POLITECNICO DI MILANO

School of Industrial and Information Engineering
Master of Science in Management Engineering

POLITECNICO
MILANO 1863

Clean production processes for the textile industry

Supervisor: Prof. Alessandro Brun
Assistants:
Federica Celeste
Gianluca Tedaldi

Thesis Author:
Jean-Valère Malleval
ID: 986063
Academic Year 2022/2023

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Abstract

This last decade has been marked by a profound questioning of our ways of consuming in the wake of concerning environmental challenges. Industries around the globe are pursuing a transformative shift towards more responsible production processes. The textile industry and especially the fashion industry is under scrutiny as one of the most polluting industries in the world. Water consumption, wastewater treatment, greenhouse gas emissions and waste management are some of the most pressing issues of the textile industry. Faced with raising concerns and stricter regulations, textile companies must change their production processes. This report sheds light on state-of-the-art cleaner production processes for the textile industry, focusing on four key levers of change: wastewater treatment, water management, natural dyeing, and waste management. By summarizing extant knowledge and compiling cleaner processes for textile production, this report can be of great value to the academic community, as well as managers operating in the sector of textile production for fashion.

Keywords: Textile, production process, sustainability

1. Introduction

1.1 Overview of the textile industry

1.1.1 History of the textile industry

Textile industry is one of the oldest industries in the world. Early trace of weaving dates back to the Paleolithic and textiles older than 5000 BC were found during excavations. During the Roman times, clothing was made of wool and leather, and silk was imported from China through the renowned Silk Road. The industrial revolutions in the 18th and 19th centuries contributed to the expansion and considerable development of the textile industry. Textiles were not anymore produced by hand, but the production was mechanized. This led to the exponential increase of production rates and the development of massive textile factories. Nowadays, the textile industry is a globalized business with a complex supply chain that includes raw material farming, textile manufacturing, garment production and commercialization. The development of an affordable fashion and intense consumption habits led to the concept of "fast fashion", which raises concerns in terms of sustainability from different perspectives: resources consumption, waste management and human rights to name a few.

1.1.2 Market size and important players

Large multinational businesses coexist with numerous small and medium-sized firms (SMEs) in the highly fragmented textile industry. Companies like Inditex (owner of Zara), H&M, Fast Retailing (owner of Uniqlo), and Gap Inc. are some of the major players in the market. To meet the demand for textile products around the world, these businesses have a presence all over the world and run enormous supply chains. We are in this report not considering the luxury segment of the textile industry, because it allows for a smaller production.

The worldwide apparel market revenue was estimated at over 1.53 trillion US dollars in 2022 (Statista). However, the market is anticipated to keep expanding and the anticipated revenue for 2023 mounts up to 1.7 trillion US dollars. In terms of global players, China keeps leading the ranking of the apparel exports. In terms of imports, the EU is the main actor followed by the US.

1.1.3 Opportunities and challenges

The textile sector has recently placed a greater emphasis on sustainability. Many businesses now use eco-friendly procedures in response to environmental concerns about waste management, chemical use, and water and energy consumption. This involves utilizing organic or recycled fabrics, employing water-saving dyeing procedures, and setting up ethical waste management systems. Additionally, as customers demand greater transparency and ethical sourcing in the textiles they buy, more certifications and labels that attest to sustainable practices are appearing. Fast fashion remains a great source of concern in terms of sustainability and some even call for stricter regulation of fast fashion companies. Upcycling and thrifting are also an emerging trend, especially among the younger generation. While luxury brands are already taking it into consideration, it seems more difficult for the global apparel industry to adapt to such new consumption mentalities.

Digital revolution is also occurring in the textile sector. Automation, robotics, artificial intelligence, and data analytics are just a few of the technological innovations that are being incorporated in all the industries in the world. In order to increase productivity and lower labor costs, automation and robotics are being employed in the textile manufacturing industry. For supply chain optimization, tailored marketing, and demand forecasting, artificial intelligence and data analytics are used. Moreover, online shopping has changed the retail industry and has led to new business models through e-commerce.

The textile sector has many prospects, but it also has many difficulties. Pressure from pricing and competitive rivalry is one of the biggest obstacles. Indeed, due to intense competition between manufacturers and retailers as a result of industry globalization, prices have fallen, and profit margins have shrunk. The textile industry is a well-established industry but now has to face sustainability challenges.

1.2 The importance of clean production processes

Due to its use of natural resources, energy use, chemical use, and waste production, the textile industry is one of the most polluting sectors. There has been a growing awareness of the need for sustainable and clean production methods in recent years. "Clean production" refers to practices and processes that reduce the environmental (and social) impact of a production by optimizing resource efficiency, waste management and the use of hazardous products.

The first line of improvement is the environmental impact reduction of the textile industry. It is well known that the textile business has a large environmental impact, with consequences like air and water pollution, deforestation, and greenhouse gas emissions. The industry can lessen its negative environmental impact by implementing effective resource management, cutting energy use, and utilizing cleaner products, processes and technologies.

The second aspect is the resource conservation. The garment industry depends heavily on natural resources like raw materials, water and through electricity for the production. Clean production aims at addressing resource consumption during the production process. Water saving technologies and energy efficient equipment are some examples of clean production improvements.

Another major concern of the textile industry is the use of chemicals that have negative impacts on both the environment and human health. Chemical management aims at reducing the use of hazardous chemical products in the textile production process or substituting them with greener alternatives. The handling of chemical substances and its disposal is greatly linked with the wastewater management.

Wastewater management is also a main axis of improvement for the industry. Indeed, during the different phases of production like dyeing, finishing, washing, large amount of water is used. This water needs to be properly treated and disposed of for safety and environmental reasons. Wastewater management aims at reducing and recycling wastewater during the production process, while selecting the cleaner technologies and processes for water treatment.

Waste reduction and recycling is part of the clean production goals. During the production of textiles, a significant quantity of waste is produced, including scraps, offcuts, and end-of-life items. Clean production practices include waste reduction and management techniques such maximizing material utilization, recycling, and efficient waste disposal. Based on circular economy theory, these practices aim at saving resources and reducing the amount of textile waste transported to landfill or burned.

Sustainable growth of the textile industry depends on clean production methods. Textile firms may help create a cleaner, more sustainable industry by limiting their negative effects on the environment, saving resources (water, energy, raw materials), handling chemicals responsibly and minimizing waste. In addition to supporting global environmental goals, adopting clean production improves brand reputation, satisfies consumer demand, and reduces regulatory concerns. Adopting clean production practices is essential for long-term profitability and resilience of the textile industry with regard to the environmental issues that our society is and will have to face in the next decade.

1.3 Considerations on the production of a textile garment

The conception of a textile garment has several phases, each on helping to create the finished result. In order to better understand the areas of improvement it is necessary to know the main phases of the production of a textile piece of clothing.

Here is a short description of the major steps in the textile production for fashion:

- Design and conceptualization

The process begins with the design phase. To picture the look and structure of the garment, sketches, technical drawings, and even digital prototypes are created.

- Patternmaking

Pattern makers provide paper or digital patterns when the design is complete to use as templates while cutting. Each piece of clothing is shaped and measured according to these patterns.

- Fabric selection and sourcing

Based on elements including the intended function, season, and design of the garment, suitable fabrics are selected. The process of sourcing fabric entails choosing vendors and buying the appropriate materials in the requisite amounts.

- Fabric inspection and preparation

The purchased fabric is examined for flaws, uniformity of color, and quality. Following examination, the cloth is washed, preshrinked, and given finishing touches like dying or printing.

- Cutting

The fabric is prepped, the pattern pieces are set down on it, and the fabric is then cut out in accordance with the lines of the patterns.

- Sewing

Using a variety of sewing methods and equipment, the fabric pieces are stitched together. This process involves assembling the garment's components, such as attaching sleeves, collars, and pockets, and joining seams.

- Fitting and quality control

The finished item is fitted on a dress form or a live model following the sewing process. To get the correct fit and appearance, adjustments are done. To find any flaws or irregularities in the construction, fabric, or stitching, quality control inspections are carried out.

- Trimming and embellishment

To improve the appearance of the garment, any additional decorations, buttons, zippers, appliqués, or decorative features are applied at this stage.

- Pressing and finishing

To remove wrinkles and give the garment a polished appearance, it is thoroughly pressed with steam irons or pressing equipment. Also finished are the finishing touches, such as tying up any loose threads.

- Labeling and packaging

Size, brand, and care labels are sewed onto the garment or fastened with tape. After that, the garment is boxed, folded, and ready for distribution or retail.

- Distribution and retail

Direct sales or wholesalers are used to deliver the finished products to retailers. Customers can purchase them from displays in stores or online marketplaces.

- Consumer use and maintenance

Customers wear and use the clothing after purchasing it. Maintaining the garment's quality and longevity involves following care recommendations, which include washing, drying, and ironing requirements.

This procedure is an overall breakdown of how clothes are made. Variations in these phases may occur depending on the complexity of the garment and the particular production techniques employed. Clean production aims at reducing the waste, energy consumption and pollution emitted for each of the production phase by implementing cleaner processes.

2. Methodology

2.1 Keywords and papers selection

I started looking for information on the topic to grasp the main challenges and areas of interest. By doing this in a disorganized way, I started gathering some articles retrieved directly from a Google search. This first step enabled me to learn more about the topic, however I realized I had to organize my research in a more structured way. This led me to use the Scopus database to retrieve papers. The database contains a comprehensive collection of scholarly publications such as journal articles, conference papers, and books. The Scopus search will look for articles that meet the specified keyword requirements.

The first step was to select pertinent keywords that adequately describe the range of the articles I was looking for. This was the first time I was conducting a methodic search and I first started looking for article by just typing one or two keywords like “Fashion industry” or “Production process”. After trying different sets of keywords, I realized I had to be more precise because the number of references was always over 500. To focus the search on publications about the textile industry, the keywords "Textile" and "Industry" were used. To draw attention to publications about clean production practices in the textile sector, the phrases "clean" and "production" have also been added.

In the end the following string was used to retrieve most of the articles: “Textile industry” AND “Clean” AND “Production”. This led to 155 references on the database. Then some filters were applied as a lot of the articles coming through were not relevant to my topic and the scope of the search was still too broad. The articles were filtered by year, excluding all the articles published prior to 2013. I chose to apply this filter to ensure that the evidence brought by the papers was timely. Only the publications in English were selected. I also filtered the references by subject areas: among the areas available, the references were limited to the following ones:

- Engineering
- Environmental Science
- Material Science
- Chemical Engineering
- Chemistry

I also excluded Book chapters because I was not able to consult them. The only source type was Journal. I filtered the papers also by keyword with the only constraint that they should include “Textile industry” in the indexed keywords.

This set of keywords and filters allowed me to compile 49 papers. Out of those papers, not all of them were useful for this work, and some papers were specifically searched out of this methodic search to retrieve specific information about a topic. For instance, some papers were directly searched for in the Journal of Cleaner Production. In the end, mainly 38 papers were used.

2.2 Statistics of the selected papers

2.2.1 Type of papers

- Research articles: these are original research studies that investigate a particular aspect of the topic. For example, “A sustainable three-layer circular economic model with controllable waste, emission, and wastewater from the textile and fashion industry” from Peter John et al. (2023).
- Reviews: review articles provide an overview of existing research and developments in a specific field. For instance, “An overview of cotton and polyester, and their blended waste textile valorization to value-added products: A circular economy approach – research trends, opportunities and challenges” by Subramanian et al. (2021).
- Case studies: case studies analyze real-world scenarios or examples. For example, “A case study of the wastewater treatment system modification in denim textile industry” from Zhanga et al. (2021).
- Conference papers: shorter written presentation of the research pursued for a subject, meant for oral presentation. For instance, “Textile sustainability: reuse of clean waste from the textile and apparel industry” by Broega et al. (2017)

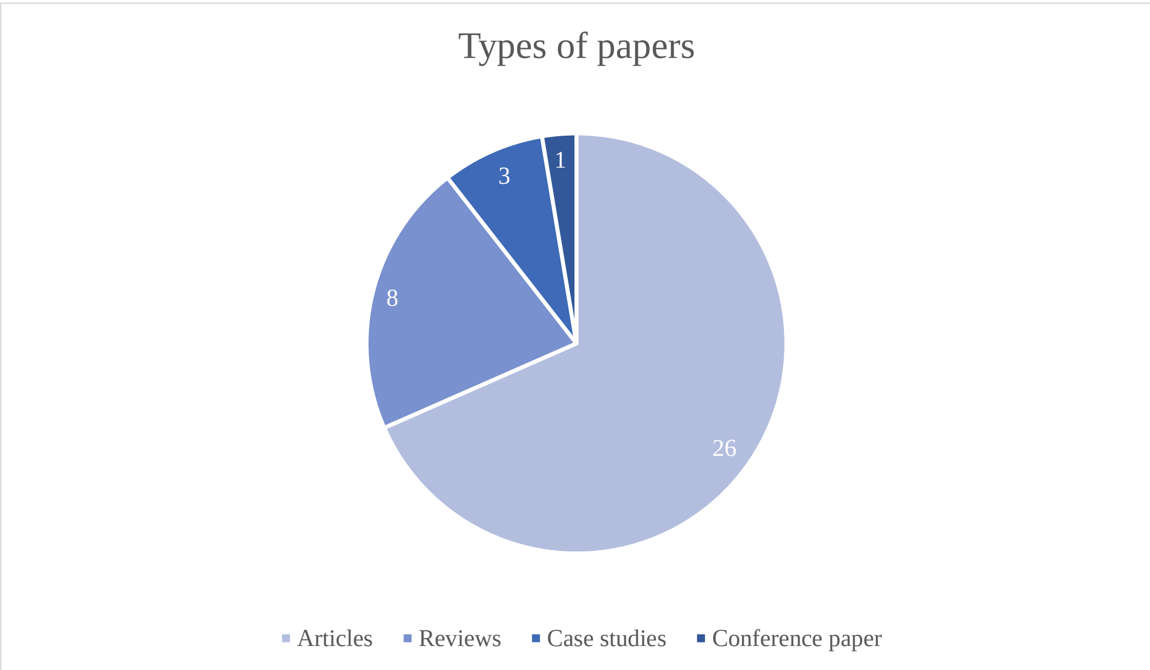

Figure 1: Repartition of the types of papers

2.2.2. Sources

The researched papers come from scientific publications such as journals. Almost half of the papers were published by Journal of Cleaner Production. Indeed, the very early step of my research began by searching papers directly in this publication, before the research as extended with Scopus. This journal focuses on cleaner production, environmental and sustainability research, and practices. The database of the journal encompasses more than 3200 references about textile industry.

