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SUSTAINABLE ERGONOMIC WOMEN'S CLOTHING BY INTEGRATING CHEMICAL RECYCLING OF TEXTILE FABRICS

BY

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Abstract. The textile industry is the second most polluting industry in the world, with a considerable impact on the environment due to greenhouse gas emissions, high water and energy use, chemical pollution, and by default the formation of a huge amount of textile waste. This has led to an imbalance in nature through loss of biodiversity and global warming. This analysis aims to provide an overview of the textile and fashion industry's impact on the environment, social and economic, promoting sustainable and ergonomic fashion. The paper also aims to punctually present the chemical textile recycling methods used in recent years to combat the environmental impact by transforming a waste product back into raw material.

Keywords: sustainability, ergonomic design, chemical recycling.

1. Introduction

The textile industry has a huge impact on the environment, due to greenhouse gas emissions, high water and energy use, chemical pollution and, by

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default, the formation of a huge amount of textile waste in pre-consumer, post-consumer and industrial processes.

The textile and fashion industry is the second most polluting industry worldwide, contributing 8-10% of total carbon emissions and 20% of global wastewater. Emissions are expected to increase by 50% by 2030. The fashion industry annually emits 1.2 billion tons of CO_2, produces over 92 million tonnes of waste and consumes 79 trillion liters of water (Andreadakis and Owusu-Wiredu, 2023; Bailey *et al.*, 2022). To make an idea about the environmental impact of textiles, in 2020 textile consumption per person in the EU required on average: 400m^2 of land, 9m^3 of water, 391 kg of raw materials, and caused a carbon footprint of about 270 kg (see Fig. 1).

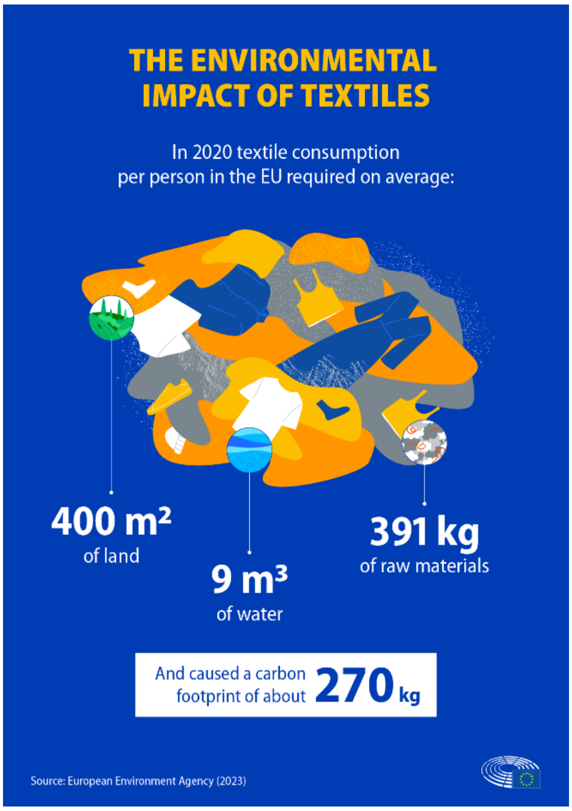

Fig. 1 – The environmental impact of textiles (*European Parliament Topic, 2020*).

Environmental impacts mean creating an imbalance in nature through loss of biodiversity and global warming. People will be forced to adapt to higher temperatures. Populations already living in very arid areas will be forced to leave their homes to migrate to cooler areas, which may create economic and political conflicts.

Getting here was more a domino effect of events over time. The catalyst factor was the accelerated development of the textile industry, which led to increased production of fibre, textile fabrics and fashion products. Global textile fibre production has almost doubled from 58 million tonnes in 2000 to 109 million tonnes in 2020 and is projected to grow to 145 million tonnes by 2030 (see Fig. 2). The export of textile and fashion production to developing countries led to the evolution of fast fashion, a linear business model characterized by fashionable products, small prices and low quality. The characteristics of fast fashion thus ensure a short product life. Clothing is quickly abandoned in favour of new trends promoted by social media, famous people and local culture (Andreadakis and Owusu-Wiredu, 2023).

