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Review article

Mobilisation of textile waste to recover high added value products and energy for the transition to circular economy

Iliana Papamichael [a], Irene Voukkali [a], Florentios Economou [a], Pantelitsa Loizia [a], Giorgos Demetriou [b], Mark Esposito [c,d], Vincenzo Naddeo [e], Marco Ciro Liscio [f], Paolo Sospiro [f,g], Antonis A. Zorpas [a,*]

[a] *Laboratory of Chemical Engineering and Engineering Sustainability, Faculty of Pure and Applied Sciences, Open University of Cyprus. Giannou Kranidioti 89, Latsia, Nicosia, 2231, Cyprus*
[b] *École des Ponts Business School, Circular Economy Research Center, 6 Place du Colonel Bourgoin, 75012, Paris, France*
[c] *Hult International Business School, 1 Education St, Cambridge, MA, 02141, United States*
[d] *Harvard University. Division of Continuing Education 51, Brattle Street Cambridge, MA, 02138, United States*
[e] *Sanitary Environmental Engineering Division, Department of Civil Engineering, University of Salerno, via Giovanni Paolo II, 84084, Fisciano, SA, Italy*
[f] *Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, Ancona, Marche, 60131, Italy*
[g] *EUAbout, Bruxelles, Bruxelles, 1000, Belgium*

A R T I C L E I N F O

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A B S T R A C T

The textile industry is a major contributor to global waste, with millions of tons of textiles being discarded annually. Material and energy recovery within circular economy offer sustainable solutions to this problem by extending the life cycle of textiles through repurposing, recycling, and upcycling. These initiatives not only reduce waste but also contribute to the reduction of the demand for virgin materials (i.e. cotton, wool), ultimately benefiting the environment and society. The circular economy approach, which aims to recreate environmental, economic, and societal value, is based on three key principles: waste reduction, material circulation, and ecological restoration. Given these difficulties, circularity incorporates the material recovery approach, which is focused on the conversion of waste into secondary raw resources. The goal of this notion is to extract more value from resources by prolonging final disposal as long as feasible. When a textile has outlived its functional life, material recovery is critical for returning the included materials or energy into the manufacturing cycle. The aim of this paper is to examine the material and energy recovery options of main raw materials used in the fashion industry while highlighting the need of close observation of the relation between circularity and material recovery, including the investigation of barriers to the transition towards a truly circular fashion industry. The final results refer to the main barriers of circular economy transition within the industry and a framework is proposed. These insights are useful for academia, engineers, policy makers and other key stakeholders for the clear understanding of the industry from within and highlight beyond circular economy targets, SDGs interactions with energy and material recovery of textile waste (SDG 7, SDG 11, SDG 12 etc.).

1. Introduction

Nowadays, worldwide consumption of textiles has the third-highest negative effect on the environment and climate change, after food, housing, and transportation. Textiles rank third in terms of water and land consumption, and fifth in terms of raw material utilization and greenhouse gas emissions (Papamichael et al., 2023b; Wojnowska-Baryła et al., 2022). In the past few decades, the textile industry has more than doubled production, while the length of time that clothing get used until being discarded has decreased by about 40%. When textile waste is discarded, 73% of it is burned or landfilled, 12% is recycled, and only 1% is reused. On a global scale, annual textile consumption has risen from 7 to 13 kg per person, surpassing the 100 million tons of textile consumption (Shirvanimoghaddam et al., 2020;

* Corresponding author.
E-mail addresses: iliana.papamichael@gmail.com (I. Papamichael), voukkei@yahoo.gr (I. Voukkali), florentios.eco@hotmail.com (F. Economou), g.demetriou@pontsbschool.com (G. Demetriou), markesposito@fas.harvard.edu (M. Esposito), vnaddeo@unisa.it (V. Naddeo), marcociro.liscio@gmail.com (M.C. Liscio), paolo.sospiro@staff.univpm.it (P. Sospiro), antoniszorpas@yahoo.com, antonis.zorpas@ouc.ac.cy (A.A. Zorpas).

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World Economic Forum, 2019). With increasing concerns relating to environmental, economic and social sustainability, energy and water consumption, natural resource scarcity, soil degradation, waste production – especially micro plastics - and emissions, the fashion sector, produces a massive environmental footprint from cultivation to fabric production to landfill disposal of post-consumer goods. Therefore, the transition to Circular and Sustainable fashion is imperative in order to minimize the use of virgin raw materials (i.e. cotton) and maximize the reintroduction of fashion waste as alternative raw materials for the industry (Papamichael et al., 2023a; Wainaina et al., 2020). A circular economy is an approach that redesigns the idea of material fabrication and resource use to production, use, and discard in favor of as much re-purpose and recycling as feasible (Jørgensen and Remmen, 2018; Morone et al., 2023). Furthermore, it promotes the redesign of business model approaches towards a more circular production chain from material acquisition to use and end of life treatment (Papamichael et al., 2022) By emphasizing the circular economy through extended product life cycles and reusing resources, it prevents waste formation and maximizes the value of products. These principles apply to all aspects of textile design, manufacture, shipping, sale, use, and recycling (González-García et al., 2019).

With the aim of supporting the transition to circular fashion, numerous initiatives and legislation, have developed globally (Chioatto et al., 2023). The Sustainable Development Goals (SDGs) of the United Nations (UN), drive worldwide efforts toward sustainable development (Ali et al., 2023). The SDGs aim to tackle social, economic, and environmental concerns (United Nations, 2015). With 169 targets to be met by the year 2030, the SDGs were developed to promote positive impacts for humanity with emphasis to the environment. The SDGs also represent current concerns and threats in the textile value chain. Textile production and consumption have a direct relationship to SDG 12 (sustainable consumption and production), SDG 6 (clean water and sanitation), SDG 13 (climate action), while the least ones are SDG 1 (zero hunger), SDG 3 (good health and well-being), SDG 4 (quality education) and SDG 14 (life below water) (Cai and Choi, 2020). In line with SDGs, the European Commission is tackling the challenges of the textiles industry and released an innovative approach that will make textiles longer lasting, repairable, reusable, and recyclable, as part of the European Green Deal, the Circular Economy Action Plan, Industrial Symbiosis, Plastics Strategy, and Zero Pollution Action Plan. The EU Strategy for Sustainable and Circular Textiles deals with fast fashion, textile waste, and the depletion of unused textiles, while also ensuring that their production is accord to human rights. It also seeks to create a more ecologically friendly, profitable industry that is more resilient to crises (European Commission, 2022).