The other half of the papers come from publications specialized in various subjects: from chemistry applied to industry to design, fashion and textiles in general.

2.2.3 Classification of the papers

I proceeded by sorting out the selected papers based on the subjects treated. Based on a first reading of the papers, some common research themes began to stand out. The textile industry being one of the most water consuming one, a lot of papers treated in some way the question of water consumption. Similarly, chemical management was discussed a large part of the papers. While discussing water management and chemical management, I understood that the dyeing process in particular was critical for both of these questions. Waste reduction and recycling constituted another part of the spectrum studied in the papers. I chose to specifically mark the papers mentioning Circular Economy as it goes beyond waste disposal and calls for a global shift of the product life-cycle approach. Energy management, at the time, seemed relevant enough to me to mark the papers mentioning it. After deeper studying the selected resources, it seemed minor compared to water, chemical or waste issues.

Autors	Year	Water consumption	Chemical management	Dyeing	Energy management	Waste reduction/recycling	Circular economy
Zhanga et al.	2021		X				
Sun et al.	2023	X	X	X			
Behera et al.	2021	X	X	X			
Peter John et al.	2023	X	X		X	X	X
Subramanian et al.	2021					X	X
Haji et al.	2020		X	X		X	
de Oliveira Neto et al.	2019						
Han et al.	2022						
Sarwar et al.	2021	X			X		
Vanacker et al.	2022						
Sharma et al.	2023		X	X			
Sandin et al.	2018					X	
Pasricha et al.	2018					X	
McQuillan	2019					X	
Nieto Zapataa et al.	2021		X				
Ozturk et al.	2020				X		
Oladoye et al.	2022		X	X			
Shamsuzzaman et al.	2023			X			
Ozturk et al.	2016	X	X		X		
Mu et al.	2023					X	
Eid et al.	2021		X				
Jin et al.	2022					X	X
Battesini Teixeira et al.	2023					X	X
Sharma et al.	2019		X	X		X	
Szajczyk et al.	2023	X	X				
Alkaya et al.	2014	X	X		X		
Teo et al.	2022		X	X			
Chang et al.	2023		X			X	X
Araque-González et al.	2022			X			
Uddin et al.	2022		X	X			
Broega et al.	2017					X	X
Jia et al.	2020						X
James et al.	2016					X	
Yang et al.	2023		X	X			
Hassan et al.	2023			X	X		
Wahab et al.	2022	X	X	X			
Allafi et al.	2022	X					
Haque et al.	2023	X	X	X	X		

Table 1: Papers classification

3. Wastewater treatment

In the modern world, the problem of wastewater produced by the textile sector represents a huge environmental burden. Unquestionably, this vast international business, which is in charge of making textiles, apparel, and other products based on textiles, has significantly influenced both economies and civilizations. However, because of its extensive effects on ecosystems, human health, and sustainability, its influence on the environment has aroused concerns, notably in terms of wastewater output and pollution.

The creation of textiles is a multi-stage process that encompasses a complex network of operations, from fiber farming and processing to dyeing, printing, and finishing. Unfortunately, the water used in these procedures becomes significantly contaminated with a variety of chemicals, dyes, detergents, heavy metals, and other pollutants because of the large amounts of water that are required for each of these operations. The unregulated discharge of this contaminated effluent into rivers, lakes, and seas frequently has detrimental effects on aquatic life, soil quality, and even groundwater sources. The following figure, from Eid et al. (2021) describes the standard wet processing steps for cellulose based fabrics:

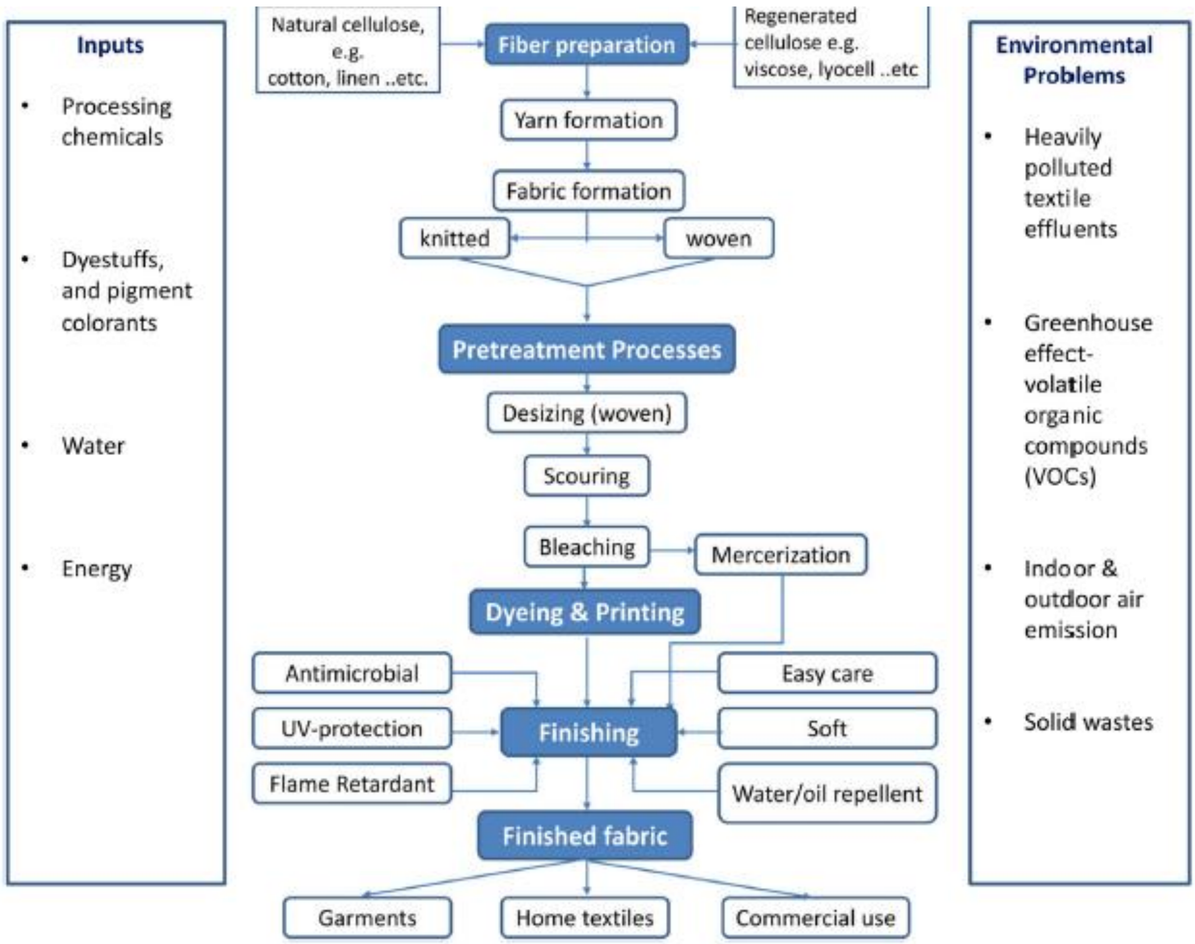

Figure 2 : Sequence of cellulose based textiles wet-processing chain, Eid et al. (2021)

Particularly, the dyeing and finishing processes have a big impact on the wastewater issue. Chemicals that are non-biodegradable and can linger in the environment for years are present in the wide variety of synthetic dyes used in the textile industry. These dyes disturb aquatic ecosystems and lower oxygen levels, which are necessary for marine life. They also change the color of the water when they enter water bodies. Aquatic species and people who depend on these habitats for food may be at danger of health problems as a result of the toxins found in wastewater that can build up in the food chain.

One of the points of attention is the treatment of the wastewater that come out of the dyeing and finishing phases of the production of textile. Different techniques have been developed over the years in order to purify the water. This purification requires removing the chemicals and physical waste contained in the water. Among the chemicals, the dye is often the most difficult element to extract and requires special attention because of the toxicity of the formulas employed in the industry. Dye removal techniques revolves around different processes. The separation can be physical, chemical, or biological. In the following section, the main processes of each of these three different approaches are described.

3.1 Physical methods

3.1.1 Adsorption

Adsorption is one of the physical methods used in order to separate the dye from the wastewater. This method is well developed in the textile industry because of its simplicity and lower costs compared to other processes. the dye molecules fixate onto the adsorbent surface under the influence of van der Waals forces and hydrogen bonding (Cooney,1998). The absorption process depends on various factors including nature of the dye, of the absorbent, the surface area, the size of the particles, the contact time, and some physiochemical parameters like pH, temperature, and pressure (Behera et al. 2021). The Absorption process can be schematized in 3 main steps (Teo et al. 2022):

(i) transport of dye molecules from an aqueous solution to the adsorbent's surface.
(ii) adsorption of the dye molecules onto the sorbent surface.
(iii) transport within the sorbent particle.

3.1.1.1 Carbon based adsorption

Activated carbon (AC) can be used as a source for the adsorption process thanks to its physical and chemical properties. In fact, AC shows a low volume pore structure that increases the surface area for maximum adsorption contact, as well as a simplicity of design and a high reusability (Teo et al. 2022) even though the effectiveness of the process is reduced over time when recycling the same AC (Behera et al. 2021).

The AC can be produced from various high carbon sources like wood, coal, or lignite. However, the production of AC from coal is costly and has led to the exploration of cost-effective production material. Powdered activated carbon (PAC) was for instance produced from rubber sees and rubber seed shells for the removal of methylene blue dye (Teo et al. 2022). However, the authors point out that one issue of the PAC is the production of subsidiary pollution due to the difficulty of separation of the PAC from the medium and dust pollution. To hinder this issues, granular AC (GAC) was developed. However, one issue of GAC is the use of binders during the synthesis process that can reduced the adsorption capacity because the pores can be blocked.

Regeneration is a crucial component in the development of AC since it helps in restoring the adsorption capability of the AC for additional reuse and lowers the cost of the technology. One of the traditional regeneration technologies is the thermal method, which involves heating the absorbent to remove the contaminants and thus allowing the carbon to be used for multiple cycles. However, this technique is time consuming and consumes a lot of energy. Additionally, Behera et al. 2021 point out that on average 40% of the carbon material is lost during the process, making the regeneration partially effective. An alternative technology is magnetic separation using magnetic adsorbent. It shows a enhanced reusability of the adsorbent thanks to the magnetic properties.

In summary, AC technology shows some interesting assets for dye separation and removal.

- High adsorption capacity: because of its porous nature, activated carbon has a remarkable adsorption capacity. It can efficiently remove a variety of organic contaminants and colors contained in textile effluent by adsorbing them.

- Versatility: wastewater from several textile production phases, such as dyeing, printing, and finishing, can be treated using activated carbon technology. It is a flexible solution since it can remove several dye types, including reactive, direct, acidic, and basic dyes (Behera et al. 2021).

- Regeneration and reuse: activated carbon may frequently be renewed and used again, lowering operational expenses and trash production.

- Decolorization: activated carbon efficiently removes color from wastewater, significantly enhancing the treated water's visual appeal and meeting discharge standards and environmental regulations. (Teo et al. 2022)

- Reduced environmental impact: activated carbon technology frequently generates less sludge and residue than some alternative treatment techniques, such as chemical precipitation or coagulation (see next sections). As a result, the environmental impact of trash disposal may be reduced.

However, the AC technologies also feature a set of drawbacks that must be taken into consideration:

- Dye specificity: while activated carbon is effective against many dyes, its adsorption capacity for some dyes is restricted. These dyes may be complex or extremely soluble. This may necessitate further treatment stages and result in an incomplete removal.

- The degradation of activated carbon particles into smaller fines over time might result in problems including clogging and fouling of treatment equipment. This may result in lower treatment efficiency overall and more frequent maintenance needs.

