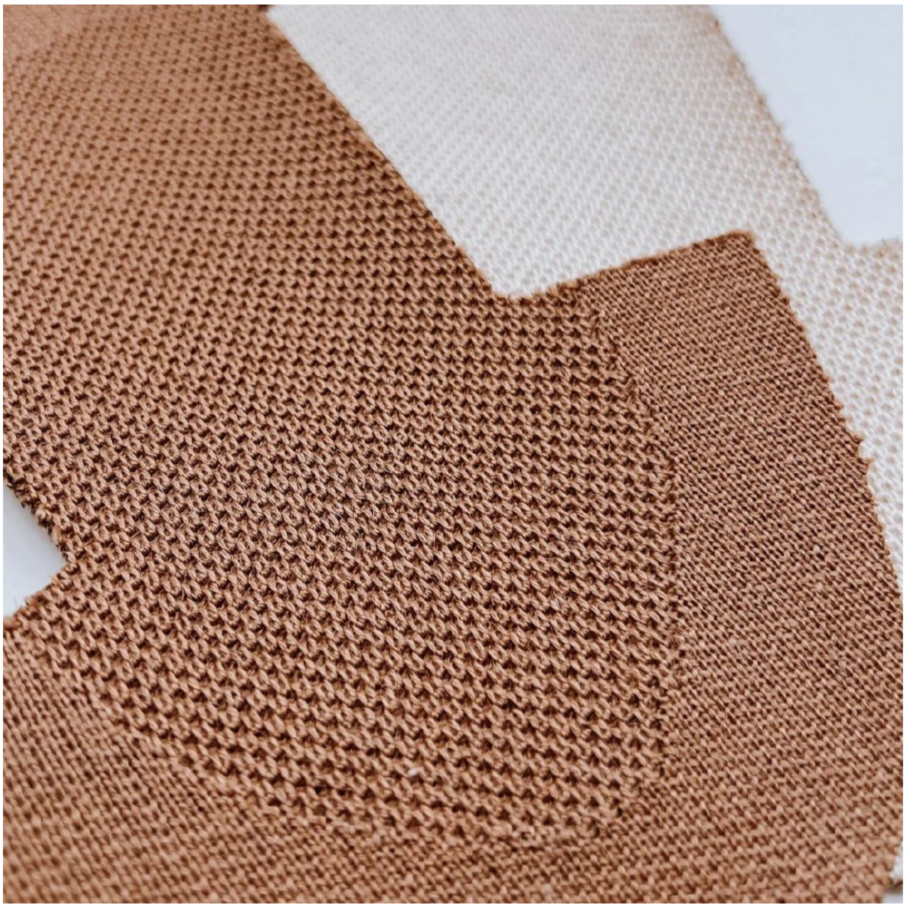


**Figure 5. Piñayarn fabric sample. Source: Piñayarn [@pinayarn]. (2024, January 12). https://www.instagram.com/p/C16kyHRofhu/?igsh=MTJhbDRyODlhY3A1MA=**