The minimization of waste generation, the circulation of materials, and the restoration of ecosystem, are the crucial principles underlying the circular economy approach, which attempts to rebuild environmental, economic, and social viability (Ellen MacArthur Foundation, n.d. According to Morone et al. (2023), the manufacturing sector should be fully involved in the transition towards circular economy as green innovation as businesses are being called to respond to new environmentally related consumer demands (i.e. circular products, sustainability practices, second-hand markets). At the same time, according to Ellen MacArthur Foundation (2017), when textile products and waste are kept at their highest value throughout the supply chain (from raw material acquisition to landfilling or recycling) and reenter the economy, this provides the never-ending global population with access to affordable clothing, providing new job opportunities and minimizing the adverse environmental effects of fashion waste (i.e. leachate, greenhouse gasses emissions, soil toxicity, waste accumulation etc.). In the light of these challenges, circularity embraces the material recovery strategy, which is based on the conversion of waste into secondary raw materials (de Oliveira Neto et al., 2022). The purpose of this concept is to and extract high added value products from resources and defer final disposal for as long as possible (Jacobs et al., 2022; Patti et al., 2021). When a textile reaches the end of its useful life, material (i.e. cotton, silk, cellulose etc.) and energy recovery is crucial for reintroducing the incorporated materials or energy into the manufacturing cycle. This strategy aims to close the loop from source to usage and back to source (Morone et al., 2023).

The goal of this paper is to explore the material and energy recovery options of key raw materials of the textile industry (i.e. cotton, denim, silk etc.) while simultaneously pinpointing key areas in need of alteration for successful material recovery (i.e. dyeing) for the transition towards circular economy as well as other barriers that hinder the smooth transformation of the industry.

2. Methodology

The PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analysis; www.prisma-statement.org) was chosen to recruit all necessary research (Fig. 1). The proposed literature was examined utilizing the PRISMA method, which consists of 27 pathways and encompasses the well-defined stages of a systematic review, such as eligibility criteria and relevant information sources, strategy exploration, selection procedure, outcomes and data analysis (Voukkali and Zorpas, 2022). Inclusion and exclusion criteria were used as eligibility criteria, as depicted in Table 1. Scopus database was used for the recovery of the articles chosen in the study while the keywords chosen by the authors were: Scopus database option search were "title, abstract, keywords'' the following keywords were used: *circular economy* AND *fashion* AND *circular economy*, AND/OR *Material recovery*, AND/OR *Energy recovery*, *recycling* AND *fashion waste* OR/AND *Material recovery* OR/AND *Waste to energy*. Through the PRISMA statement, from a total of 4800 articles reviewed, 143 were chosen, including 126 articles and 17 reports.

According to the protocol and research, to the authors' knowledge, there is a lack of adequate analysis and possible life cycle assessment of different key aspects of circular economy (i.e. recycling, energy and material recovery etc.) as opposed to landfilling. The authors did not manage to retrieve any analysis comparing the two when using the following keywords and phrases: *landfilling* AND *LCA* OR *Life Cycle Assessment* AND *Textile waste* OR *Fashion waste* *VS* OR/AND *and* *Material Recovery* OR/AND *Circular Economy*.

3. Results and discussion

Every year, approximately 56 million tons of clothing are purchased, and this amount is predicted to increase to 93 million tons by 2030 and 160 million tons by 2050 (Ardhan and Affandi, 2022). Throwaway culture has progressively worsened over the years. Many products are now worn only seven to ten times before being discarded. That's a more than 35% drop in just 15 years (Yousef et al., 2019a,b). Each year, the fashion industry produces up to 100 billion garments, up to 92 million tons of clothing end up in landfills, and only 20% of them are recovered for reuse or recycling (Kahoush and Kadi, 2022). Plastic accounts for over 60% of all clothing material. Textiles made of nylon, acrylic, and polyester are among the synthetic fibers that have become so common in our wardrobes. The textile industry produces 42 million tons of plastic waste each year, making it the second-largest industrial sector behind packaging. When synthetic clothing is cleaned, small plastic microfibers are released into the water. Every year, up to 500,000 tons of microfibers end up in the ocean contributing to 9% of the annual microplastic ocean contamination (Khan et al., 2023). At the same time, microplastic accumulation from fashion products have an increasing effect on soil health and toxicity. Hossain et al. (2023) carried out a research aiming to examine the occurrence of microplastics in agricultural land neighboring textile industries and in textile sludge samples in Bangladesh. From a total of 32 soil samples from four different agricultural farmlands, the concentration of microplastics in the soil of agricultural farmlands was 2.13×104 microplastics per kg of soil. This can have a

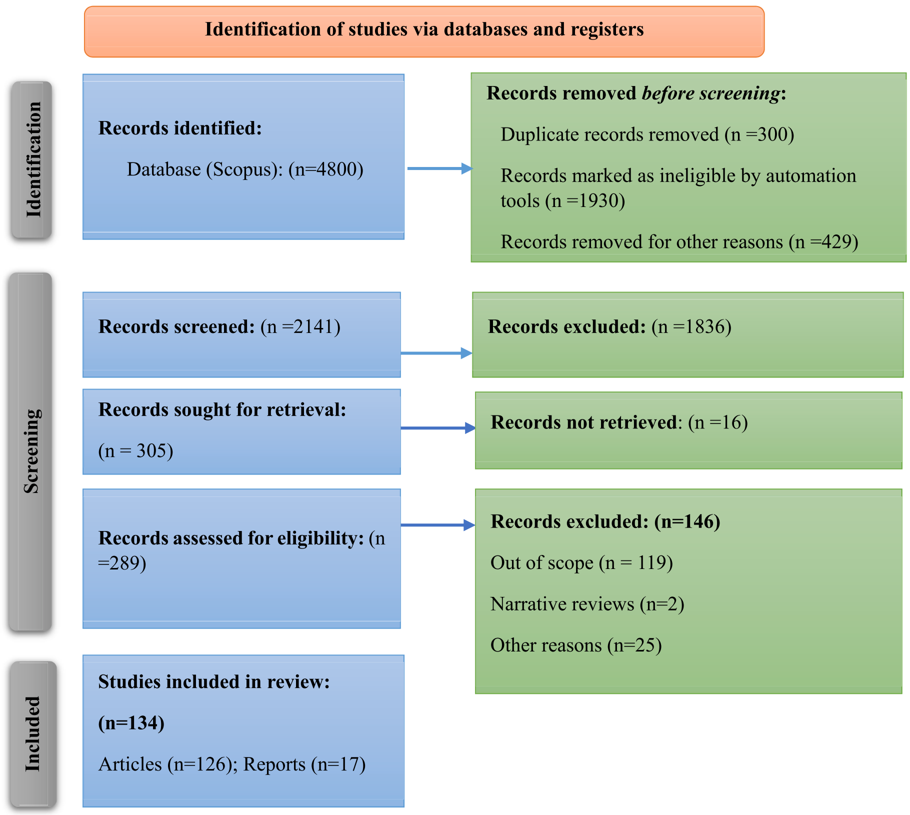

Fig. 1. PRISMA STATEMENT for the current research.

Table 1
Inclusion and Exclusion criteria for PRISMA statement.