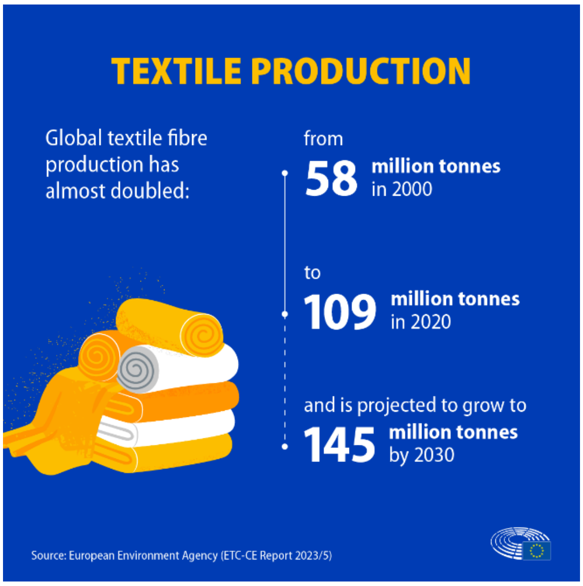

Fig. 2 – Textile production (*European Parliament Topic, 2020*).

The social and economic impact of the textile and fashion industry are other aspects caused by the production of disposable fashion through unsafe working conditions, exploitation and gender-based discrimination faced by workers in the industry. The economic attraction of fast fashion often leads to ignoring ethical considerations, while perpetuating a cycle of abuse and vulnerability among textile workers, predominantly women (Jyoti and Shefali 2024; Pătruț 2024).

In the context of sustainability researchers have addressed several aspects to improve and sustain this concept. Bottani *et al*. (2020) analysed costs and CO_2 emissions at different stages of the manufacturing process in a fashion industry supply chain in order to assess economic and environmental sustainability. Hong *et al*. (2024) investigated the factors influencing sustainable fashion consumption behaviour among adults, in particular the role of values, attitudes and norms in shaping such behaviour. Pătruț (2024) investigated the barriers hindering the transition to a more sustainable future in the fast fashion industry. Lee and Lee (2024) examined the impact of conscious consumption of sustainable fashion brands. Ki *et al*. (2020) analysed sustainable development through a circular economy and stakeholder engagement and pointed out that the fashion supply chain involves multiple stakeholders, both internal and external stakeholders.

High-cost pressures and competition make it difficult to change business practices, but the industry must take responsibility for its environmental impact (Niinimäki *et al*., 2020). Barriers that hinder the transition to a more sustainable future from the perspective of organizational dimensions can be financial barriers, insufficient management involvement, lack of government support and infrastructure, eco-friendly packaging, stakeholder and supplier barriers. The most mentioned driver dimension from an organizational perspective in Romania is the existence of a financial reward system for stakeholders, government and EU funding programs, implementation of mandatory regulations and the possibility to create an infrastructure (Pătruț, 2024).

Addressing global environmental challenges requires a systemic transformation embracing ethical production, the circular economy and increased consumer awareness. A sustainable and ethical fashion industry requires a collective effort. Governments need to enforce strict environmental regulations, industries need to adopt green technologies and ethical production methods, and consumption needs to be addressed at different levels, with active collaboration between designers, producers, stakeholders and consumers (Jyoti and Shefali 2024; Pătruț, 2024; Niinimäki *et al*., 2020). The European Waste Framework Directive requires all EU member states to set up separate collection systems for used textiles from 2025. According to the European Environment Agency (EEA), more than half of the member states have already introduced an obligation for the separate collection of textiles.