- Management of spent carbon: to avoid the reabsorption of contaminants into the environment, spent activated carbon must be properly disposed of or regenerated, which may lead to energy consuming additional processes (Behera et al. 2021).

3.1.1.2 Metal-composite based adsorption

Metal-composite adsorbents are materials that incorporate metal nanoparticles or ions into a composite matrix. They present several interesting characteristics (Teo et al. 2022):

- Enhanced adsorption capacity: when compared to conventional adsorbents like AC, metal-composite absorbents have much higher adsorption capacity. The availability of active sites for dye adsorption is increased when metal nanoparticles or ions are present, resulting in more effective removal.

- Selective adsorption: metal-composite absorbents can display selectivity towards particular dye molecules, depending on the type of metal utilized. This can be useful in situations when certain dyes need to be removed with precision.

- Rapid adsorption kinetics: by using metal nanoparticles, the adsorption kinetics can be accelerated, enabling quicker dye removal. Shorter contact times and possibly fewer treatment units may result from this.

- Regeneration and reusability: metal-composite absorbents may occasionally be regenerated and used repeatedly resulting in long-term cost reductions and a decrease in waste production.

- Potential synergies: when the properties of the metal nanoparticles and the composite matrix are combined, metal-composite absorbents can occasionally show synergistic benefits. This may result in enhanced adsorption capacity and selectivity overall performance.

However, they also display some negative sides that have been pointed out in the literature:

- Complexity of synthesis: when using metal nanoparticles, the manufacture of metal-composite absorbents can be more difficult than that of conventional adsorbents. This complexity may result in increased production costs and scalability issues.

- Metal leaching: the composite material runs the danger of introducing metal into the wastewater that has been treated. Metal ions released into the water can be hazardous to the environment and human health, particularly if the metal is poisonous or difficult to degrade.

- Limitations of selectivity: selectivity has both advantages and disadvantages. Metal-composite absorbents could not be efficient for a variety of dyes, which limits their usefulness in situations when several different types of dyes need to be removed.

- Long-term stability: metal composite absorbents' long-term stability can be a source of worry. The performance and uniformity of the absorbent may be impacted by the accumulation or degradation of metal nanoparticles as well as potential deterioration of the composite matrix.

- Complex waste management: due to the probable presence of metal impurities, the disposal or treatment of used metal-composite absorbents might be difficult. To stop environmental pollution, sound waste management procedures must be used.

- Cost considerations: higher costs, including material and production costs, may result from the integration of metal nanoparticles and the complexity of composite synthesis.

3.1.1.3 Gel-based adsorption.

Gel-based adsorbents are materials that have a three-dimensional network structure capable of absorbing and retaining large amounts of water and other liquids (Teo et al. 2022). They also display interesting properties:

- High adsorption capacity: gel-based adsorbents are capable of absorbing large amounts of dissolved compounds, including colors, as well as water. They are therefore successful at getting colours out of wastewater from textiles.

- Application ease: gel-based adsorbents can be utilized in a variety of forms, including granules, sheets, and hydrogels, and are frequently simple to apply. They don't require major changes to be implemented into the current wastewater treatment procedures.

- Rapid adsorption: a lot of gel-based absorbents have a rapid absorption kinetics, which allows them to swiftly absorb and immobilize wastewater colors. Shorter interaction times and possibly more effective treatment procedures can result from this.

- Reduced sludge generation: gel-based absorbents often do not produce significant volumes of sludge, unlike other classic adsorbents or coagulants. This can lessen the total environmental impact of the trash disposal process.

Again, this technology presents some flaws that must be considered:

- Limited reusability: after adsorbing dyes, gel-based adsorbents are frequently difficult to regenerate or reuse. Increased expenditures for waste production and material replacement may result from this.

- Concerns about disposal: to avoid the possibility of contaminating the environment, it is important to appropriately handle and dispose of used gel-based adsorbents that contain colors that have been adsorbed. Disposal may be complicated by some colors that are challenging to get out of the gel structure.

- Limited adsorption capacity for some dyes: depending on the kind and concentration of the dye, gel-based absorbents' adsorption capacities can change. Due to restrictions in the gel's affinity for particular molecules, some colors may not be properly removed.

- Gel-based adsorbents can change the physical and chemical characteristics of the treated water when they are added to the wastewater treatment process. To comply with regulatory requirements, this can call for further treatment procedures.

- Production and cost: compared to alternative treatment options, the production of gel-based adsorbents can involve sophisticated processes that could result in higher production costs.

3.1.2 Coagulation flocculation process

Coagulation-flocculation process (CF) revolves around the treatment of colloidal particles. Those particles, because of their inner properties, repel each other and have a sedimentation speed close to zero. To counter this effect, coagulation-flocculation process has been used (Behera et al. 2021).

Coagulation: a coagulant (usually a metallic salt like iron, ferrous sulfate, or ferrous chloride) is added to the wastewater. The coagulant's property (opposite charge) neutralizes the repulsive charge of the particles and allows the particles to meet, thanks to Van der Waals forces.

Flocculation: another issue of the colloidal particles is their very low mass, making sedimentation difficult. To counterbalance this, a flocculant is added to the wastewater to further agglomerate the particles and allow sedimentation.

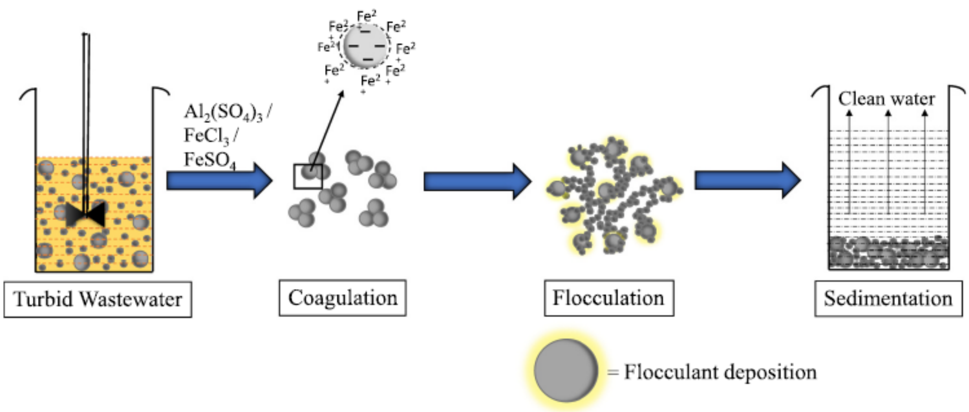

Figure 3 : Typical coagulation-flocculation process, Behera et al. (2021)

In their review, Behera et al. discuss the positive but also the negative aspects of this physical process for dye removal. The main positive aspects are the following:

- Effective for a wide range of colors: the coagulation-flocculation method is capable of removing both soluble and insoluble colors from textile effluent.

- Reduced color and turbidity: coagulation and flocculation can dramatically reduce the color and turbidity of treated wastewater, enhancing its aesthetic appeal and ensuring that it complies with regulatory requirements.

- Infrastructure compatibility: coagulation-flocculation systems can frequently be integrated into pre-existing wastewater treatment systems without requiring significant changes.

However, there are some major drawbacks to this method, especially from a clean production perspective:

- Chemical costs: using coagulants and flocculants increases treatment process chemical costs. To balance effectiveness and cost, attention must be taken in the selection and dosage of these compounds.

- Management of sludge: coagulation-flocculation creates high volume sludge that needs to be handled, treated, and disposed of properly.

- Residual chemicals: the treated water may still include trace amounts of coagulants and flocculants. This may affect how well the water is released and necessitate additional chemical removal processes.

- Coagulant recovering: the colored coagulant produced by the process is not easy to dispose of and it is difficult to retrieve the synthetic chemical for further recycling.

3.1.3 Membrane technologies

Membrane filtration technologies have been vastly documented in the literature. They split into 4 main processes: Microfiltration (MF), Nanofiltration (NF), Ultrafiltration (UF) and Reverse osmosis (RO). This different type of membrane can be used for different stages of production and of water treatment. While MF and UF are more likely used as pre-treatment of the wastewater, NF and RO are meant for the end of the chain cleansing, detecting small and light weighted particles (Behera et al. 2021)

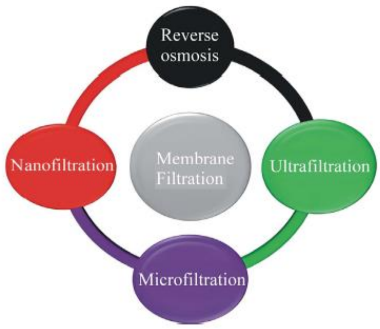

Figure 4 : Membrane filtration processes

Membrane technologies' positive aspects are also described :

- High removal efficiency: membrane filtration effectively removes pollutants like dyes. Small particles and molecules can be successfully separated by the semi-permeable membrane, producing treated effluent of excellent quality. For instance, Yang et al. (2023) present a membrane technology specifically designed for the Congo Red dye removal with a separation efficiency of 99.93%.

- Compact design: membrane filtering systems frequently have a small footprint and are modular, so they may be used in a range of treatment plant sizes. They take up less physical space than certain other forms of treatment.

- Performance consistency: over time, membrane systems with proper maintenance can deliver performance that is constant and dependable. This predictability is useful for completing legal requirements and accomplishing objectives for water quality.

- Flexibility: membrane filtration has a wide range of applications in wastewater treatment, including pre-treatment, primary treatment, and polishing. It is capable to efficiently removing dyes in a range of wastewater conditions and concentrations.

- Low chemical requirements: membrane filtering frequently uses fewer chemicals than procedures like flocculation or coagulation. This may lead to lower chemical costs and a smaller impact on the environment.

- Reduced sludge generation: membrane filtration, in contrast to several other treatment techniques, generates little or no sludge. This can lower disposal costs and streamline the waste management process.

The main negative aspects of membrane filtration are exposed here:

- Membrane fouling: membrane fouling, in which pollutants and particles build up on the membrane surface and reduce filtration effectiveness, is one of the fundamental problems with membrane filtration. To combat fouling, regular maintenance and cleaning are necessary.

- High operational costs: higher operational costs may be caused by the energy needed to pump water through the membranes as well as the price of membrane maintenance, cleaning, and replacement.

- Capital expenditure: compared to certain alternative treatment options, the initial expenditure in membrane filtration systems is significant.

3.1.4 Hydrodynamic cavitation process

Hydrodynamic cavitation is an innovative physical process that consists in creating and exploding small "cavities" (bubbles) in order to generate localized high pressure and temperature turbulences resulting in the degradation of impurities. These cavities are created through an orifice plate after a decrease and immediate increase of the pressure (Nieto Zapataa et al. 2021).

The main advantage of this process is the effectiveness of degradation, not generating secondary waste and low energy consumption. However, its application seems still to be minimal in the industry, probably because of the system complexity and maintenance costs. The full potential of this new process for textile wastewater treatment still needs to be fully assessed by the scientific community.

3.2 Chemical methods

The most common chemical method of dye degradation is the chemical oxidation process (Behera et al. 2021). However, this process generates high volume of sludge that is difficult to dispose of. It usually ends up being burnt as an energy source, but this is not a clean waste disposal. Other chemical methods like peroxy-electrochemical and Advanced oxidation process (AOP) are interesting from an operative point of view (high degradation rate and easy to operate) but involve toxic or harmful chemicals in the process.

One of the most recent processes is the photocatalysis process. Reactive oxygen species (ROS) are produced when photocatalysts (frequently based on materials like titanium dioxide TiO2), are subjected to ultraviolet (UV) light. These ROS efficiently transform the organic pollutants contained in the wastewater into benign byproducts (Behera et al. 2021). It has the following advantages compared to other degradation processes:

- Mild operation conditions: the photocatalysis process operates at standard (room) temperature and pression conditions which is an important consideration for practical implications.
- Reduced sludge production: since the pollutants are converted into smaller, less-solid waste products through photocatalysis, it generates less sludge than other treatment processes.

- Environmentally cleaner: the method uses UV light and photocatalysts instead of harmful chemicals and doesn't create secondary pollutants.

Of course, photocatalysis also has some drawbacks.

- Light dependent: being UV dependent also has a constraining side since UV radiation is required for the activation step in the photocatalysis process and it may not always be present or in every location. It may be necessary to use artificial UV sources, increasing energy costs.

- Catalyst deactivation: over time, photocatalysts may become inactive or fouled, reducing their effectiveness and necessitating replacement or regeneration.

- Cost considerations: the cost of the photocatalysis system's initial setup, which includes the purchase of photocatalyst and UV sources, and the operational costs are high compared to other chemical or physical dye removal processes.

Overall, while some chemical methods are efficient for dye removal, they are often not as viable as the physical ones like absorption because of secondary effluent production, higher costs, and design complexity (Oladoye et al. 2022 discussing the example of Malachite Green dye treatment).

3.3 Biological methods

After reviewing the main physio-chemical processes for dye removal and wastewater treatment, it is clear that those processes have been implemented widely in the industry for their operational and practical advantages such as flexibility and reduced costs. However, we have seen that they usually come with major concerns toward sustainability, because of toxic chemical, waste and sludge disposal or secondary pollutant production.