Inclusion Criteria	Exclusion criteria
Research related to circular economy and material recovery in the fashion industry	Technical reports
Published articles from 2015 to 2023	Research unrelated to the textile industry
Review papers	Non English papers
Records relevant to the subject mater	Everything not included in the inclusion criteria
Record identified by the author's keywords	

severe effect on al environmental impact, agricultural production and human health due to the presence of cadmium (Cd) which is widely distributed in soil ecosystems (Huang et al., 2023). At the same time, the presence of polyethylene (PE) along with Cd can lead to synergistic toxicity, affecting plant growth, suppressing photosynthesis and causing heightened oxidative damage. (Bethanis and Golia, 2023; Hurley and Nizzetto, 2018).

Textile waste is classified into two main categories: pre-consumer waste and post-consumer waste as depicted in Fig. 2. However, a more detailed classification includes: **(i) Pre-consumer waste:** This sort of waste comprises manufacturing scraps and leftovers such as fabric cuttings and sampling (Crang et al., 2022); **(ii) Post-consumer waste:** Clothes and textiles thrown by customers since they are no longer desirable or have become damaged without repair (Rotimi et al., 2021); **(iii) Deadstock fabric:** This is extra fabric that was not utilized during manufacturing and is usually offered at a discount (Coppola, 2023; Dhir, 2021); **(iv) Misprinted or overstocked items:** These refer to items that were manufactured incorrectly or did not sell as intended (Dominguez and Bhatti, 2022; Mishra et al., 2021); **(v) End-of-life textiles:** These

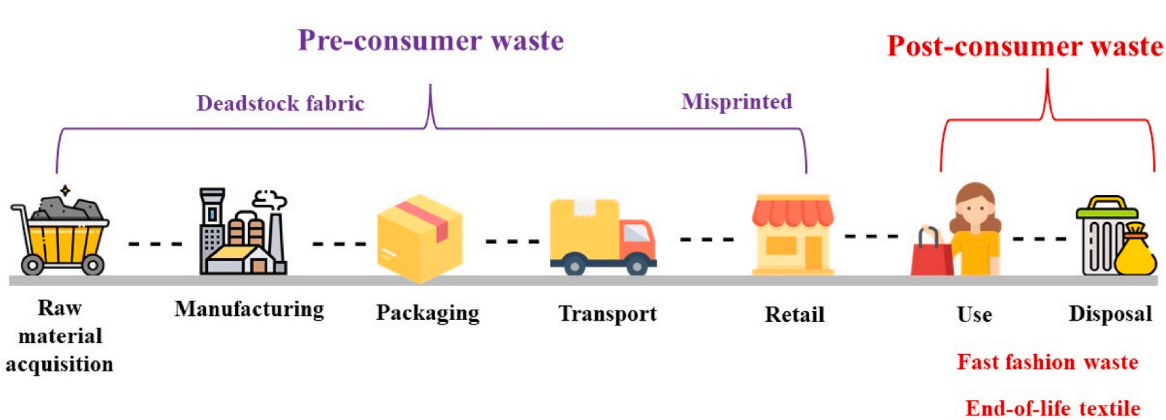

Fig. 2. Types of fashion waste throughout the production line of textiles (Figure created by authors).

include textiles that have outlived their usefulness and are unable to be repaired or reused, for instance old towels or bedding (Furferi et al., 2022; Marques et al., 2020; Palacios-Mateo et al., 2021; Papamichael et al., 2023) and **(vi) Fast fashion waste:** This is clothing that is intended to be trendy and economical, yet it frequently falls apart, contributing to a disposable fashion culture (Colasante and D'Adamo, 2021; Guillot, 2022; Papamichael et al., 2023b; Stenton et al., 2021; TheRoundUp, n.d.).

However, according to the European Waste Catalogue of the European Commission (2015) (2000/532/EC), pre and post-consumer fashion waste referring to clothing and textiles can been seen to have several categorizations. Table 2 depicts these categories which fully summarize textile waste that can be utilized within the circular economy concept. These categorizations include waste from leather, fur and textile industries (Specific to fleshing waste (04 01 01), unprocessed (04 02 21) and processed (04 02 22) textile fibers and other waste (04 02 99), hazardous (15 02 02*) and non-hazardous (15 02 03) protective clothing, disposable clothing within the context of human and animal health care (18 01 04) and clothing (20 01 10) and textiles (20 01 11) within the context of municipal solid waste (European Commission, 2015).

Sustainable end of life material management that encircles circular economy involves the R strategies (Chamorro-Mera and Robina-Ramírez, 2023; Charnley et al., 2022; Papamichael et al., 2022, 2023a) of reuse, recycling, recover, remanufacturing etc. The recycling and material recovery routes of textile waste are categorized in five different ways: (i) mechanical, chemical, thermal and biological treatments (Behera et al., 2021; Damayanti et al., 2021); (ii) downcycling-production of material with lower quality (i.e. shorter length of fiber) (Kukreja et al., 2023); (iii) upcycling-production of higher quality materials (Stanescu, 2021); (iv) open-loop recycling-raw materials are separated by utilizing them as part of a randomly used item (usually not recyclable) (Chairat and Gheewala, 2023); (v) closed loop recycling-materials are being recycled in a similar material from which they are being recycled from (i.e. recycling pre or post-consumer waste into new garments, cradle to cradle methodology to reclaim products again in the form of same or higher value, reuse of existing garments etc.) (Colasante and D'Adamo, 2021; Papamichael et al., 2022).

Where mechanical treatment is concerned, two main processes are involved (Zhou et al., 2023): waste material sorting and mechanical decomposition. Sorting of the material to be recycled or recovered is done through distinguishing between fibers, type, colour, quality and other physical characteristics. Disintegration of the textile material to a more fibrous form is done through shredding or garneting, which is the most common technology linked with mechanical recycling of textile waste. Even as a vital technology, mechanical recycling has some major shortcomings (Majumdar et al., 2020) including the loss of fiber quality (75%) due to aggressive techniques, loss in fiber lengths, significant decrease in material quality, long processing times making blending with virgin materials (i.e. cotton, wool) almost inevitable. Nevertheless, mechanical recycling has shown very promising results for specific textile waste categories reprocessing (i.e. denim) (Akı et al., 2020).

On the other hand, chemical recycling (Ribul et al., 2021) is a tertiary recycling approach which involves the chemical treatment of polymers (fibers) through depolymerization of dissolving. The yield of the chemical process depends on the quality of the processed waste. Additionally, thermal and thermochemical conversion processes have been utilized, referring to the combustion of textile waste and their conversion into energy (Stefan et al., 2022). Textile waste contains high energy content (16.80 MJ/kg) and can therefore be used as raw materials of heat energy generation (Nunes et al., 2018). Thermochemical processes used to decompose polymers include pyrolysis in the presence of catalysts or reactive gases, or sometimes thermolysis. Pyrolysis (Hadroug et al., 2019; Jellali et al., 2021, 2022; Kwon et al., 2021; Malinauskaite et al., 2017; Stylianou et al., 2022, 2023; Yousef et al., 2019, 2021) is referred to the decomposition process with high temperature (400–900 °C) (Jalal et al., 2022) in the absence of oxygen condition. Chemical recycling of polyesters also includes glycolysis, metanolysis and hydrolysis (Lang et al., 2023). Consequently, chemical recycling allows the recovery of more high added value products (such as transparent films, construction and automotive materials, high value synthetic fibers etc. (Asaadi et al., 2016; Johnson et al., 2020; Xia et al., 2021). in comparison to mechanical recycling. The use of selective degradation methods for each garment is more suitable for larger scale recycling of blended materials. Still, some major shortcomings (Akı et al., 2020) include a high chemical and water consumption (70% higher than mechanical treatment), high cost, many processing steps requiring operational staff knowledge, high energy requirements for heating and scouring.