Action interventions aimed at promoting sustainable fashion consumption should focus on promoting values and beliefs that prioritize the environment, encouraging individuals to take responsibility for their actions, creating an environment in which sustainable fashion consumption is normalized and through which confidence in recycling is increased (Hong *et al*., 2024). This has the potential to stimulate manufacturers to implement eco-friendly production methods and comply with stricter regulations on post-consumer waste handling (Andreadakis and Owusu-Wiredu 2023).

Consumer habits, such as washing clothes at cooler temperatures, using and donating second-hand clothes, can contribute, in the context of an emerging economy, to reducing environmental impacts (Chen *et al*., 2021; Wu *et al*., 2023). In addition, efficient recycling, energy recovery and careful waste management can contribute substantially to pollution reduction and resource conservation (Rigamonti *et al*., 2010).

Investments in pollution control technologies are necessary yet costly, but reductions in chemical use, waste management and process efficiencies can reduce costs and provide economic stimulus for sustainability development. New business models, such as renting, leasing, upgrading, repair and resale, also promote longer product lifespan and slower lifestyle (Niinimäki *et al*., 2020).

2. Sustainability in textile and fashion industry

Sustainable fashion refers to the efforts taken by fashion brands to protect the environment by applying methods in the manufacturing process that minimize the impact on the industry currently created by excessive fast-fashion production and extend the lifespan of textile and clothing products. Key aspects related to sustainable fashion include textile materials, production process and product life cycle.

The cultivation and production of cotton textiles has a significant environmental impact due to the use of a large amount of water, energy, fertilizers and pesticides, whereas organic cotton can reduce this impact (Chen *et al*., 2021). Cotton is one of the most common textile fabrics, and cotton waste accounts for 24% of all textile waste. Recycling and reusing cotton waste are common practices to reduce overall waste production (Lu *et al*., 2023). The most common fabric type studied for recycling is unblended cotton (50%), followed by cotton/polyester blends (29%), although as a percentage of production polyester fibres rank first, followed by cotton and the other textile fibres (see Fig. 3).

Mechanical recycling was found to be the most studied recycling method (43%), while chemical and biochemical recycling accounted for 38% and 14% respectively. Open-loop recycling is currently the dominant form of textile waste recycling, with a major focus on the building and construction sector (34%) (Dissanayake and Weerasinghe, 2021). Awareness of environmental pollution resulting from textile production and disposal has increased significantly. This increase has pushed research activities towards more sustainable recycling alternatives for proper end-of-life management of textiles (Baloyi *et al*., 2023). For the textile industry to become sustainable, knowledge of the resource origin and production is necessary. Recycled raw materials are expected to form a significant part of the resources to be used in the future (Harmsen *et al*., 2021).

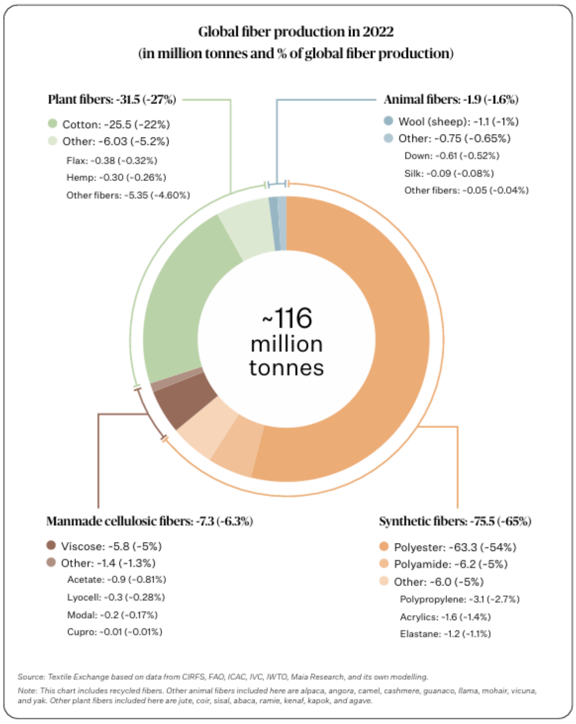

Fig. 3 – Global fibre production in 2022 - in million tonnes and % of global fibre production (*Textile Exchange, 2023*).