*Table 3. Piñayarn System analysis. Source: own elaboration, 2024*

| | **REFLECTION Initial state** | **ANALYSIS Requirements and targets** | **SYNTHESIS Developments** | **EXPERIMENTATION Implementation of Circular Economy** |
|---|---|---|---|---|
| **SOCIETAL SYSTEM Contextual Landscape** | Negative environmental impacts caused by improper management practices of leaves obtained from pineapple cultivation in the Philippines, considered waste | Identification of alternative uses for pineapple cultivation waste, considering the local ecosystem | Development of a new value chain for the production of a bio-based yarn for textile applications from residual leaves. Activation of a closed-loop system | Waste becomes an input for the activation of a new supply chain. Involvement of local communities in the development of a new closed-loop system, integrating into the local cultural and economic context |
| **SOCIO TECHNICAL SYSTEM System innovations and market** | The development of materials from waste often requires significant investments and long innovation periods | Overcoming commercialization barriers and optimizing costs through the creation of a partnership system | Development of partnerships with local farmers and producers in the Philippines, creating an environmentally and economically sustainable system with benefits for all stakeholders | Example of activating a circular system based on the specificities of the local context, reproducible and adaptable in other contexts |
| **PRODUCT-SERVICE SYSTEM Business and process innovation** | Most bio-based materials derived from waste exhibit low performance | Development of a bio-based and circular material through a low environmental impact process, with performance suitable for the textile industry | An efficient process with lower $CO_2$ emissions compared to traditional yarns and "zero water technology" for the spinning process. It adapts to industrial knitting and weaving machinery. Use of blends to enhance performance | Material competitive both environmentally and economically compared to less sustainable alternatives |
| **PRODUCT-TECHNOLOGY Product innovation** | The market is dominated by petroleum-based materials, leading to high usage of non-renewable resources and the issue of microplastic | Development of innovative bio-based and circular materials to reduce environmental burden | Development of a bio-based material with a material-first approach. Biodegradable and compostable, with performance suitable for various applications (footwear, apparel, accessories) | Promotion of efficient resource use and the "waste to resource" paradigm. Design of the material's end-of-life from a circular perspective |

In order to extend the results to the general panorama of the Circular Economy, the results of the three case studies considered have been compared in Table 4 through a cross-scale analysis, following the methodology identified in the literature (De Los Rios & Charnley, 2016). The role of design and sustainability strategies of the "DfX" type were defined based on the theoretical framework found in the literature (De Los Rios & Charnley, 2016; Go et al., 2015; Holt & Barnes, 2010).

*Table 4. Cross-scale analysis of the results. Source: own elaboration, 2024*

| Case study | Business model | Role of design | DfX strategies |
|---|---|---|---|
| **EarthArt** | Circular supplies | * Implementing material performance<br>* Defining applications and usage scenarios<br>* Facilitating use and maintenance<br>* Promoting durability<br>* Communicating sustainability and generating desire | DfSupplyChain<br>DfQuality<br>DfMaintenance |
| **Herewear** | Circular supplies | * Reorganizing the supply chain and systemic relations-hips among stakeholders<br>* Integrating circular principles<br>* Promoting value retention during use and end-of-life<br>* Prototyping development | DfSupplyChain<br>DfQuality<br>DfMaintenance<br>DfRecycling<br>DfReuse<br>DfRemanufacturing |
| **Piñayarn** | Circular supplies | * Prototyping development<br>* Redefining applications and usage scenarios<br>* Implementing material performance<br>* Facilitating recycling<br>* Communicating sustainability and generating desire | DfSupplyChain<br>DfQuality<br>DfRecycling |

## Conclusions

The research aims to explore the evolving role of design within the context of the circular economy and its interaction with other relevant actors in transitioning towards circular production and consumption models, specifically addressing the theme of recovering agro-industrial waste and by-products for applications in the textile sector. To this end, it was conducted a comparative analysis of three case studies considered representative of different approaches, where design played a significant role in the valorization process - EarthArt, a product born in an industrial setting; Herewear, a project funded by European funds and carried out by a consortium of research centers and universities; and Piñayarn, a product of a company initiated by a textile designer.

A preliminary observation can be made regarding the development status of the solutions - a pilot scale in the case of Herewear and solutions already available on the market in the remaining cases. This reflects a tendency towards disparity between academic and industrial research in the commercialization and expansion of solutions, which can be attributed to various factors, including differing objectives - the discovery of new knowledge and understanding of basic research mechanisms in academic research and practical application and profit generation in industrial research (Mansfield, 1995). Additionally, academic research often relies on public funding or grants, as in the case of the Herewear project, and may be limited and constrained by specific research requirements, whereas industrial research has access to more substantial financial resources. Furthermore, academic research may be characterized by longer timelines and greater flexibility in development programs, while industrial research is often subject to commercial pressures and short-term objectives.