Furthermore, biological treatment through biodegradation is denatured in the industry, where the organic matter of textile waste is broken down by microorganisms (i.e. bacteria, fungi etc.) (Mustafa et al., 2021). This ensures natural cleanup of waste while simultaneously providing nutrients for growth and energy for various biological processes. According to many researchers (Akı et al., 2020; Hasanzadeh et al., 2018; Meng et al., 2019), biochemical transformation has been used for obtaining glucose and ferment it further into higher added value products, biogas production and other.

Table 2
Textile waste categorization according to the Catalogue of the European Commission (2015).

Code	Description
04: Waste from leather, fur and textile industries	
04 01: Waste from leather and fur industries	
04 01 01	Fleshing and liming split waste
04 02: Waste from the textile industry	
04 02 21	Wastes from unprocessed textile fibres
04 02 22	Wastes from processed textile fibres
04 02 99	Waste not otherwise specified
15: Waste packaging, absorbents, wiping cloths, filter materials and protective clothing not otherwise specified	
15 02: Absorbents, filter materials, wiping cloths and protective clothing	
15 02 02[a]	Absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, protective clothing contaminated by hazardous substances
15 02 03	absorbents, filter materials, wiping cloths and protective clothing other than those mentioned in 15 02 02
18: Wastes from human or animal health care and/or related research (except kitchen and restaurant wastes not arising from immediate health care)	
18 01 04	Wastes whose collection and disposal is not subject to special requirements in order to prevent infection (for example dressings, plaster casts, linen, disposable clothing, diapers)
20: Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions.	
20 01 10	Clothes
20 01 11	Textiles

[a] The asterisk depicts hazardous waste.

3.1. Dye removal

Main aspect to be considered when circular economy in the concept of material recovery is considered, is the removal of dyes (Hynes et al., 2020). In general, dyes are used throughout the industry as synthetic organic colorants (i.e. azo) with resistance properties in conventional treatment methods (Ziarani et al., 2018). For cotton and denim use (containing cellulose fibers), the types of dyes used include reactive, direct, naphthol and indigo dyes (Lin et al., 2022). Other types of fibers correspond to different dyes used (i.e. acid, Lanaset dyes for protein fibers, dispersed, direct and basic dyes for dye synthetic fibers etc.) (Lin et al., 2022)). Major issue (Amutha et al., 2020) is the fact that the removal of dyes needs to be done before the material recovery stage as even small concentrations of dyes (even 1 ppm) affect can affect the environment waterborne toxicity by blocking penetration of light and even the transfer of oxygen. At the same time, due to the dye content of textile waste, heavy metals like Pt, Cd, and Cr can be found leaching into the environment with negative environmental issues (i.e. water and soil toxicity, healthy implications like respiratory issues, cancer etc.) (Arora and Chauhan, 2021).

Therefore, main method employed for dye removal involves enzymatic degradation while parameters like temperature and acidity can be monitored as they affect the stability of dye complexes (Bento et al., 2020). Vermicomposting (ZeynepCiğeroğlu, 2020) has also been employed to reduce metal content of textile waste sludge but also to decrease the spread of fungal pathogens. Main disadvantages of vermicomposting is the time needed for the transformation of waste yet the introduction of earthworms seem to accelerate this process (Stefan et al., 2022).

3.2. Material recovery

3.2.1. Denim

Denim is characterized as a sturdy cotton twill woven fabric with diagonal ribbing known for its use in jeans and clothing on a global scale (Aman et al., 2022). According to Statista (2023), the global denim jean market is over 70 billion dollars with an increase in an annual growth rate of 2%. Global denim markets are categorized into North America, Europe, Asa-Pacific, Middle East and Africa as well as South America. Specifically, in 2019, global denim market value was almost 90 billion USD and expected to reach 107 billion USD by the end of 2023. At the same time, global denim fabric exports key players include China, Pakistan, India, Hong Kong and Turkey with 42%, 11.7%, 8.2%, 7.4%, 6.8% of global exports respectively. On the other hand, biggest consumers of denim around the world include Europe, the United States and Japan (Akı et al., 2020; Statista, 2023c).

As cotton is one of the main components of denim production, there has been an increasing pressure to the fashion industry to increase the recycling potential of cotton. This is requested in order to ensure the use of recycled materials (i.e. yarns, fibers etc.) to substitute cotton use while simultaneously covering the prospective market demands for denim. According to Statista (2015), one pair of jeans consumers 2900 L of water while indigo dye is one of the organic colorants used to color them. Even as an organic substance, textile effluents containing indigo dye increase water toxicity, deeming it harmful to both humans and animals and causing adverse effects on aquatic ecosystems. Simultaneously, the use of synthetic indigo and sulfur dyes also create severe adverse environmental effects including water pollution (i.e. dyeing effluent discarded in water bodies) (Rafiq et al., 2021), air pollution (i.e. cotton dust, airborne chemicals etc.) (Yalcin-Enis et al., 2019) and solid waste (i.e. sludge) (Akı et al., 2020).

To tackle such adverse environmental effects of denim production and waste, fashion companies turn to circular economy strategies beforehand, to prevent the production of denim waste to begin with, by encouraging their customers to take care of their worn-out denim jeans (Papamichael et al., 2022). Still, less than 1% of collected clothes are recycled and 80% of them are being sold in secondhand markets in low-income countries (LICs) (Papamichael et al., 2023b). The remaining 20% is either sold in secondhand stores within the EU or landfilled (Akı et al., 2020; D'Adamo et al., 2022).

In reality, large amounts of denim waste are being landfilled or incinerated along with solid waste. Globally, the consumption of denim jeans in particular is 2.3 million tons per year while 90% of this is landfilled or incinerated and only 10% recycled (Luiken and Bouwhuis, 2015). This is often referred to as 'thermal recycling' but, in essence, valuable materials that could have been recovered and recycled into high added value products (e.g. composite reinforcements, yarns, cellulose fibers, cellulose nanocrystals, flexible electronic devices, biofuels adsorptive materials etc.) are being destroyed (Lu et al., 2023). In addition to this, post-consumer denim recycling is even more complex, as materials are not homogeneous (i.e. color, fibers) while also including other non-textile parts that hinder the recycling of denim and recovery of cotton (i.e. buttons, zippers, labels). Furthermore, according to Wojnowska-Baryła et al. (2022), when testing the degradability of denim, silk and cotton by using the D 5988-03 test of the American Society of Testing and Materials (ASTM), denim was deemed the least degradable material while silk was the most degradable one.