To reduce environmental impacts, researchers confirm the need for fundamental changes in the fashion business model, such as slowing down the production process, adopting sustainable practices to extend the lifespan of textile fabrics and garments (Niinimäki *et al*., 2020). Bottani *et al.* (2020) pointed out that the supply stage is the most costly and the production is the most polluting in the textile industry. Dyeing, for example, is a valuable process in production and polluting (Chien *et al*., 2024). Researchers recommend using the developed model to identify where companies can save money and reduce pollution, such as using more eco-friendly shipping (Bottani *et al*., 2020). Efficient production planning is essential to optimize resource management and increase the recycling rate of damaged fabrics to reduce waste and residual water.

Life cycle assessment is also essential for sustainable decision making in the textile industry by identifying areas that can be improved and minimizing environmental impacts throughout the product life cycle (Chen *et al*., 2021; Abagnato *et al*., 2024). The main variables affecting the assessment of life cycle impacts have been found to be productivity and demand for materials resulting from the recycling process, use-phase variables, assumptions on virgin production, replaced by reuse or recycling, substitution factor in reuse and shipment data in distribution-based business models (Abagnato *et al*., 2024). Aspects of environmental, economic and social sustainability need to be assessed throughout the product life cycle. It is important that the integration of complex decisions is realized in manufacturing as well as marketing companies to develop long-term sustainability (Daukantienė, 2023).

3. Chemical Recycling of Textile Fabrics

The textile and fashion industry has a significant impact on the environment due to high production as well as production practices that apply the use of toxic substances in the manufacture, treatment and dyeing of textile fabrics, which has led to the development of sustainable textile recycling processes (Damayanti *et al*., 2021; Furferi *et al*., 2022). Besides the harmful environmental impacts, the demand for textile waste recycling is also driven by the prospect of recovering landfilled textile resources (Dissanayake and Weerasinghe, 2021). Proper management of discarded textiles and their conversion into sub-products or inputs for production, has a great potential for energy and resource savings (Bartl, 2019; Furferi *et al*., 2022). The separate collection of textiles, followed by reuse and recycling, brings relevant environmental benefits, with the impact of recycling being higher than that of reuse. When mixed municipal solid waste is destined for energy recovery, the textile fraction has the second highest climate change impact, after plastics (Abagnato *et al*., 2024). Current recycling methods for textiles include mechanical, chemical recycling and biological recovery.

Baloyi *et al*. (2023) reviewed post-industrial textile waste recycling technologies, which tend to be uniform in terms of dyes and fibre types presented. The authors recommend chemical and biological options to recover waste into high-value products. Traditional fibber-to-fibber recycling often results in inferior recycling, whereby the quality of textile fibbers deteriorates. A suitable alternative is chemical recycling for low-quality textiles that cannot be resold or recycled in any other way (Sanchis-Sebastiá *et al*., 2021). Chemical recycling has great potential to keep fabrics in a closed loop, but only 1% of textile recycling uses this method at industrial level (Ribul *et al*., 2021; Sanchis-Sebastiá *et al*., 2021). Closed-loop recycling refers to the recycling of fabrics that can be carried out indefinitely without degradation of properties. Turning the used product back into raw material allows repeated manufacturing of the same type of product (Penn State, 2023).

Chemical recycling can be used to separate fibbers that are part of different types of fabrics. This type of process can be considered as one of the most efficient forms of recycling, given that a large proportion of fabrics is made up of fibber blends (Costa *et al*., 2022). There are two main types of chemical recycling: monomer recycling, which decomposes polymers into monomers to create virgin-quality fibbers, and polymer recycling, which retains the polymer but often results in lower-quality fibbers. Monomer recycling is currently used mainly for synthetic fibbers, such as ECONYL, made from disposed nylon, while polymer recycling involves chemical dissolution and has been applied to various fibbers, including cellulose and synthetics. Innovations such as the use of ionic liquids and sustainable catalysts improve these processes, making them more environmentally friendly (Ribul *et al*., 2021).