In this regard, biological wastewater treatment methods have been brought to attention as a more sustainable and natural alternative to the processes previously described. Coined bioremediation process, these techniques utilize natural elements to purify the wastewater.

Phytoremediation (plant based) is used for removing organic and heavy metal components from contaminated soil or water. The undesired elements are either filtrated through the roots of the living plant or from the upper part and leaves. In case of the root filtration, a stage of adsorption (sedimentation) is needed.

Phycoremediation (microbial, fungi or bacteria based) exploit a natural process already in action. In fact, wastewater already contains bacteria and micro-organisms that contribute to degrading the macro components into smaller particles. This process has been investigated in the last decade to support wastewater treatment, using fungi, algae or bacteria as a cleaning agent (Behera et al. 2021). This process can occur with the presence of oxygen (aerobic) or without (anaerobic).

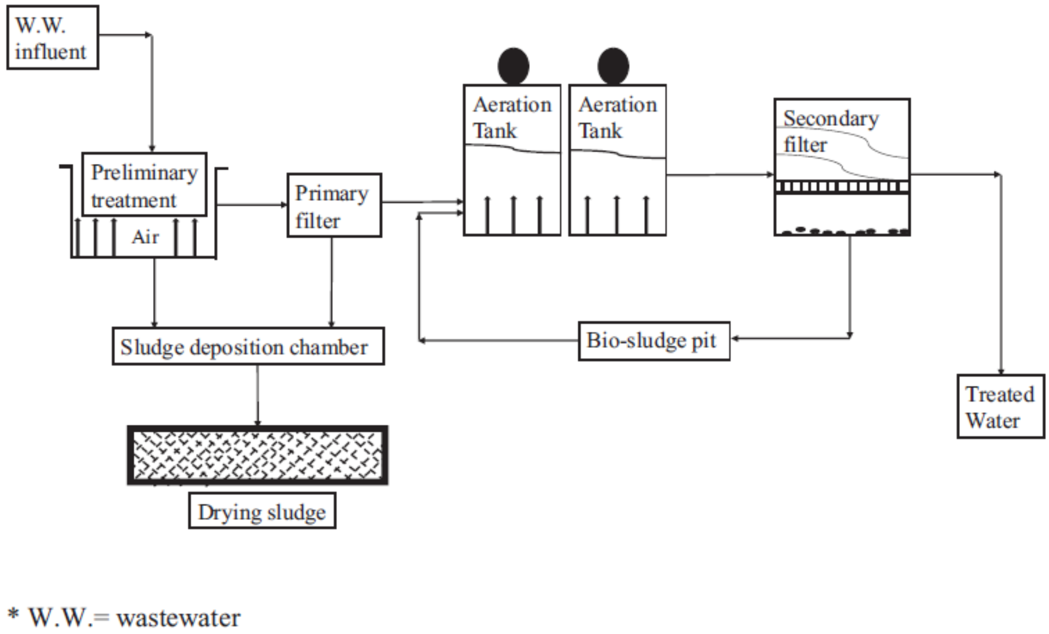

Figure 5 : Biological treatment of textile dyes, Behera et al. (2021)

For instance, Sharma et al. (2023) developed a bioremediation method using a member of the non-toxic mushroom (*Trametes flavida*) under aerobic conditions to clean wastewater containing Congo Red dye, removing 99.48% of the dye concentration.

The main advantages of bioremediation process are the following:

- Natural and sustainable: biological processes replicate how organic components are broken down in nature, making them sustainable for the environment.

- Cost-effective: because biological treatments rely on natural organisms, they are less expensive than some chemical or physical treatment approaches.

- No harmful byproducts: the final byproducts of biological decomposition are usually harmless substances like water, carbon dioxide, and microbial biomass that do not cause secondary pollution.

However, biological processes also imply some disadvantages compared to other dye removal methods:

- Slower process: when compared to some chemical or physical processes, biological processes can be considered slow, because of the amount of time needed for micro or macro-organisms to break down the organic components.

- Biomass disposal: although the biomass formed during degradation is safe to dispose of, it still need to be handled correctly. As Sharma et al. (2023) point out, it can be used for energy production.

- Incomplete removal: natural microorganisms may not be able to entirely biodegrade some complex color compounds, resulting in incomplete removal. For instance, Behera et al. (2021) emphasize that bioremediation is not enough to break down nitrogen and potassium.

3.4 Hybrid methods

We now have reviewed most of the traditional physical, chemical, and biological treatment processes. As we have seen, they all come with interesting assets like process speed, cost effectiveness or versatility for different dyes. However, each process also has a set of drawbacks that have been identified, like fouling, high volume sludge production or production of secondary pollutant.

In this regard, Behera et al. (2021) emphasize the need to combinate the different methods and processes to get the best results. It is often possible to enhance old equipment with newer processes and combining the positive effects.

An example of hybrid technology is the membrane incorporated bioreactor (MBR). This process combines membrane filtration with biological treatment. Some of the main advantages are a constant process rate, low volume of sludge and lower maintenance charge. However, Behera et al. (2021) underlines the fact that MBR alone is not sufficient and requires pretreatment process based on coagulation or reverse osmosis to tackle the fouling effect that diminishes the membrane efficiency over time. The right combination of physical, chemical, and biological processes is the key to achieve maximal results in terms of water purification, cost effectiveness and sustainability.

Zhang et al. (2020) applied a hybrid process to the denim industry wastewater treatment. They successfully combined flocculation, MBR and RO processes to achieve complete purification of the wastewater, which can then be reused in the dyeing process.

The following scheme depicts a 3-phase process of wastewater treatment using physical, chemical, and biological technologies. The first stage of the process is based on physical treatment methods like filtration and coagulation-flocculation. The second stage is based on reverse osmosis followed by photocatalysis. Finally, the last stage uses aerobic and anaerobic biological treatment. This standard 3-phase process leads to lower volume of sludge, no production of secondary pollutant, while achieving complete purification in a cleaner way.

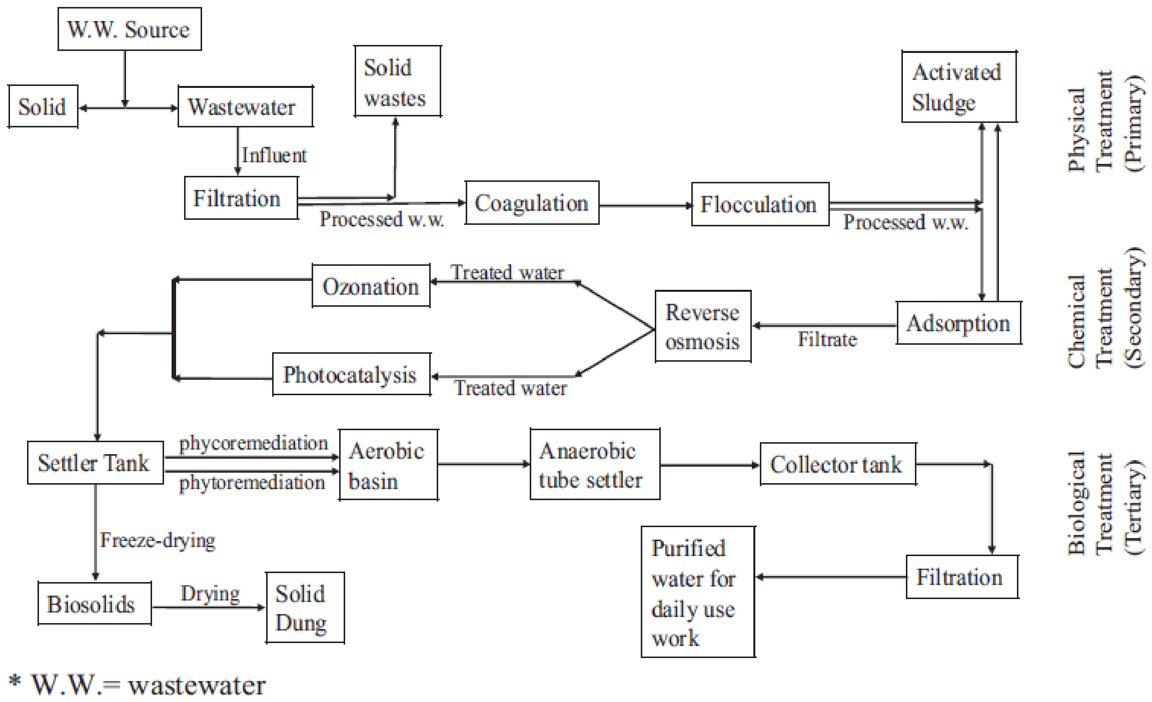

Figure 6: Schematic diagram of a hybrid process used for textile wastewater treatment, Behera et al. (2021)

3.5 Table of the processes for wastewater treatment

In their study, Behera et al. (2021) compiled some specific physical, chemical and biological processes from the literature with their main advantages and drawbacks. Using the data collected, I confronted them with some other processes found in the literature. The following table summarizes the processes discussed in the previous sections and adds a few other very specific processes (especially hybrid ones) previously compiled by Behera et al.

N.	Type	Process	Subprocess	Advantages	Drawbacks
1.	Physical	Adsorption	Carbon based (AC)	1. High flow rate	1. Adsorbent selection
2.			Metalcompsite based	2. Rapid process	2. Exhaust easily (saturation)
3.			Gel based	3. Moderate costs 4. Low sludge production	3. Waste disposal
4.		Chemical Coagulation-flocculation		1. Easy to handle 2. Large scale	1. High sludge production 2. Use of toxic chemicals
5.		Membrane filtration	Microfiltration (MF)	1. High removal efficiency	1. Fouling
6.			Ultrafiltration (UF)	2. Low sludge production	2. High Capital and Operational (OP) costs
7.			Nanofiltration (NF)		
8.			Reverse osmosis (RO)		
9.		Hydrodynamical cavitation		1. No toxic chemical 2. No secondary waste 3. Low energy	1. Complex operating conditions 2. Lack of information
10.	Chemical	Photocatalysis		1. High degradation rate 2. Operating large volume 3. Room temperature conditions 4. Low sludge production	1. Catalyst deactivation 2. Dependent on light 3. High OP costs
11.		Peroxy-electrochemical		1. High degradation rate	1. Toxic chemicals
12.		AOP/floatation		2. Operating large volume	2. High sludge production
13.	Biological	Aerobic/anaerobic process		1. Non-toxic/Cleaner	1. Lower degradation efficiency
14.		Bioremediation	Phytoremediation Phycoremediation	2. Cost effective 3. Easy to handle 4. No harmful byproducts	2. Slower process
15.	Hybrid	MBR (Membrane bioreactor) process			
16.		Hybrid membrane (EO-microfiltration)		1. Mitigate the single process flaws	1. High CAP costs
17.		Ozonation/Biological treatment		2. Sustainable/Cleaner	2. Skilled workforce needed
18.		Integrated ozone biological aerated filters		3. Cost effective 4. Existing process enhancement	
19.		Membrane filtration/ozonation			
20.		Forward osmosis/flocculation-coagulation			

Table 2: Processes for wastewater treatment

4. Water management

Dyeing is one of the most water-consuming process in the textile fabrication. It involved the physical or chemical adsorption of dye molecules on textile fibers. However, the interaction is often weak and thus the amount of water needed in the process is huge. Sun et al. (2023) estimates at more than 200m3 the amount of water to produce 1ton of dyed textile. As we have seen before, the wastewater produced during the process contains dissolved dye molecules that are difficult to recover from the water. The treatment processes often involve the destruction of the dye molecule. Bleaching and fiber sterilization are two other phases of textike production that involve large amount of water. In this section we focus on innovative techniques for standard wet processes such as dyeing, and water conservation techniques.

4.1 Plasma treatment for reduced water consumption during dyeing stage

Plasma treatment and natural dyes are gaining a lot of attention as a combined method for textile dyeing. Natural dyes have been considered to reduce the chemical impact of dyeing. However, they require special treatment due to their low affinity towards textile fibers. To counter this effect, plasma treatment of the fibers has emerged as an effective and clean technique. Haji et al. (2020) investigated the use of natural dyes with plasma pre-treatment of the fibers as a clean dyeing process. They compiled the main natural dyes and their chemical properties and investigated the best appropriated plasma parameters (Gas, pressure, power, and duration) for each dye. They investigated the effect of this process on different types of fabric. Wool, cotton, and silk were tested as natural fibers, and polyester, nylon and acrylic were tested as synthetic fabrics. Plasma pre-treatment of the fabric enhances the fixation of dyes on the fibers and thus reduces the wastewater generation and water consumption from rinsing phases. Overall, the results show the effectiveness of the dyeing process and its potential as a cleaner approach to textile dyeing.

Similarly, Haque et al. (2023) developed an innovative sustainable wool dyeing method using organic waste (onion peel) supported by plasma pre- and post-treatment. They compared the water consumed using this process with respect to a standard wool dyeing process. They achieve a 4 times water consumption reduction using the plasma method. One of the most water consuming phase of the standard process is the washing stage. During the washing stage, the unfixed dye is eliminated from the textile and the color fastness improves. With plasma post-treatment, the unfixed dye is fixed to the wool surface which ensure less dye loss during the whole process, while achieving similar color fastness results to the standard process.