In terms of material recovery, denim waste is usually shredded into fibers in a mechanical process. The fibers are mostly shorter than the virgin fibers (downcycling) but can still be reused in weft insert yarns when mixed with the original virgin fibers (Wojnowska-Baryła et al., 2022). According to Luiken and Bouwhuis (2015), up to 50% of the recovered shortened fibers can be added without influencing the quality of the new product while simultaneously reducing the use of indigo dye as the recovered fibers are already blue in color. Still, a main problem with recycling jeans and recovering high value materials from denim products is the sorting of such textile waste. Even though many countries (e.g Denmark, France, Netherlands, Sweden etc.) have textile collection systems in place (Christensen, 2021; Obando, 2022), consumers keep discarding jeans (along with other fashion products) with municipal solid waste, thus leading to landfills or incineration (Guillot, 2022; Malinauskaite et al., 2017). Once mixed with solid waste, jeans become wet and high-end recycling is no longer implementable. Furthermore, non textile parts of the products (i.e. buttons, zippers etc.) have to be removed (Luiken and Bouwhuis, 2015; Wojnowska-Baryła et al., 2022).

When investigating the production of biogas from denim jeans, Hasanzadeh et al. (2018), a maximum methane yield of 361.1 Ml/g VS was obtained, with cotton and polyester fibers feedstock. First, the jeans were treated with calcium carbonate at 50, 100 and 150 °C) to reduce the crystallinity of cotton thus making it easier for enzymatic treatment to catalyze hydrolysis. Additionally, Meng et al. (2019), created three kinds of 3D waste denim fiber needles felts/epoxy composited, composed of different areal densities. Through their research, the areal density effect of mono-layer fiber webs as well as cross-section morphologies were examined in terms of mechanical properties (tensile, blending, and compressive tests). The results revealed that high fabric density of denims can restrict the flow of resins while, with denim-reinforced composited were not limited by fabric density yet fiber volume content cannot be strictly controlled.

3.2.2. Cotton

According to the International Cotton Advisory Committee (2023), 25 million tons of cotton are produced globally each year while the annual production of cotton and other cellulose materials (i.e. hem) is estimated to be around 53 megatons (MTs), while cotton accounts for 13 MTs. According to Statista (2021), in 2021 China was the leading country of cotton production, with 6423 million metric tons, while global cotton production is estimated to reach 28 MTs by 2030 (Papamichael et al., 2023a). According to Mazotto et al. (2021), cotton is responsible for 35% of existing fibers in the market and the humongous amount of water consumption of 15.5 billion tons/year. Specifically, 10000 L of water are needed for the production of 1 kg of cotton, corresponding to 2700 L of water for the production of one cotton t-shirt (Papamichael et al., 2023a; The World Counts, 2022).

Due to these increasing and high demands, other sources of cotton production, apart from agricultural cotton produced are necessary. As cellulose is the main component of cotton, the recovery of cellulose from textile waste is a main area of focus throughout the research community (de Oliveira Neto et al., 2022; Harmsen et al., 2021; Hubbe et al., 2019; Pervez et al., 2023; Provin et al., 2021; Stefan et al., 2022). Natural cellulose fibers constitute a renewable biomass source for production high-value products by employing cellulose hydrolysis. However, the cellulose used in cotton fabrics has high crystallinity thus being ineffective and inefficient for biofuel conversion. However, alkali and acidic pre-treatment at moderate temperatures transforms the crystalline structure into an amorphous form more easily biodegradable (Stefan et al., 2022). The treatment of cotton textile waste by NaOH was used by Palme et al. (2017) in mild temperatures (70–90 °C) to separate cotton and polyethylene terephthalate polyester (PET). PET was degraded to terephthalic acid (TPA) and ethylene glycol (EG). At the same time, Gholamzad et al. (2014) researched the use of recovered cellulose from cotton fabrics for ethanol manufacturing.

Lv et al. (2015) used dissolution process by 1-allyl-2-methylimidazolium chloride ionic liquid to separate both cellulose and nylon 6 from nylon or cotton waste. Using such an approach, cotton is separated and recovered as cellulose solutions, but more steps are necessary from then on to regenerate cellulose from the liquid phase. At the same time, leaching is used to recover metals from textile waste, by using different acids (mostly nitric acid). Therefore, the removal of heavy metals from textile dyes for treated cotton waste and polyesters, has the potential to be very slightly contaminated by organic materials from textile dyes. The use of nitric acid in a concentration lower than 68.4% is vital, as higher concentrations will alter the chemical structure of cellulose through nitration. In that case, instead of pure cotton, a combination of modified and virgin fibers can be obtained.

Yousef et al. (2019), processed cotton textile waste with a 60% nitric acid at mild temperatures. According to their research, the selection of solvents was vital for the dissolution process to avoid and reduce the degradation of the extracted cotton and cellulose. Their strategy included three main steps: leaching using nitric acid, the use of dimethyl sulfoxide for dissolution and bleaching using sodium hypochlorite and dilute hydrochloric acid. The processes were used for the removal of textile dyes by dissolving the polymeric parts to liberate the cotton fibers. Raw cotton fibers can be recovered with such strategies while recovery rate was estimated at 93% with a −1.534 kg CO_2 eq./ton carbon footprint (Yousef et al., 2019a,b).

In one of their similar studies, Yousef et al. (2020) developed a sustainable green technology for the recovery of cotton fibers by leaching through nitric acid (concentration of 60%) and the regeneration of acid spent by activated carbon. Further on, the polyester was separated by the cotton by dissolving it through hydrophilic solvent and carbon dioxide was added to the solution to extract the polyester and regenerate the solvent. According to their results, cotton fibers were recovered and recycled by 96% while the carbon footprint of the methodology was −1.440 kg CO_2 eq./tons of waste.

On the other hand, the benefits of moving from traditional cotton cultivation to organic farming of cotton has also been discussed among the scientific community (Agrawal et al., 2021; Capriotti et al., 2021; Esteve-Turrillas and de la Guardia, 2017; Textile Exchange, 2016; Yousef et al., 2019a,b). However, the use of organic cotton does not exclude the dyeing process for the products. On the contrary, according to Esteve-Turrillas and de la Guardia (2017), the introduction of recovery technologies based on the use of the produce product (upcycled, downcycled etc.) bypasses the impacts of cotton cultivation and dyeing when the appropriate raw materials from textile waste are selected while energy costs of shredding the fibers increases compared to the usage of virgin agricultural cotton for textiles production. However, similarly to denim, key components in a successful recovery of high added materials from cotton products involve the correct collection and sorting at source of textile waste according to their quality, color and additional non-textile materials. Furthermore, the use of open-end spinning technologies allows for textile production yield of 90%, mixed with synthetic fibers (i.e. polyester, acrylic etc.) (Damayanti et al., 2021).