Sanchis-Sebastiá *et al*. (2021) investigated the use of acid hydrolysis to decompose cotton fibers from textile waste into glucose, which can be used to produce chemicals or fuels. A two-step process combining concentrated sulfuric acid and dilute sulfuric acid achieved a high glucose yield of over 90%, demonstrating that acid hydrolysis can efficiently recycle cellulose-based textile waste (Sanchis-Sebastiá *et al*., 2021). This method can also extract cellulose from mixed textile waste, with a percentage of recovered cellulose powder between 65 and 88%. In order to evaluate the feasibility of using the extracted cellulose as a raw material for the production of cellulose derivates, two strategies have been applied: etherification to obtain sodium carboxymethyl cellulose and esterification, to obtain cellulose acetate (Costa *et al*., 2022). Domestic post-consumer cotton waste is identified as the most suitable feedstock for Lyocell-type chemical recycling, although it may require pre-treatment to remove contaminants and adjust viscosity. Household textiles, washed at home, maintain a similar degree of polymerization as virgin textiles, with only a slight decrease (-15%). In contrast, service sector textiles, washed industrially, show a significant decrease in polymerization degree of up to 80% (Wedin *et al*., 2019).

Lu *et al.* (2023) summarized the characteristics of cotton waste and value-added products derived from cotton waste, e.g., yarns, composite reinforcements, regenerated cellulose fibers, cellulose nanocrystals, adsorbent fabrics, flexible electronic devices, and biofuels, by mechanical, chemical, and biological recycling methods (Lu *et al*., 2023). To visualize the fibber properties more easily, Harmsen *et al.* (2021) presented the classification of fibbers based on the chemical groups and bonds that form the backbone of the polymers from which they are made. In addition to this, they also devised a textile recycling classification based on the polymer structure of the fibbers, thus facilitating communication on recycling.

Damayanti *et al*. (2021) paper reviews the current recycling technologies, chemical and mechanical method, and discusses their challenges and limitations. Mechanical recycling can remelt textile waste into yarns, while chemical recycling decomposes textiles into monomers, with enzymatic hydrolysis showing high yields under mild conditions. Digital innovations, such as the Internet of Things (IoT) and RFID technology, improve sorting and identification of textile waste, increasing recycling efficiency (Damayanti *et al*., 2021). However, it was observed that the use of MR-CO in different proportions generally produced similar results to the usage properties obtained when using virgin cotton. Single jersey fabrics were produced using open-ended rotor yarns with two different yarn counts, from cotton blends obtained in three different proportions of mechanically recycled cotton blend. The fabrics were analysed in terms of pilling strength, tear strength, dimensional stability and resistance to perspiration, water and friction (Sari *et al*., 2024). Lu *et al.* (2023) propose new technologies and products for cotton waste recycling in their study, providing a guide and direction for traders and researchers. The analysis focuses on textile waste converting processes into value-added products. Proposed solutions are: bleaching treatment of coloured cotton waste, cellulose extraction process from cotton waste.

Chemical recycling by selective depolymerization of polyester (PET) into textiles can produce fabrics as good as those made from virgin resources. The process shows that fabric disintegration in order to increase surface area does not affect the reaction rate, due to the high accessibility of the yarn structure. The reaction mechanism for the hydrolysis of textile PET mirrors that of bulk polyester, taking place via end peeling, and results in a yield of almost 100% pure terephthalic acid (TPA). Mechanical pretreatment, such as shredding, is not necessary, as the apparent low density and textured yarns already provide a high accessible area for the reaction (Bengtsson *et al*., 2022).