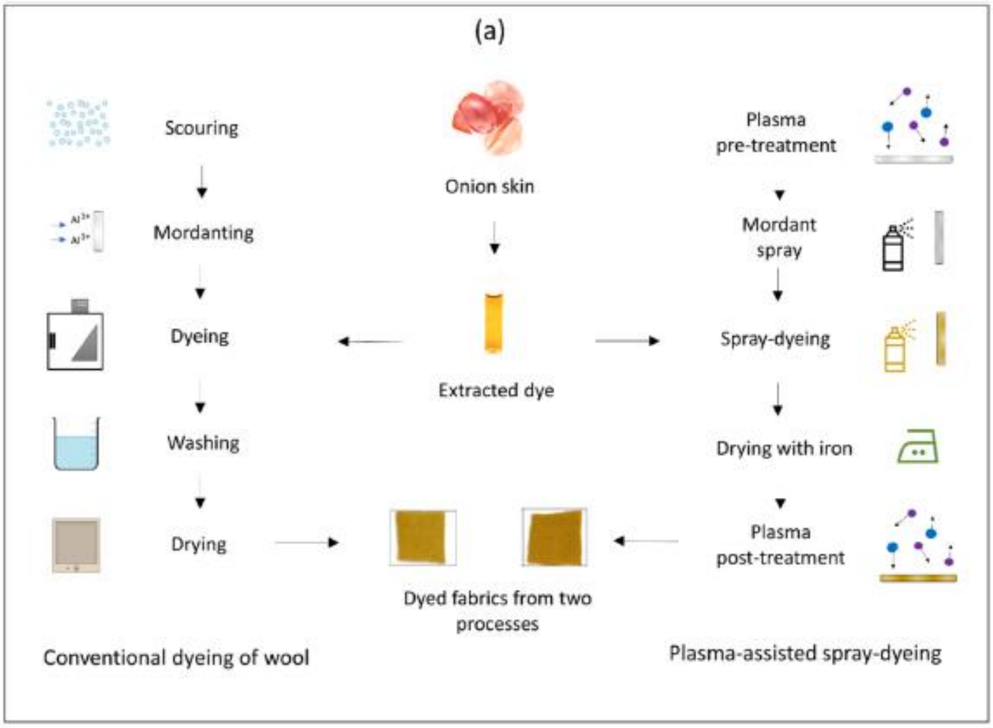

Figure 7: Schematic of conventional dyeing and plasma-assisted spray-dyeing, Haque et al. (2023)

The plasma assisted process energy, water and time consumption were investigated by Haque et al. proved the efficiency of the method. Indeed, since no wastewater was discharged, the process consumed 4 times less water than the standard one. The total process time was also 3 times lower than the standard process and the energy consumed was also 3 times lower.

Hence, the combination of natural dye (onion peel) with the plasma pre- and post-treatment technology showed convincing results in terms of cost effectiveness and sustainability as a wool dyeing method. Haque et al. also believe in the scalability of the process for industrial application.

4.2 Innovative processes for fabric treatment

Bleaching is a wet process that aims at removing the yellow color of textile fibers and increase the white appearance of the garment. The standard process involves important quantities of water due to the rinsing and neutralization phases that follow the bleaching phase. Wahab et al. (2022) studied an alternative bleaching method using aerosol technology. The quantitative results of the standard and aerosol bleaching process were analyzed. The study shows that the aerosol process led to 75% reduced water consumption than the standard one. The aerosol method also reduced the consumption of most of the chemicals used in the bleaching process (60% softener and 28% citric acid), except for the hydrogen peroxide which is the main whitening agent (remained equal). The bleaching results were also compared, and the aerosol technique resulted in a whiteness slightly lower than the standard process. Overall, this innovative bleaching method can bring important cost reductions in terms of water and chemical, as well as wastewater treatment. Wahab et al. emphasize the easy scalability of the process and implementation on existing production plants.

Wool is a very dirty raw material and hosts bacteria that can be hazardous for the human. Thus, it needs to be processed and cleaning for garment production. Wool cleaning techniques normally requires large amounts of water and chemicals, leading to important volume of wastewater and high energy costs. The water consumption in wool wet cleaning process varies from 111L/kg to 659L/kg (Allafi et al. 2022). Some standard sheep wool cleaning techniques involve carbonizing, detergent cleaning, ultrasonic cleaning, solvent cleaning, electric and electrohydraulic discharge cleaning, and hot steam cleaning. These techniques utilize chemicals like strong acids and need proper washing afterwards, contributing to the release of waste and effluent.

Allafi et al. (2022) investigated a waterless wool cleaning process using supercritical carbon dioxide (scCO2). Carbon dioxide enters the supercritical state (neither gas nor liquid) under specific temperature and pressure conditions, modifying its properties. It can then be used as a sterilizing agent with various advantages during the process: less wool fiber damaging, reduced toxic waste and wastewater production and lower processing time. While the cleaning process led to increased whiteness of the wool compared to the raw stage (thanks to the removal of most of the impurities), Allafi et al. point out that reaching a higher whiteness index might require the addition of a solvent, like hydrogen-peroxide. Although this innovative wool sterilizing process can be improved in terms of final aspect of the fibers, it shows great potential as a sustainable alternative to standard cleaning techniques.

Interestingly, Sarwar et al. (2021) developed a sustainable finishing process for easy-care textile production. Their goal was to implement a finishing technique that would increase the textile's aspect, maintenance, and comfort with a non-toxic formulation. Using a foam technology based on succinic acid and xylitol, they managed to achieve promising results on cellulosic fibers: 32% increased strength and 13% increased stiffness. Although it was not precisely quantified in the article, Sarwar et al. emphasize the cost-effectiveness, water, and energy savings of the process.

4.3 Water reuse for zero water discharge goals

In their study, Sharma et al. (2019) found an innovative use of henna dyebath for linen fabric coloration and finishing. Henna is a natural dye used for fabric dyeing and finishing. Natural dyes have some interesting properties like antibacterial, UV protection and insect repellent. However, they lack affinity towards the fabric fibers and require the use of metallic mordant. Sharma et al. point out that natural dyebath was often only used once and discarded, even though the bath still contains unexhausted dye molecules. Sharma et al. discovered that satisfactory functionalization (achievement of properties like color fastness, UV protection…) was possible while reusing the same dyebath for several cycles, with only minimal color diminution. By doing so, they were able to reduce the toxicity and volume of wastewater. This type of process can be a cleaner alternative when the functional properties of the fabric are more important than the final shade.

Sun et al. (2023) worked on a very innovative and promising technology involving hydrates. Hydrates are described as a "crystalline solid formed through the encapsulation of guest molecules (such as CH4, CO2, CCl2FCH3) in a cage-like skeleton of hydrogen-bonded water molecules, under high pressure or low temperature conditions" (Sun et al.). These hydrates can "trap" guest molecules from liquid water into solid hydrates. Afterwards, the hydrates can be decomposed again into water and the guest molecules. While this technology has already gained a lot of attention for water desalination, gas storage and CO2 capture, Sun et al. believe in its potential for wastewater treatment. The main advantages are that the dye molecules are not destroyed and can be recovered and reuse. The clean water can be recycled and reused as well following the Zero-Water Discharge goal.

4.4 Best practices for water conservation applied to manufacturing plants

Alkaya et al. (2014) investigated a woven fabric manufacturing mill based in Turkey according to several sustainability indicators. One of the main aspects of the study was the soft water consumption. Water was used to dry the fabric after the finishing stage. Water if often used as a cooling fluid for various production phases. The water cannot be in direct contact with the fabric, and thus, remains clean from any chemical or organic contamination. However, often, for sake of simplicity, the cooling water is directly dumped into the wastewater. For instance, clean water was used as a cooling fluid for heat exchangers in the case study. This water wasn't contaminated by any chemical or organic agent, so they introduced a recycling system that stored this water in a tank to reuse for various process like dyeing. Similarly, the singeing process involved water-cooled system, and a closed loop was introduced to reuse this clean water.

Another striking figure from the case study is that over 10% of the water was missing from the balance between entry and exit of the production system as a whole. This means that 10% of the water was being lost through leaking and evaporation. Since the production mill was relatively old, some of the pipes and valves were damaged. This calls for the importance of maintenance in the textile production systems in order to achieve sustainability.

Washing, preparing, and finishing are wet processes that consume large amount of water. Switch from overflow washing/rinsing to drop/fill process led to more than 50% decrease in monthly clean water consumption.

After implementing all the changes described before in the mill, the total water consumption decreased from 40.2% while the produced wastewaters decreased from 43.4%.

In another case study of a production mill in Turkey, Ozturk et al. (2016) analyzed the current process and discovered that almost none of the wastewaters from various production stages were reused or recycled. By analyzing the wastewater compositions, they were able to decide whether or not these waters were reusable for the same process or needed treatment. Overall, it was found that most of the flows of water from dyeing, finishing, pretreatment, cooling, etc. were reusable in the system. For the final wastewater flow, a treatment process based on membrane technology was suggested to clean the effluent. Ozturk et al. (2016) proposed a set of best available techniques for cleaner water and chemical management in the textile facility:

Good management practices	1. Establishment of environmental management system 2. Preparation of preventive maintenance-repair programs 3. Application of monitoring and control techniques 4. Preparation of annual waste inventory reports 5. Improving R&D activities 6. Revision of production schedule according to Cleaner production principles
Water consumption minimization	7. Reuse/recovery of washing/rinsing and softening wastewater 8. Reuse of suitable dyebath 9. Optimization of water softening unit, recovery/reuse of regeneration wastewater 10. Application of counter-washing techniques in pad-batch washing process
Chemical consumption, minimization, and substitution	11. Removing iron from fabric surfaces before scouring process and prevention of complex chemical usage 12.Wide spreading of automatic chemical dosing 13. Caustic recovering from mercerization process wastewaters using membrane techniques 14. Chemical substitution

Table 3: Suggested best practices from Oztruk et al. (2016)

Among the best practices, we can underline the maintenance and repair program as Alkaya et al. (2014) also emphasized. The main part regarding water management is the recycle and reuse of specific wastewater within the production process. Implementing these best practices could lead according to Oztruk et al. (2016) analysis between 43-51% reduction in water consumption, 16-39% in chemical consumption, and 45-52% in combined wastewater flowrate.

4.5 Table of the processes for water conservation and reuse

Below is a table summarizing the main processes and implementations from the literature for water conservation and reduced consumption, during the most critical stages of textile production such as dyeing and finishing.

Innovative processes		
Haji et al. (2020)	Wool dyeing using natural dies and plasma pre-treatment of the fabric	1. Clean innovative process 2. Applicable to natural and synthetic fibers
Haque et al. (2023)	Wool dyeing method using organic waste (onion peel) supported by plasma pre- and post-treatment	1. 75% reduced water consumption 2. 66% reduced chemicals
Wahab et al. (2022)	Bleaching method using aerosol technology	1. 75% reduced water consumption 2. Reduced chemicals
Allafi et al. (2022)	Waterless wool cleaning process using supercritical carbon dioxide (scCO2)	1.Less fiber damaging 2. Reduced toxic waste/wastewater production 3. Lower processing time
Sarwar et al. (2021)	Foam finishing approach for cellulosic textile employing succinic acid/xylitol crosslinking system	1. Cost effectiveness 2. Zero toxicity formulation 3. Water and energy savings
Sharma et al. (2019)	Reuse of henna dyebath for linen fabric coloration and finishing	1. Reuse of dyebath 2. Reduced water consumption 3. Reduced wastewater generation
Sun et al. (2023)	Dye recovery and water conservation using hydrates	1.Nondestructive dye recovery 2. Clean water separation
Production plant enhancement processes		
Alkaya et al. (2014)	Water conservation techniques for textile production mill	1. 40.2% reduced water consumption 2. 43.4% reduced wastewater production
Ozturk et al. (2016)	Best practices for water conservation in a production mill	1. 43-51% reduced water consumption 2. 16-39% reduced chemicals 3. 45-52% reduced wastewater production

Table 4: Processes for water conservation

5. Focus on dyeing using natural colorants

The natural world is rich of colorful sources that have been used as colorant since the dawn of civilization. Mankind has since perfected its ability to extract those substances and has been using them for food, textile, pharmacology, and cosmetics industries. In 1856, the first synthetic colorant was created, and it marked the fall of the natural colorants. Since then, natural colorants have been used only by small entrepreneurs, artisans and enthusiasts who wanted to keep these ancient techniques alive (Uddin et al. 2022).

Nevertheless, synthetic colorant applied as dyes in the textile industry are causing great environmental concerns from a sustainability point of view. Indeed, they are often produced from toxic chemicals. As we have seen, wastewaters from dyeing process remain an important source of pollution, especially when dumped into aquatic sources. In response to these environmental concerns, dyeing using natural colorant has gained again interest from the scientific community.

5.1 Types of natural colorants

In their review, Uddin et al. (2022) studied and classified all the major natural dyes. Natural dyes can be extracted from various sources. Historically, the majority of natural pigments come from plants. Different parts of the plants (root, leave, fruit, bulb, seed,) can produce different pigments. Uddin et al. point out that in India, more than 150 plant-sources of dye have been classified.