3.2.3. Silk

According to Statista (2023b), silk production in India alone stands over 36 thousand metric tons in 2023 with an increased trajectory since 2008. Silk is one of the most biocompatible and biodegradable raw materials employed in the fashion industry (Lu et al., 2022). Its unique mechanical strength, insulating properties and thermal conductivity gives it a broad application prospect but also, as a big part of fashion product designs. Wasted silk from the fashion industry is usually a result of worn and out of fashion clothing and scraps obtained during textile production while additional sources of wasted silk include curtains and bedding (Wojnowska-Baryła et al., 2022).

Even though wasted silk can be converted into bioenergy through combustion. One ton of textile waste combusted releases 10 tons of carbon dioxide into the atmosphere, thus making it a less ideal solution for wasted silk utilization. Silk is made up of proteins which can be employed for energy and food for poultry (Kirrella et al., 2021; Mahanta et al., 2023). At the same time, mechanical recycling of silk refers to the impregnation and melting without destroying its molecular structure to recycle silk into fibers for textile raw material usage or reinforcements of composites. The recovery of silk for textile waste, however, usually results in the reuse of the material to make fabric (Haq and Alam, 2023). Through the different types of processing techniques of the fashion industry (i.e. blended fibers, weaving etc.), performance and aesthetics can be improved. According to Hazarika et al. (2018), wasted silk was used with pineapple leaf fibers to create yarns, following by weaving the materials into blended fabrics. The material was a higher value product than the ones made purely from wasted silk in terms of texture and had the potential to be used in women's clothing, jackets, home furnishing and other (Lin et al., 2022b).

3.3. Energy recovery

Due to the latest energy crisis partly from the Russian-Ukraine war, there is a growing demand and need for alternative energy forms to replace fossil fuels in an economic beneficial way (Zheng et al., 2022). The adoption of waste-to-energy system could leverage on the possibility of reducing the adverse environmental impact occasioned by waste generation and ensuring production of renewable and sustainable energy while achieving circular economy (Testa et al., 2017). As traditional energy production relies heavily on centralized systems using fossil fuels like natural gas (Safari et al., 2019), coal and oil (Stoner et al., 2021), more than 84% of the world's primary energy supply comes from fossil fuels (Statista, 2023a). The current waste textile management system is not only environmentally unfriendly but also ill-equipped to handle the current pace of waste generation (Alao et al., 2022). In this regard, the use of textile waste for the production of thermal energy is an adequate alternative worth to research (Nunes et al., 2018). Energy recovery from textiles involves the conversion of discarded items into useful energy sources for both the reduction of the environmental impacts of textile waste (i.e. carbon emissions, landfilling space, water and energy consumption etc.) (Stanescu, 2021). The thermal technologies for fashion waste mostly used are incineration pyrolysis and gasification to generate vapor, heat, char and other gases (Nayak et al., 2021).

Starting off from within the industry, gas is usually used for generators and steam-producing boilers. According to Roushan (2020), many factories around the world cannot start production due to lack of new gas connections. Waste fabrics could be utilized as an alternative source of energy for a boiler of a small and medium-sized factory. The waste fabric within the context of the industry itself refers to nonproductive by-products of ready products that remain unused (i.e. fibers, defective products etc.). Therefore, through combustion, the utilization of textile waste can cut production cost and limit the pressure on natural gas and fabric waste globally. According to Roushan (2020), the waste to energy process through incineration involves burning fabrics at 154 °C or above. Textiles such as wool and knit can be used as fuel without pretreatment, except when dyeing is involved (Testa et al., 2017). In particular, according to the study (Roushan, 2020) a factory can save up to almost 64 thousand L of diesel and 87 thousand m^3 of natural gas by utilizing textile waste for gas generation. At the same time, utilizing wool waste as a co-substrate in biogas reactors offers the potential to convert it into both sustainable energy and liquid fertilizer through anaerobic microbial digestion. However, given its intricate composition rich in keratin, various preparatory methods are required before subjecting wool waste to anaerobic digestion (Wojnowska-Baryła et al., 2022).

According to Rabbat et al. (2022), in 2018, woven fabrics were assessed to account for 62400 t of marketable items while only 40% were collected. After sorting, 59% were reused (as secondhand products), 10% were recycled (wipers). The remaining fraction was recruited as garneting materials yet has the potential to be employed to produce new textiles, composite materials in construction and other uses within the context of circular economy. However, the non-recyclable part can be subjected to energy recovery to reduce the amount of woven textiles ending up in landfills (Rabbat et al., 2022).

Compressing cotton and woven waste for heating a boiler (1542 MW) that produces 2 tons of stream per hour (10 bar) to produce thermal energy, can of course be utilized from post-consumer textile waste (Yalcin-Enis et al., 2019). According to Nunes et al. (2018), cotton waste can be used as a renewable resource of thermal energy production after the characterization of the waste. Its energetic potential is determined comparing it to other fuels (i.e. wood pellets) while the obtained results suggest that cotton briquettes contain almost 17 MJ/kg heating value and 0.006 $/kWh cost when used as a fuel. Such data suggest a decrease of 80% in annual fuel cost and deem wool valorization as a viable alternative for the production of thermal energy (Nunes et al., 2018).

Concerning pyrolysis, the pretreatment of textile waste is very important for good pyrolytic degradation. Pyrolysis is the thermal degradation of materials in the absence of oxidizing agents, leading to the production of carbon monoxide, carbon dioxide, hydrogen, hydrocarbons (C1–C4), liquid oil and char, performing at 300–700 °C (Stylianou et al., 2022). The pyrolysis of jeans at 800 °C provided a recovery rate of 93% and € 1676 of revenue while the carbon footprint was 836 kg CO_2 eq. per ton of textile waste (Yousef et al., 2019a,b). According to Espinoza Pervez et al. (2022), the average carbon footprint for 1 ton of landfilled textile waste is 718.6 kg CO_2 eq. which is lower than the carbon footprint for the incineration of wool, jeans as presented above. This indicates that any endeavors for the 'reuse' of textile waste either of recycling, waste to energy and other key elements of circular economy is not carbon neutral by considering merely the avoided landfilling emissions.

Similarly, the incineration of textile waste (Dissanayake and Weerasinghe, 2021; Zhou et al., 2022) involves heat energy generation by burning waste producing energy, carbon dioxide, water vapor and char. According to Yalcin-Enis et al. (2019), electrical configuration has been suggested for energy recovery of solid waste (including textiles) for energy recovery. The reason for this is the environmental implications arising from incinerations which involve hazardous gas emissions such as dioxins and furan. However, taking into account the yield of energy recovery of incineration of textile waste as the procedure involved the reduction in greenhouse gas emissions (370 kg CO_2 eq. per to of waste) and economic profit of 24.5 Euros per kilotons of waste (Stanescu, 2021).