Recent progress in recycling technologies include advanced sorting techniques, innovative chemical processing and emerging biochemical processes, and efforts are being made by companies to implement these technologies on a commercial scale. The recycling methods analysed include mechanical, chemical and biochemical recycling of standard fabrics used in confections, cotton, wool, polyester, polyamide 6 6 and acrylic (Baloyi *et al*., 2023).

4. Ergonomic Design in Women's Clothing

Ergonomics is the science of equipment design, workplace design, focused on the study of human adaptation and the reduction of fatigue and discomfort through product design (ElSayed *et al*., 2019). Ergonomics in clothing is a type of applied science that improves the overall function of clothing. It is based on the characteristics of human body shape and motor function and fully considers the harmony, comfort of the human body and clothing (Varnier and Merino, 2022). Ergonomics in apparel engineering and design brings together knowledge from apparel fabrics, textile science, human psychology, human anatomy, environmental hygiene, anthropometrics, fashion design, medical science and many other disciplines (Rafiu King *et al*., 2021).

Ergonomics applied to clothing design requires consideration of how the clothing fits the people who will wear it. When clothing fits the wearer, the result can be more comfort, higher productivity and less stress. The 5 most important dimensions that define ergonomic clothing are comfort, aesthetics, safety, ease of use and performance (ElSayed *et al*., 2019).

In the current production scenario, where the apparel industry is developing products at fast speed, it should, in fact, intensify the pursuit of performance excellence to meet the user's needs. Therefore, it is necessary to adopt a working mode that incorporates the use of ergonomics into production processes, after all, this is the science that improves the clothing function with harmony and comfort in mind (Varnier and Merino, 2022). Rafiu King *et al*. (2021) study aimed to emphasize the need for an organized knowledge framework for ergonomics suitable for education and research in engineering and fashion design. The application areas of ergonomics in engineering and fashion design were discussed under the headings of consumer product design, namely apparel design, workplace or office design, manufacturing process design, and human-machine system.

Singh and Kapoor (2024) propose a framework for analysing and evaluating the ergonomic design and sustainable fabrics integration in the fashion product manufacturing. The framework consists of three components: ergonomic design, selection of sustainable fabrics and environmental impact assessment of the manufacturing process. Wanderlayne *et al*. (2023) analysed the methods and techniques used in the ergonomic assessment of garments - which cover the upper body - with a consumer-centred approach. The study led by Zhao and Wang (2022) involved yoga clothing development and performance evaluation, and proposes an ergonomic design process for functional clothing design. The study conducted by ElSayed *et al*. (2019) involved the development of a fashion design collection using ergonomic aspects to fit professional women educators. Application of ergonomic aspects in 9 products made of bio-polished cotton fabric, a sustainable textile surface finishing treatment. Bio-polishing of cotton fabrics is applied for fashion products to improve the fabric quality by decreasing the tendency of pilling and fuzziness in (cellulosic) fabrics (ElSayed *et al*., 2019). A comprehensive approach to ergonomic design and fabric sustainability can lead to improved working conditions for employees, reduced environmental impacts and improved product quality in the apparel manufacturing industry (Singh and Kapoor, 2024).

Ergonomic properties can be identified and assessed through the gathering of anthropometric data, wear experience, trial tests, function analysis and fit tests that can be customized and further developed according to the target audience and context of use of each ergonomic analysis of the garment. The consumer's perspective becomes relevant for designing effective and comfortable fashion products (Wanderlayne *et al*., 2023).

5. Consumer awareness of sustainable fashion

Social norms and recycling beliefs positively influence intentions to sustainable fashion consumption (Hong *et al*., 2024). The more people feel a stronger connection to sustainable fashion brands, the more they talk about them, especially if they care about social issues. People who follow fashion trends use sustainable fashion brands to express themselves and talk more about them (Lee and Lee, 2024). Attitudes toward sustainable consumption, awareness of environmental issues, attribution of responsibility, sense of community, and perceived hedonic benefit significantly influence people's intentions and practices of donating second-hand clothes in a positive way (Wu *et al*., 2023).