Another range of pigments can be extracted from minerals, such as chrome yellow, ultramarine blue or charcoal black. These pigments are produced from insoluble and inorganic metal salts and oxides.

Insects are also a source of a vast range of colorants, from red to pink to yellow and blue. Often extracted from the dried bodies or eggs of insects, these colorants have numerous applications in food, pharmacology, and textile industries.

Fungi, both from soil or wood, can produced interesting shades of pigments and have been applied to textile coloration. Moreover, some species of bacteria can also produce red/orange pigments.

Color index	Number of dyes	Source examples
Yellow	29	Barberry (plant), Chrome (mineral), *Penicillium Murcianum* (fungus), …
Orange	6	*Bixa Orellana* (plant), *Rhodobacter sphaeroides* (bacteria), …
Red	32	Madder (plant), Cochineal (insect), Cinnabar (mineral), …
Blue	4	Tsuykusa flowers (plant), Sea snails (animal), *Indigofera* species (plant), …
Green	5	*Chlorociboria Aeruginosa* (fungus), usually very rare other than mixing other colorants
Brown	12	Acacia tree (plant), *Alchemilla vulgaris* (plant), …
Black	6	Iris roots (plant), charcoal (mineral), carbon, …

Table 5: Classification of the main natural dyes, Uddin et al. (2022)

5.2 Merits, demerits, and challenges

Textile dyeing using natural pigments has gained interests as a cleaner alternative to synthetic dyes. However, the sustainability and feasibility of natural colorants is not evident.

The main advantage of natural dyes is that it doesn't rely on chemistry to be produced but is rather directly extracted from natural resources. Synthetic dyes are chemically conceived relying on toxic compounds from petrol. The production process of synthetic dyes inevitably leads to the pollution of aquatic sources through wastewaters (Haji et al. 2020). Thus, natural dyes make a cleaner alternative than synthetic one from a production perspective.

Interestingly, natural dyes also demonstrate interesting properties for functional treatment of the fabric, as Eid et al. (2021) explain. Indeed, the dye molecules interact with the functional groups (–OH, –SO3H, –COOH, –C6H5OH, –NH2) of the fabric to improve the properties of the textile, such as UV protection, antioxidant, antimicrobial or anti moth. However, Uddin et al. (2022) point out that these properties tend to get weaker after successive washing of the garment.

Natural dyes production favorizes plantation and thus contributes to reduce carbon dioxide from the atmosphere. Plantation for natural dyes could also contribute to maintain land fertility thanks to rotating crop cultivation.

One of the main demerits of natural dyes is its need for mordants. Natural dyes are mostly non-substantive, which means they require a chemical to improve the link between dye and fabric. Mordants alter the hue and shade of the colorant depending on the type of fiber. Most of the mordants are metallic salts and tannins synthetically produced, which cause environmental concerns because of polluting effluents. Natural mordants on the other hand have gained interests, however they show mostly non satisfactory results in terms of color fastness (Uddin et al. 2022).

Natural dyes, with or without mordants, also display mitigated results in terms of color fastness (resistance to washing, light or rubbing). While high color fastness to light and wash is achievable for wool, cotton fibers show low color performances with natural dyes. To counter this effect, pre-treatment of the fabric is often necessary (Haji et al. 2020 and Eid et al. 2021).

Unfortunately, natural dyes remain a niche and costly process because of its lower yield, longer extraction process, limited range of colors and lower replicability compared to synthetic dyes. From an industry-scale perspective, the use of natural dies seems to remain unfeasible unless a global action is initiated by all stakeholders, including actors of the supply chain and governments (Uddin et al. 2022).

However, there are some promising challenges and areas of innovations regarding natural dyes. Sustainable pre-treatment of fabric for better fastness like plasma treatment (Haji et al. 2020) are being investigated. Moreover, bio-mordants are promising alternatives and Uddin et al. (2022) emphasize some of the great results on various fabrics. While traditional extraction processes like acidic/alkaline aqueous medium or fermentation usually require long process time, innovative extraction methods based on ultrasound and microwaves demonstrate encouraging results to improve the production process of natural dyes (Uddin et al. 2022, supported by the review from Hassan et al. 2023).

Below is a table summarizing the merits and demerits of natural dyes and its challenges.

Merits	1. Nonchemical production, no toxic and polluting effluent production	
	2. Interesting properties for fabric functioning (UV, antibacterial, …)	
	3. Contributes to cultivation and land maintenance	
	4. Renewable	
Demerits	1. Low replicability	
	2. Restricted color range	
	3. Costly production	
	4. Low yield	
	5. Low color performances	Response: Clean pre-treatment of fabric
	6. Need for mordanting	Response: Bio-mordants as a cleaner alternative
	7. Long extraction process	Response: Clean ultrasound assisted extraction technique

Table 6: Merits, demerits, and challenges of natural dyes

6. Textile waste management

Increasing population and intense consumerism have led to massive textile and garment production in order to meet the demand. However, this increase resulted in huge textile waste production. Peter John et al. (2023) estimate at 92 x 10^6 t the amount of textile waste produced yearly. Out of this amount, only 14% is recycled and the rest is either burned or dumped in landfills. In either case, the disposal of waste is unsustainable. This calls for critical actions in terms of waste recycling and circular economy implementation for the textile industry.

In their review, Jia et al. (2020) proposed a model for the application of circular economy to the textile and apparel industry. They identify sources of waste along the production process and several end-of-life outcomes. The following figure describes their insight:

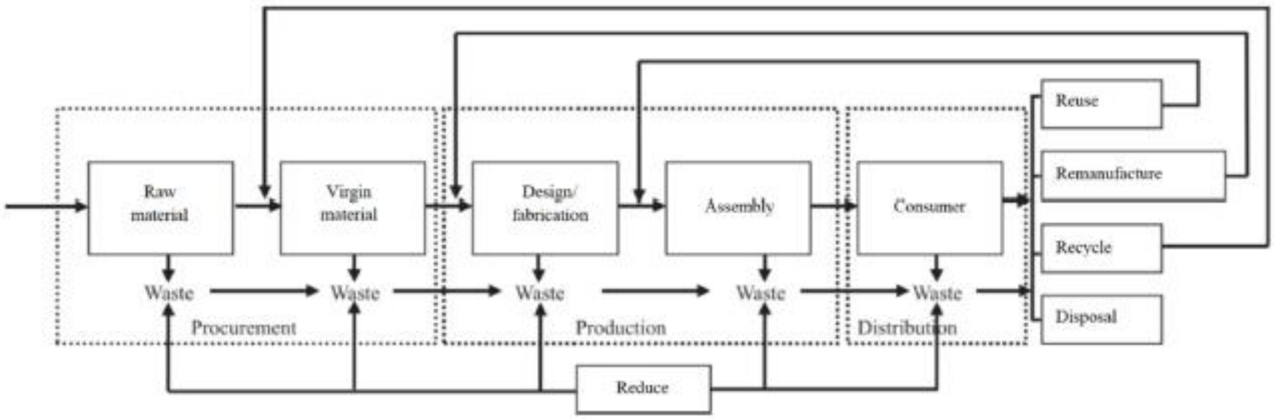

Figure 8: Circular economy model in T&A industry, Jia et al. (2020)

Additionally, Jia et al. developed a model for better understanding the drivers, barriers, practices, and performance indicators for the application of circular economy in the textile industry.

The main drivers stem from competitive, community and customer pressure following the global awareness regarding sustainability. Government and top manager can also be drivers of change by promoting a cleaner vision of the textile industry.

Jia et al. divided the barriers into two groups. Ex-ante barriers regard the investment phase, with examples like the lack of support from stakeholders, the lack of financial support, or the lack of information and technology. Ex-post barriers focus on the adoption process in the long term, with factors like lack of strategic plan, lack of performance measurement systems, or lack of infrastructure.

The practices compiled by Jia et al. refer on the one hand to building a collaborative system: collaboration with external stakeholders, suppliers, and the development of collection system. On the other hand, practices also involve reuse and recycling, and re-designing. These practices are substantially developed in the following sections.

In terms of performance measurement, Jia et al. state indicators like warehouse gas emissions, wastewater and solid waste generation, and toxic material consumption.

The next figure represents the synthetic model proposed by Jia et al.

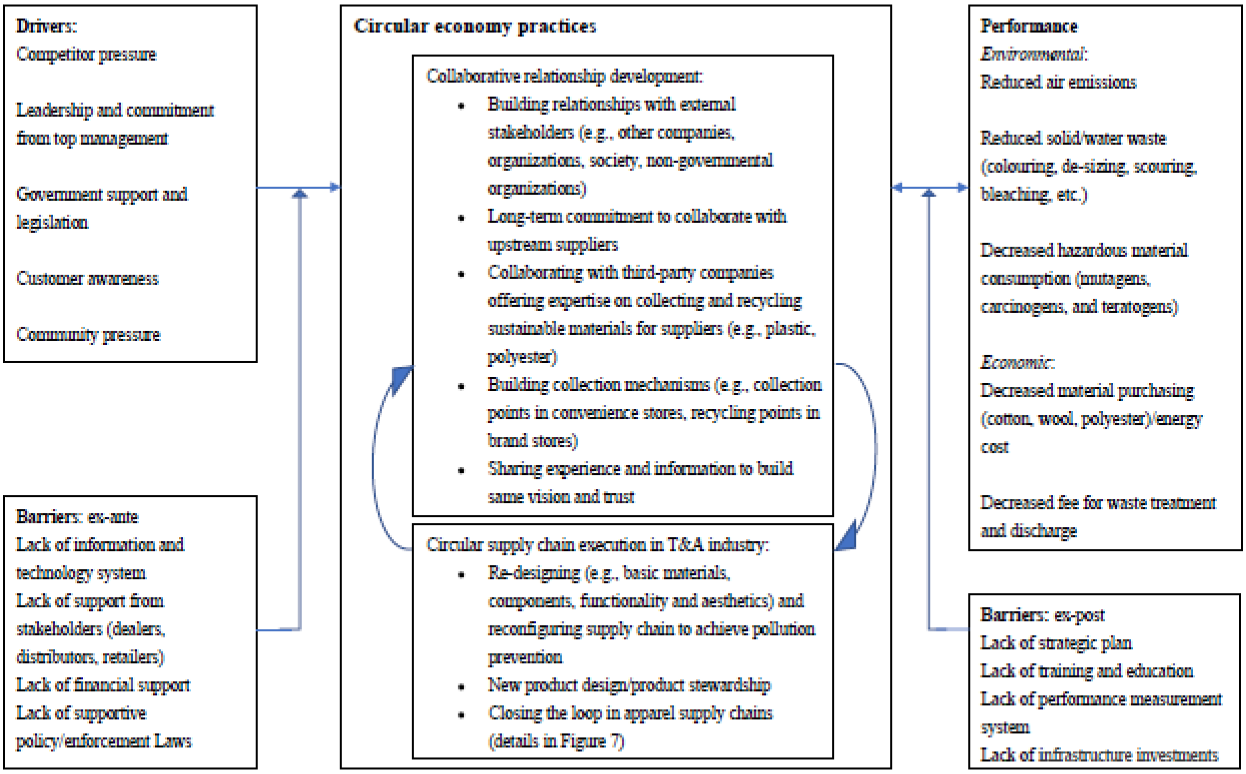

Figure 9: Conceptual framework, Jia et al. (2020)

In the following sections, we will deep-dive into the practices and barriers highlighted by Jia et al.

6.1 General considerations on textile reuse and recycle

Textile reuse aims at increasing the practical life of a textile product, with or without modifications. This can be done through change of owner with renting, trading, or borrowing.

Textile recycling refers to the reprocessing of pre- or post-consumer waste to create new textile or non-textile products.

In their study, Sandin et al. (2018) proposed a new classification of recycling "routes", often overly simplified in the literature as either mechanical, chemical, and thermal. Indeed, they they argue that textile recycling often involves both mechanical and chemical processes and that the definition of thermal is somewhat inaccurate. Sandin et al. called *fabric recycling* the recycling of the fabric of a product for new products. If the fabric is decomposed into fibers, then it is a case of *fiber recycling*. Going further into the disassembly of the fabric, if the fibers are decomposed into polymer and oligomer, it is called *polymer/oligomer recycling*. Finally, polymers/oligomers can be further decomposed into monomers, in the case of *monomer recycling*.

Another classification of recycling worth mentioning is the distinction between *downcycling* and *upcycling*. On the one hand, *downcycling* refers to the recycling of a product into products of lower quality or value. Sandin et al. highlight that the main recycling routes nowadays are in fact *downcycling*. Fabric and fibers recycling are often *downcycling*. They take the example of textile recycled into low-grade blankets or insulation materials. On the other hand, *upcycling* refers to the recycling of a product into products of higher quality or value. Polymer/oligomer and monomer recycling can yield *upcycling* because the emerging product typically has fibers of similar quality to the normal ones.

Sandin et al. also differentiate open- and closed-loop recycling. *Closed-loop recycling* refers to a product being recycling into a similar product. For instance, a T-shirt into a T-shirt but also a T-shirt into another piece of clothing, depending on the definition of similar product. *Open-loop recycling* refers to a product being recycled into other products (also known as cascade recycling).