According to many researchers (Karmakar et al., 2023; Sonu Rani et al., 2023; V et al., 2023; Vlasopoulos et al., 2023) the choice of burning waste for energy production is not the ideal solution. Direct burning of solid waste leads to the creation and reformation of harmful carcinogenic compounds, such as dioxins and furans, especially when plastics are part of the waste composition. This has stirred considerable public discontent and opposition to the introduction of incineration technology in numerous countries, resulting in the halting or postponement of incineration projects (Alao et al., 2022).

Still, there is no perfect solution regarding waste management -and by extend textile waste-, since the overproduction and lack of space concerning existing landfilling waste needs to be tackled. The choice of waste to energy for the non-recyclable part of textile waste could be coming second to reuse and recycling of waste yet far before landfilling (Sandin and Peters, 2018). As indicated in Fig. 3, this is due to the fact that energy recovery from textile waste aids at the reduction of the volume in landfills thus minimizing the associated environmental risks (i.e. leachate greenhouse gas emissions etc.), health risks and land use for the accommodation of a landfilling site (Wen et al., 2023).

Simultaneously, heat energy, electricity and biogas can be produced, contributing to renewable energy production and the reduction of fossil fuels reliance and usage (de Oliveira Neto et al., 2022). Furthermore, according to Zero Waste Europe, (2020), the carbon footprint of energy recovery from solid waste, and by extend textile waste has almost the same value (95425 kt CO_2 eq.) than landfilling yet landfilling has a far higher value of methane emissions that energy recovery. Thus, this will continue to occur for both waste to energy and landfilling without the added value of energy recovery from waste for the latter. In future reference, the close examination to determine and sort the recyclable vs non-recyclable part of textile waste (to be used for energy recovery) provides the opportunity for resource recovery and utilization of valuable materials.

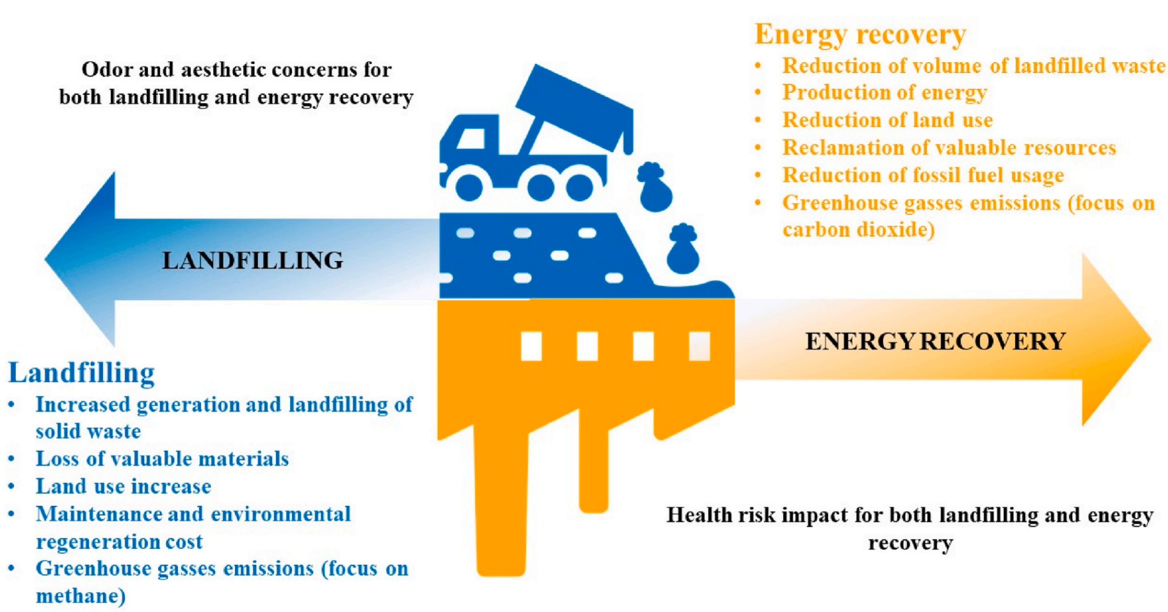

Fig. 3. Landfilling and energy recovery in regard to textile and solid waste (Figure created by Authors).

3.4. Circular economy implementation: barriers of material recovery and textile recycling

The true, evolving and efficient implementation of circular economy in the fashion industry in regard to material and energy recovery is hindered by some yet unanswered issues (Fig. 4). Due to widespread production of low-quality products (downcycling), several recycled textile wastes are not suitable for multiple circulation and use (including multiple recycling cycles) (Celep et al., 2022). There is a threshold of economic viability when it comes to recirculation and reuse which is discouraging for investment in textile recycling and recovery in the first place (Leal Filho et al., 2019).

At the same time, the composition and base structure of existing textile fashion products does not allow for recycling or material recovery. According to Aki et al. (2020), the presence of plastic or metals in textiles, hinders or slows down material recovery of true high added value products (i.e. cellulose), creates a barrier between textile sorting and recyclability (i.e. correct sorting is necessary) and also, there is a limited use or utilization of non-textile parts of fashion waste (i.e. buttons, zippers etc.). Major issue is the limited quantity of used textile waste collected or sorted for recycling (also limited by the lack of sorting technologies, inadequate methods for dye and contaminant separation etc.) (Sandvik and Stubbs, 2019) or material recovery, as many of such waste are either incinerated with municipal solid waste, sold or dumped at LICs (i.e. Chile), as mentioned in section 1 (Papamichael et al., 2022).

Therefore, there is a limited supply of raw material (i.e. recycled cotton, cellulose, recycled fibers etc.) to give incentives for an industrial movement towards material recovery (Papamichael et al., 2023b). Furthermore, lack of information (i.e. quantitative data, KPIs, other key metrics etc.) and limited public participation and awareness on the merits of recycled fabrics contribute to low recycling rates and create a perpetuating cycle of low raw material, low economic viability and low economic and technological motivation from the industry (Akı et al., 2020). Coupled with poor coordination and weak policies (Huang et al., 2021) of standardization of textile waste, leads to uncoordinated collection of such waste and absence of integrated framework, including all industry, public, policy makers and other key players, which would enhance the recyclability and by extend material recovery of textile waste (Akı et al., 2020).