Social influence has the most significant impact on consumer purchase intentions for sustainable fashion, followed by environmental concerns and altruism (Farzin and Shababi, 2023). Attitude, consumer motivation, quality perception towards sustainable clothing and brand also influences purchase intentions, but accessible information is needed. On the other hand, the intention-behaviour relationship is negatively influenced when consumers question product environmental declarations and concerns about the attractiveness or up-to-date character of sustainable clothing - perceived aesthetic risk. Perceived economic risk does not significantly influence this relationship (Hamati *et al*., 2024). Indonesian consumers are already leaning towards sustainability, providing an opportunity for fast-fashion brands to capitalize on this trend, despite limitations in scope and variables studied (Wijaya and Lidia Paramita, 2021).

In terms of awareness, women tend to perceive themselves as more aware of sustainability in fashion compared to men. There is also a gap between positive attitudes towards sustainable fashion and actual purchasing behaviour. This gap underlines the need for greater consumer awareness and education to overcome these discrepancies. Educating consumers through effective marketing strategies beyond product promotion could increase their engagement in sustainable fashion choices (Mandaric *et al*., 2021).

Institutional regulations and market trends are driving companies to invest in sustainable and eco-friendly products. Canio's (2023) study presents practical solutions for manufacturers: increasing the re-use of recycled fabrics, targeting different consumer segments with adapted communication strategies and promoting sustainably packaged products made from zero plastics and biodegradable plant-based materials (Canio, 2023).

6. Conclusions

The latest research on chemical recycling of fabrics highlights the increasing accessibility and flexibility of this method, due to the fact that a wide variety of fibbers can be recycled. Chemical recycling has a great potential to keep fabrics in a closed loop and can be used to separate fibbers that are part of different types of textile fabrics, a very important criteria considering that a large part of fabrics is made from fibber blends. Cellulose extraction from mixed textile waste achieves a percentage of recovered cellulose of up to 88%. Chemical recycling can also produce fabrics as good as those made from virgin resources.

The latest progress in technology includes advanced sorting techniques, chemical processing and emerging biochemical processes. But it is also necessary to engage manufacturing companies in the industry to implement sustainable methods in their production process and embrace a circular economy. Most companies fear that implementing a sustainable operating system will decrease their profits and are not economically prepared for major changes in the manufacturing workflow.

Consumers, on the other hand, are very open to sustainable fashion if they are correctly informed about the environmental claims of products. Environmental issues awareness, responsibility attribution, sense of community and perceived hedonic benefit significantly and positively influence consumer perception. The synergy between ergonomics and sustainability is also very important. Ergonomics addresses the consumer's needs for aesthetics, comfort, safety, functionality and ease of use together with the sustainability property, to protect both the environment and the consumer.

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ÎMBRĂCĂMINTE ERGONOMICĂ DURABILĂ PENTRU FEMEI PRIN INTEGRAREA RECICLĂRII CHIMICE A MATERIALELOR TEXTILE

(Rezumat)

Industria textilă este a doua cea mai poluantă industrie la nivel mondial, cu un impact considerabil asupra mediului, datorită emisiilor de gaze cu efect de seră, utilizării unei cantități mari de apă și energie, poluării chimice, și implicit prin formarea unei cantități imense de deșeuri textile. Acest aspect a condus la crearea unui dezechilibru în natură prin pierderea biodiversității și a încălzirii globale. Această analiză își propune formarea unei imagini de ansamblu a impactului industriei textile și de modă asupra mediului înconjurător, social și economic, promovarea modei sustenabile și ergonomice. De asemenea, lucrarea are ca scop prezentarea punctuală a metodelor de reciclare chimică a textilelor, utilizate în ultimii ani, pentru a combate impactul asupra mediului prin transformarea unui produs uzat din nou în materie primă.