Below is a figure summarizing the different categories of recycling and the touchpoints they can have with a textile supply-chain (Sandin et al.):

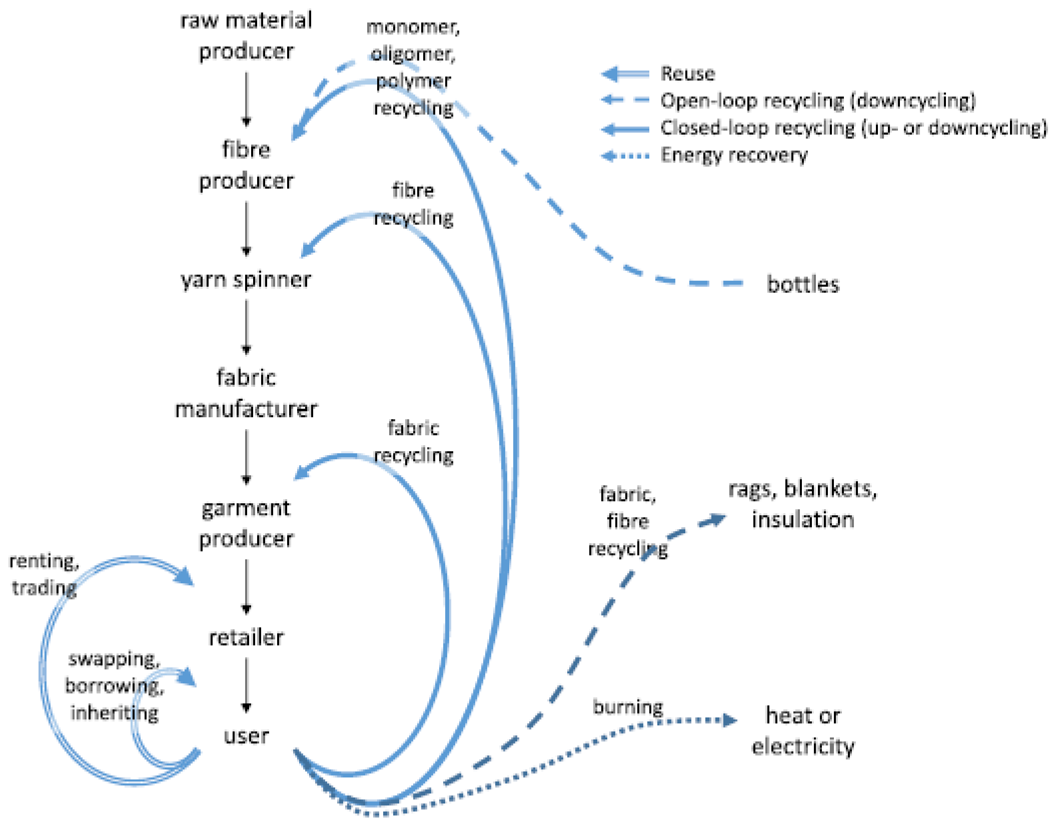

Figure 10: A classification of textile reuse and recycling routes, Sandin et al. (2018)

In their review, Sandin et al. draw some interesting conclusions. While the beneficial impact of textile recycling and reuse is widely demonstrated in the literature, compared to other waste management methods such as incineration, there are some subtilities that must be acknowledged. First of all, reuse will always be more beneficial than recycling in terms of environmental impacts. The true benefit of reuse and recycling lies in the avoidance of the production of new products. However low replacement rates can counterbalance this effect. Moreover Sandin et al. note that textile recycling can have substantial environmental impact under certain conditions. For instance, recycling processes can be powered by fossil fuels which have considerable impacts on the environment. Part of the literature concludes that adding lifecycles to a product with a short lifespan can have a counterproductive effect in terms of sustainability as the environmental cost for recycling will exceed the one of new production. Sandin et al. also explain that recycling might shift the overall environmental impact from one region of the world to the other. For instance, increased recycling in the UK might lead to lower cotton production in the US, and thus lower impact from cultivation of cotton (highly water dependent). However, this might lead to an increased use of energy in the UK for the recycling process, with the associated environmental impacts. Here we understand that these notions are way more complex than what it may seem at first sight and need global considerations to be effective. Additionally, Sandin et al. note that few studies include the processes of waste collection and sorting, discarding possible additional difficulties of the recycling and reuse process. Overall, all the steps of the process need to be assessed and analyzed, adopting a life-cycle approach in order to draw realistic conclusions on the benefits and feasibility of recycling and reuse.

6.2 Design thinking as a tool towards circular economy practices

In their recent paper, Battesini Teixeira et al. (2023), study the applications of Design Thinking processes to implement Circular economy within the textile industry. Design thinking is defined as "*the systemization of design mechanisms applied to innovation […] characterized by creative, iterative, and human-centered approach.*" Design thinking is a tool that can help company develop or transition towards a cleaner business model. Design thinking can be applied at various stages of production, especially for new product development process. Circular economy refers to a product lifecycle approach that aims at replacing the "end of life" phase using disposal methods such as reuse, recycle or remanufacturing. Moreover, circular thinking reduces waste generation, energy consumption and the overall environmental impact of the product throughout its entire life. Battesini Teixeira et al. found that circular thinking through design thinking was applicable at various stages of a textile company in order to transition towards cleaner business models.
After systemizing their investigation, they came up with a process that aims at moving towards circular economy in the new product development phase. The process is composed of 2 main cycles: the design cycle and the consumption cycle. However, the two cycles are connected. Design thinking concepts are applied in the design cycle: Learn, understand, define, ideate, and prototype, following a creative and iterating approach. The design process keeps human in the center through stakeholders' feedback and consumer needs. Eco-innovation is at the core of the define-ideate-prototype phases of the cycle where options are assessed before production. The second cycle encompasses manufacturing, consumption, and disposal. For each of these phases, circular thinking is applied. Disposal options of reuse, recycle or remanufacturing are studied in the last phase.

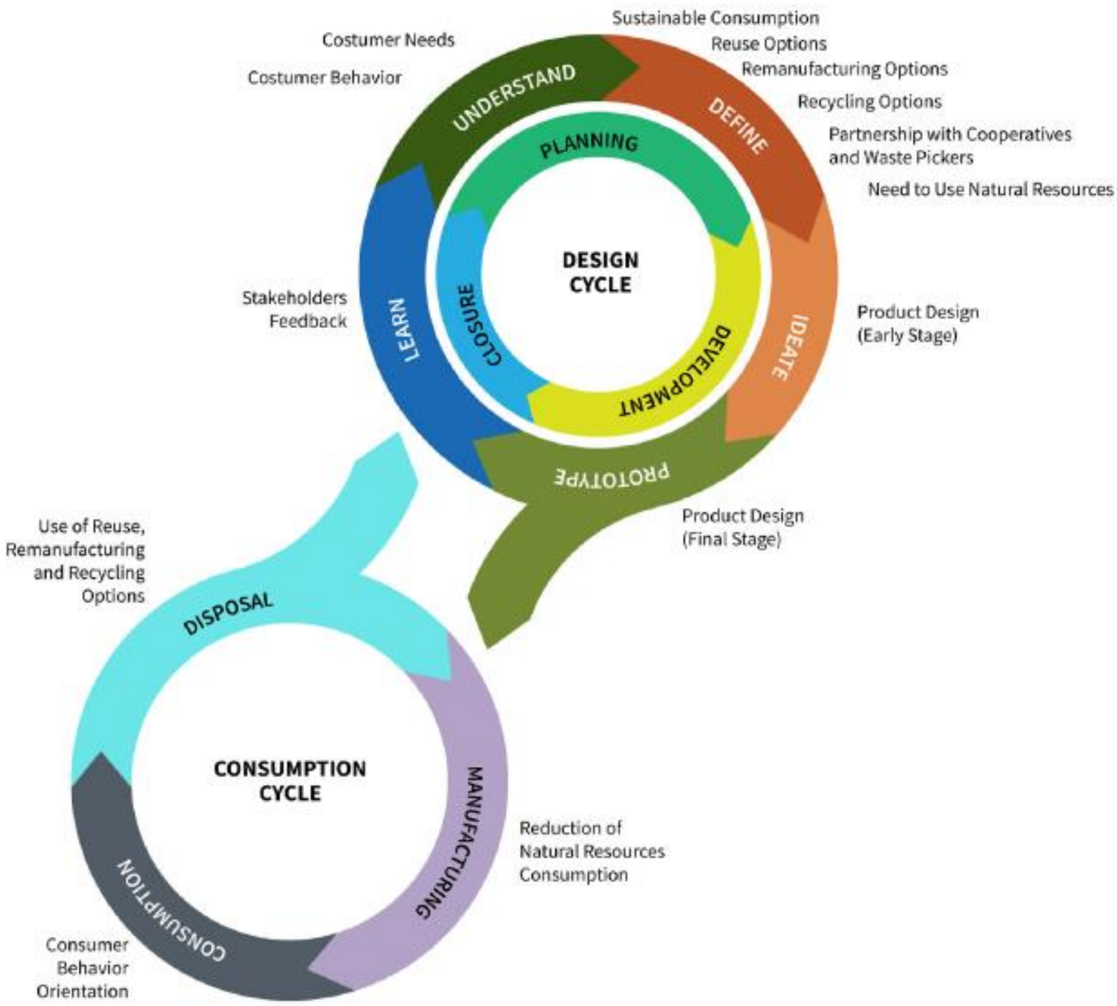

Figure 11: Methodology for circular thinking in the textile industry, Teixeira et al. (2023)

Through interviews with companies, Battesini Teixeira et al. noticed that companies usually understand the importance of design thinking, but don't apply it necessarily. Battesini Teixeira et al. emphasize the competitive advantage that design thinking can offer, and its power as a transition tool towards circular economy and cleaner production.

6.3 Pre-consumer waste reduction: zero waste pattern cutting and design

Most of the pre-consumer waste happens during the cutting stage of the fabric. Traditionally, patternmaking is the process of taking a 3D design and flattening it to a 2D scheme in order to facilitate cutting and construction of the garment. Some research has been done on Zero Waste Cutting patterns with the objective to exclude generation of waste during this production phase. Various creative pattern cutting techniques have been developed, such as jigsaw, creative cut, minimum cut and even origami (Peter John et al. 2023).

James et al. (2016), describe the traditional design and make process for garment production. They point out that the design and make stages are separated and share low interaction. The only iteration process occurs between the first and second patterns that are respectively concepted in 2D and 3D.

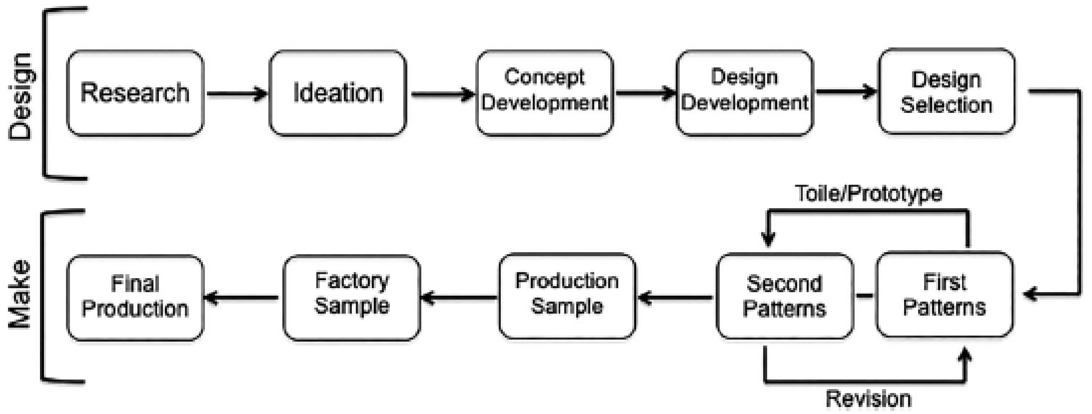

Figure 12: Interpretation of the design and make process, James et al. (2016)

James et al. then studied a second process based on zero waste pattern cutting techniques. As Peter John et al. (2023) also notice, a lot of iteration takes place with zero waste methods, and the design and make process is not linear anymore. Following almost a trial-and-error approach, the process goes back and forth between pattern design and sample production. In the end, differences between final design and original idea are unavoidable.

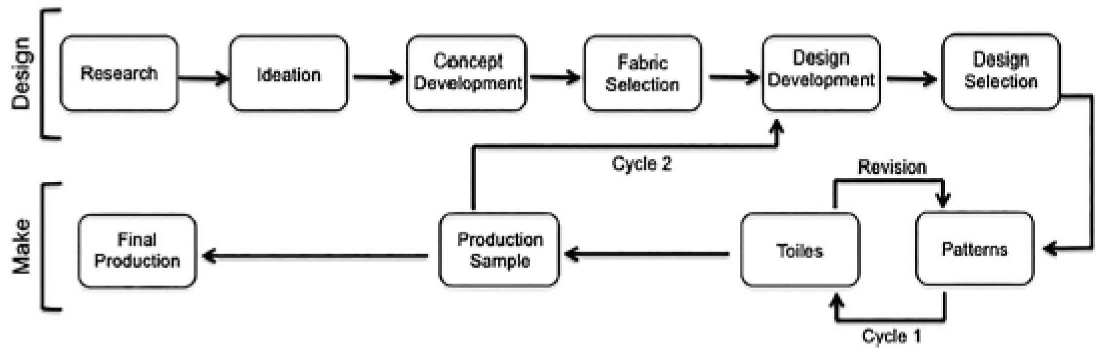

Figure 13: The design and make process when utilising zero-waste principals, James et al. (2016)

When zero waste pattern cutting methods are applied, the pattern cutter and designer need to work together in a cyclic process. James et al. investigated 3 different case studies.