In order to overcome these barriers, several steps have to be taken into consideration (Fig. 5). According to Loizia et al. (2021), it is impossible to measure something that isn't there. Therefore, the main steps regarding energy recovery and circularity implementation for the textile industry include: **(i) data collection** (Vecchi, 2020) on current situations of a system under question (i.e. industry, urban textile collection systems etc.) has to be a priority in order to **(ii) conduct a comprehensive assessment** of the current textile waste management system. This can be done by employing quantifiable assessment methods like Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) in order to predict and assess whether or not energy recovery of the current system is viable and possible (Corona et al., 2019; Daddi et al., 2017; Marrucci et al., 2022; Wiedemann et al., 2022); **(iii) Research and Development (R&D)** (Wójcik-Karpacz et al., 2023): Encourage the design of textiles with recyclability and reusability in mind, using sustainable and easily recyclable materials, reducing chemical usage, and employing modular design principles for easy disassembly. At the same time, the implementation of efficient waste segregation methods at the source and establish collection systems that facilitate the separation of different types of textile waste to streamline the recycling process is vital in order to fast forward the correct sorting for material and/or energy recovery (Chen et al., 2021). **(iv) Legislative perspective** for the establishment and investment of various technologies (i.e. mechanical, biological, chemical recovery etc.) is important as any actions need to be in line with existing regional/national/European legislations (i.e. SDGs, the European Green Deal, EU strategy for sustainable and circular textiles) in order to foster collaborations among various stakeholders, including textile manufacturers, recyclers, policymakers, and consumers, to build a robust circular economy ecosystem that encourages the exchange of knowledge, resources, and best practices (European Commission, 2022). **(v) The continuous monitoring and optimization** of such systems will ensure the correct interventions by the users, while at the same time ensure environmental (i.e. decrease is greenhouse gasses emissions, landfilling etc.), social (Job opportunities, minimization of textile waste) and economic (long term revenue, job creation etc.) viability (Papamichael et al., 2023c).

4. Conclusion

This manuscript focuses on material and energy recovery within circular economy for addressing the growing problem of textile waste. Through the employment of PRISMA statement for the recruiting of adequate references, 143 records were collected, including 126 articles and 17 reports. Through the research, main barriers for the smooth transition to circularity were identified. Notably, the prevalence of low-quality products and the resultant downcycling of textile waste limit its potential for multiple cycles of recycling and reuse. This situation is compounded by economic viability thresholds that deter investment in textile recycling and recovery. Moreover, the presence of non-recyclable components such as plastics and metals in textiles impedes material recovery, complicating the sorting process and reducing the utilization of non-textile parts. Insufficient collection and sorting technologies, as well as a lack of public awareness and comprehensive data, further hinder progress. Without a coordinated approach involving industry, policymakers, and the public, the full potential for material recovery and

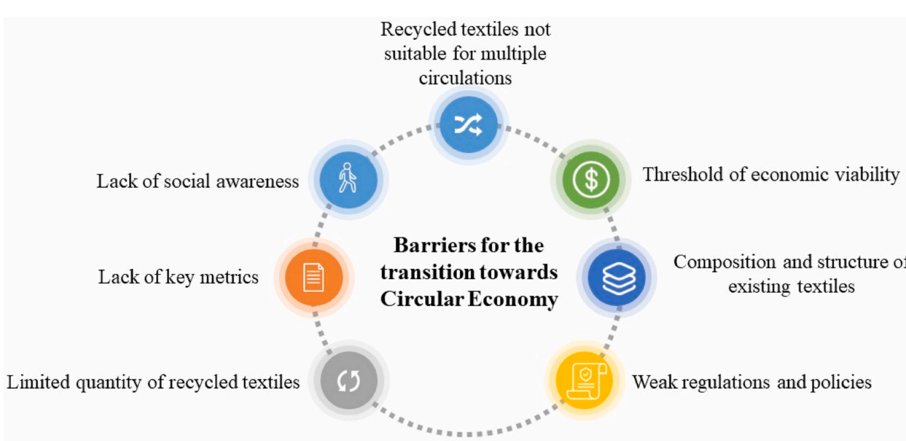

Fig. 4. Barriers for the transition towards circular economy in the fashion industry (Figure created by Authors).

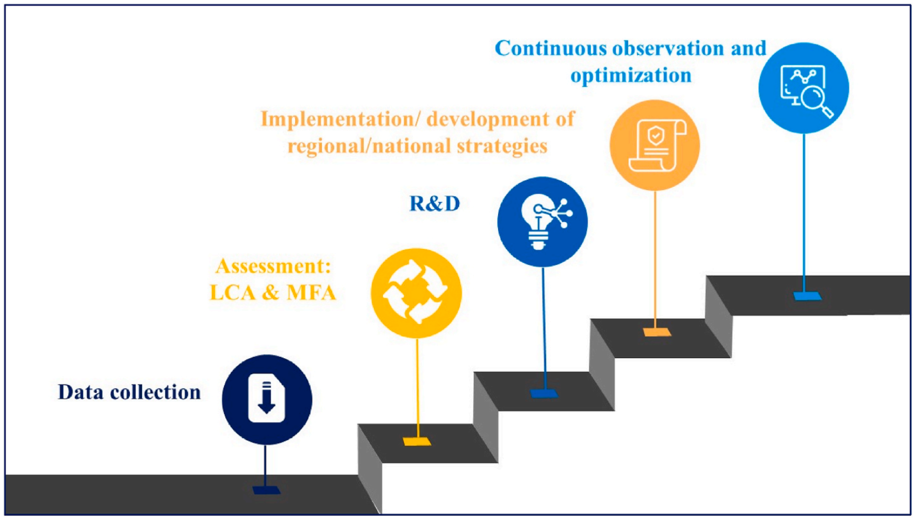

Fig. 5. Main steps toward circular economy in the fashion industry, in the context of material and energy recovery (figure created by the authors).

textile waste recycling remains unrealized.

Regarding these barriers, key actions were proposed including the necessity of assessing the existing system before any measurement, highlighting the imperative of data collection, comprehensive evaluation through LCA and MFA, research and development initiatives to promote recyclable and reusable textile designs, efficient waste segregation practices, and the integration of appropriate collection systems. At the same time, legislative considerations should be taken into account, to align actions with regional and international sustainability agendas, fostering collaborations among diverse stakeholders while continuous monitoring and optimization of these systems are crucial for ensuring environmental, social, and economic sustainability.

These efforts can help create a more sustainable textile industry that not only reduces waste but also benefits the environment and society. Therefore, it is imperative for stakeholders in the textile industry to collaborate and adopt sustainable practices to achieve a circular economy and a more sustainable future. At the same time, the adequate analysis and possible life cycle assessment of different key aspects of circular economy (i.e. recycling, energy and material recovery etc.) as opposed to landfilling need to be explored as, to the authors' knowledge and according to the literature used and employed, there is a lack of data concerning numerical proof of the latter comparison.

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Author contributions

Iliana Papamichael: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Irene Voukkali: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. Florentions Economou: Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization. Pantelitsa Loizia: Validation, Formal analysis, Investigation. Giorgos Demetriou: Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization. Mark Esposito: Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. Vincenzo Naddeo: Validation, Formal analysis, Investigation, Writing – review & editing. Liscio Marco Ciro: Formal analysis, Investigation, Validation, Formal analysis, Investigation, Resources, Data curation. Paolo Sospiro: Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. Antonis A. Zorpas: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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