Regarding the degree of innovation, although in the case of EarthArt and Piñayarn, it primarily concerns the product, in all three cases the application of a holistic and systemic vision allowed the designer to broaden the perspective and investigate broader project problems and scales. In the analyzed cases, adopting a broader perspective, where attention is not limited to the analysis of the user and their experience but investigates the entire context in which people live and consume, as it evolves, and the new meanings users attribute to things, allows for a "design-driven" approach to innovation (Verganti, 2009). In this sense, innovation is the product of collective research in which different actors, such as companies, cultural organizations, designers, technology providers, institutions, academia and research are engaged in continuous and mutual dialogue (Verganti, 2009).

The analysis of case studies has highlighted that the contribution of design appears significant at multiple levels and manifests in various ways, such as in implementing material performance and sustainability communication. However, in the context of the Circular Economy, it is mainly attributable to the ability to apply systemic thinking capable of addressing complexity and "bringing together seemingly distant elements" (Lotti et al., 2020). In particular, in the investigated case studies, this occurred through:

- The reorganization of the production chain and management of complexity: through the adoption of a systemic approach, the designer can organize and optimize all parts within an ecosystem so that they evolve coherently with each other, program the flow of input and output flowing from one system to another, manage mutual dialogue and collaboration between various actors in all stages of research development.
- The implementation of valorization strategies: through comparison with stakeholders and other professional figures involved in the process, this includes the implementation of valorization strategies, optimizing the value of biomass and using data from the characterization of residues to identify the most suitable application sectors.

- The integration of circular principles: includes the selection and setting of criteria for evaluating circularity and the environmental impact of valorization processes and the use of circularity tools and indicators.

The contributions identified through the analysis of case studies reflect the need for designers to develop new skills in line with the five competencies for sustainability described by Weik et al. (2011). These include the "System-thinking competence", i.e., the ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and on different scales (from local to global) (Wiek et al., 2011; Meadows, 2008; Ellen MacArthur, 2013); the "Anticipatory Competence", which is the ability to predict how the system and interactions between actors will evolve over time to ensure the satisfaction of predefined sustainability and circularity requirements; the "Normative Competence", linked to the ability to select and establish criteria for evaluating circularity and the environmental impact of design choices and to use circularity tools and indicators (Sumter et al., 2019); the "Strategic Competence", which reflects a broader perspective of sustainability connected to planning, organization and decision-making abilities; the "Interpersonal Competence", which includes advanced skills in communication, negotiation, collaboration, leadership, pluralistic thinking and transcultural competence (Wiek et al., 2011) to facilitate collaboration among stakeholders along the entire value chain (Bistagnino, 2011).

In this regard, the analysis of case studies has demonstrated the validity of an interdisciplinary and collaborative approach that includes continuous interchange between design and other professional figures. Synergistic cooperation among stakeholders has been identified as a fundamental tool for the development of sustainable solutions and their scale-up: institutions, through effective strategies and action plans; industry, through the implementation of circular production and business models; academic research, by providing support through new technologies, tools, methodologies, and approaches; designers, as a junction point between academia and industry, through the integration of circular design principles into the design process and the development of closed-loop systems. Through the development of practical case studies, design can contribute to the implementation of the circular economy by intervening at various levels of the supply chain.

The contribution represents a starting point for investigating the role of the designer in the valorization processes of agro-industrial waste, promoting the exploration of new opportunities for application in the textile sector. However, the literature analysis has highlighted a lack of methodological references to guide design activity. Possible research developments include the development of guidelines, best practices and tools to provide designers with a roadmap for the effective implementation of sustainable valorization strategies for agro-industrial waste.

Furthermore, research conducted on the analysis of innovation in the textile field, in reference to the specific study area, can serve as a basis for exploring new areas of innovation, including new types of waste and new applications in different environmental, socioeconomic, and cultural contexts.

Finally, the importance of interdisciplinary collaboration among different actors - such as designers, universities, research centers, and industries - in defining strategies for the sustainable valorization of agro-industrial waste can be further investigated through the exploration of partnership models and innovation networks that encourage the exchange of knowledge and resources across different disciplines and sectors.

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