The first one was a high-end designer company. While investigating their design and make process, James et al. discovered a close relationship between designer and pattern cutter, even though they were working at different locations. However, the designer was the only responsible for design aspects and the pattern cutter was responsible for the realization of the designer's vision. The creative leadership remained in the hands of the designer.

The second case study was a high-street department store with a multi-channel business model. This time, the design and make process was very linear with almost no interaction between designer and pattern cutter, and the creative leadership fully controlled by the design team.

In case study number three, the design and make process of a small artisan company was auditioned as part of the niche high-end luxury sector. In this case, the design and make process, because of a reduced production, was following a downsized traditional design and make process. However, designer and pattern maker were working hand in hand throughout the process, working from the same location and taking decisions together.

James et al. emphasize the importance of a share creative leadership between the design and pattern cutting team for zero waste pattern cutting implementation. These case studies show that traditional high-production textile companies have a very linear design and make process which will be difficult to transform following a zero-waste design and pattern cutting approach.

McQuillan (2019) describes a hybrid zero waste design approach that aims at eliminating waste directly from the design phase of the garment supported by digital tools. To do so, the textile structure is done simultaneously with the garment 3D model. In her research, McQuillan worked with a large fast fashion brand and tried implementing some design changes on a specific dress design, in order to reduce waste generation. One of the iterations led to 26% less fabric without any major design modifications, by adding a single seam. However, after the design modifications were translated in terms of costs for the company, it appeared that it was less expensive for the company to keep the original design than implement the proposed one. The fabric was so cheap that using 26% less fabric was not cost-efficient compared to adding one seam. In the context of high-volume and low-cost fashion production, implementing zero waste design changes to improve waste generation are simply not worth it for factories from a financial perspective. This study shows that higher motivations need to be found to promote change towards sustainability for fast fashion industry.

One of the criticisms of zero waste design is the lack of aesthetic control the designer has on the garment. However, for McQuillan, we need to broaden our perspective and redefine the norms of aesthetic, forms, and volume. According to her, redefining form-making in the fashion industry could enable the use of zero waste design practices and completely reshape the textile industry in a more sustainable way. She sees the use of 3D modeling software as a communication tool between fashion design and textile weaving. McQuillan adopts a radical approach to garment design: refusing the high-scale industry, she envisions a fashion industry as a “high-tech cottage industry”, praising digital crafting (3D models) while advocating for traditional garment production techniques such as the jacquard loom.

While zero waste design approaches are not technologically difficult to implement, they imply a profound modification of the design and make process, through iteration and close collaboration between designer and pattern cutter. Waste generation from the early stages of the product lifecycle (especially production stage, cutting phase) must be addressed. In order to do so, profound changes will be needed from high-scale production chains. Often financially inefficient for the companies, these design and make changes need to be motivated by a common will to move towards cleaner textile production.

6.4 Post-consumer textile waste recycling techniques

Textile waste from disposed clothes at the end of the product's lifecycle are composed by different types of fabrics, natural, synthetic, and natural/synthetic blends (Chang et al. 2023, Subramanian et al. 2021), as well as buttons and zips. Hence, the recovery of fibers and disposal of textile waste is challenging. As we have seen for pre-consumer textile wastes, post-consumer wastes also have a variety of applications such as insulation materials, composited material, or renewable energies applications. However, recycling also involves energy and chemicals consumption and greenhouse gas emissions. Circular economy principles also apply for post-consumer textile waste with the aim of recovering textile fibers and subsidiary products (such as dyes) in order to revalorize them and avoid waste production.

6.4.1 Solid textile waste valorization and applications

Subramanian et al. (2021) produced an extensive review of the post-consumer textile solid wastes and their applications for fiber recycling.

Most of the wastes are cellulosic fibers such as cotton and synthetic fibers such as polyester (PET). Cotton is the most used cellulose fiber and is composed of 90% of cellulose. However, the cultivation of cotton demands important amount of water and involves the use of pesticides that are harmful to the ecosystem and human health. Synthetic fibers production involves petrochemicals with severe sustainability issues. The environmental issues associated to extensive cultivation and synthetic fibers productions have led to the development of synthetic cellulosic fibers such as viscose and lyocell. Based on cotton waste upcycling these fabrics have relatively clean production processes. Blended textiles such as polyester-cotton blends have gained interests from the scientific community and processes of separation have been studied (see next section). Cellulose also has found applications outside of the textile industry, for instance as a glucose and bioethanol production source. However, Subramanian et al. note the low conversion rate and product yield for cotton recycling application. Synthetic fibers can also be extracted and recycled into similar yarns.

Textile waste types	Valorization process	High value-added products obtained	Applications
Cotton waste (short fibers, mixed with dust and other unknown components)	Mixed acid hydrolysis	Cellulose nanocrystals (CNCs)	Hydrogels and biomedical applications
Cotton-based fabric waste	Hydrothermal method	Microcrystalline cellulose	Bio composites
	Polymerization and carbonization	Microbial fuel cell (MFC)	Electrode
	Enzymatic saccharification	Bacterial cellulose (BC)	Food packing, biomaterials, cosmetics, electric conductors or magnetic materials
Cotton/PET blended textile	Enzymatic hydrolysis	Glucose	Bioethanol production
	Submerged filamentous fungal fermentation	Fungal cellulase	Biofuel production
Textile fibers with different blends (cotton/polyester, acrylic/wool, acrylic/polyester, acrylic/viscose)	Torrefaction	Biochar	Bioenergy
Pretreated cotton fabric	Ethanol fermentation	Bioethanol	Alternative fuels
Waste jeans	Acid leaching, regeneration of the spent acid	Polyethylene Terephthalate	Fibers
Denim fabric waste as a carbon precursor	Pyrolysis	Activated carbon fibers (ACFs)	Removal of textile dye from aqueous solution
Mixed fiber bulk	Multiphase blends	Textile fiber-reinforced composite (TFRC)	Building

Table 7: Value-added products from textile wastes and their applications, adapted from Subramanian et al. (2021)

6.4.2 Innovative processes for fibers recycling

We have seen that an important part of the textile waste come from polyester (PET) and cotton blended fabrics. Cellulose regenerated from cotton fibers can have various application for downcycling, such as antibacterial filler or packaging applications (Chang et al. 2023). In their review, Subramanian et al. (2021) depict a closed-loop process for textile post-consumer recycling. Starting from a blended fabric of natural and synthetic fibers, the textile wastes are treated and transformed in fibers and secondary products recycled in textile or other industries.

The process starts with a pre-treatment of the waste fabrics. Pre-treatment enhances the properties of the fabric for future treatments and transformations. For instance, it can reduce the structural compactness of the fabric, or increase the ability to produce fermentable sugars after enzymatic saccharification for the purpose of glucose or bioethanol production, as depicted in Table 7. The pre-treatment can be of different nature. Chemical pre-treatment involves acid, alkali, or ionic liquid. All three of these methods have shown satisfactory results depending on the operational conditions. Still, ionic liquid treatment is lacking documentation in order to properly assess the benefits of this method. The fabric can also be physio-chemically pre-treated. This method involves using organic acids as a cathalyser for a hydrothermal reaction. In this way, the PET and cotton are separated through filtration. The main advantage of this technique is the biodegradable acid and its cost-effectiveness compared to other expensive ionic solvents. After pre-treatment, the cellulose is transformed into glucose through hydrolysis by cellulase, which is an enzyme that can be produced from natural sources such as bacteria and fungi. Interestingly, fungal cellulase can be directly extracted from cotton textile, with similar properties as commercial cellulase, which reinforces the circularity of the process. The resulting glucose rich solution is then fermented and value-added products are extracted, such as glucose for bio carburant production. Some of the products can be directly reinjected in the system, such as enzymes. In the meantime, PET has been separated from cotton and can be recycled into PET fibers. Below is a simplified representation of the closed-loop process studied by Subramanian et al.

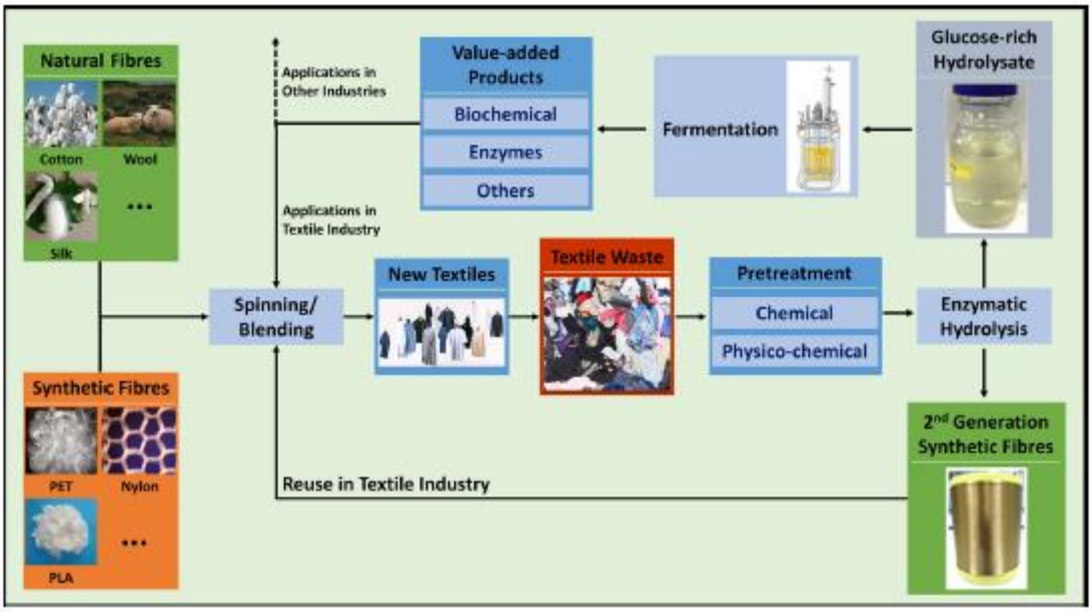

Figure 14: Existing valorization strategies and by-products obtained, Subramanian et al. (2021)

In their study, Chang et al. (2023) developed a sustainable method for PET-cotton jean fabric recycling without bleaching. We have seen that PET-cotton textile blends can be separated by dissolving the cellulose in an ionic liquid (IL) using a solvent, while the undissolved PET can be retrieved separately. It is essential that the IL solvent be retrieved without impairing its solvation ability. Moreover, in the case of jean fabric for instance, dye removal is needed in addition to the dissolution process. Usually, dye removal involves bleaching or leaching with chemical acids, and generate potentially harmful secondary effluents.

The cellulose dissolution happens in an IL using the specific [Bmim]Cl solvent, and the undissolved PET is extracted. Discoloration process is done through photocatalysis using $Bi_{11}VO_{19}$ catalyst, which doesn't affect the dissolution power of the solvent. In order to fulfill the cellulose extraction, 10% of water needs to be added to the solution. However, the water is extracted and reused in the process through distillation. In the end, the PET and cellulose are extracted, while the IL, water, catalyst, and solvents are reinjected in the process. According to Chang et al. their closed-loop process opens a new area for blended textile waste recycling. Below is a figure representing the full process:

Figure 15: Schematic illustration and results of a sustainable process for producing regenerated cellulose from waste polyester-cotton blended jeans, Chang et al. (2023)

In their study, Mu et al. (2023) focus on PET textile recycling. They begin by emphasizing several issues. As we have seen before recycling can occur at different scales: for PET recycling, it can be done yarn-to-yarn, fiber-to-fiber, polymer-to-polymer, and monomer-to-monomer. Polymer and monomer levels recycling prove to be long process and cost-inefficient compared to virgin PET production. Another issue is dye removal from the PET fibers, which is essential to achieve high value recycling of the PET fibers. One of the two option for dye removal is the destruction of dye molecules. However, Mu et al. highlight that dye destruction (through oxidation or photodegradation for instance) also leads to PET damaging and raises environmental concerns. Indeed, the damaged dye molecules can display higher toxicity than the plain ones when released in the environment. This could seem contradictory to the research from Chang et al., however in their process, Chang et al. separate the PET before discoloration happens. Thus, the extracted PET is still colored, and the main focus of the process is the cellulose discoloration for recycle.

The second and cleaner option is dye separation and recovery. Mu et al. propose a rapid and clean process for fiber-to-fiber PET recycling with dye recovery. The process involves PET and dye separation using sustainable solvent, dye recovery, PET fiber spinning, and dyeing using recycled dyes. Below is a figure representing the whole closed-loop process:

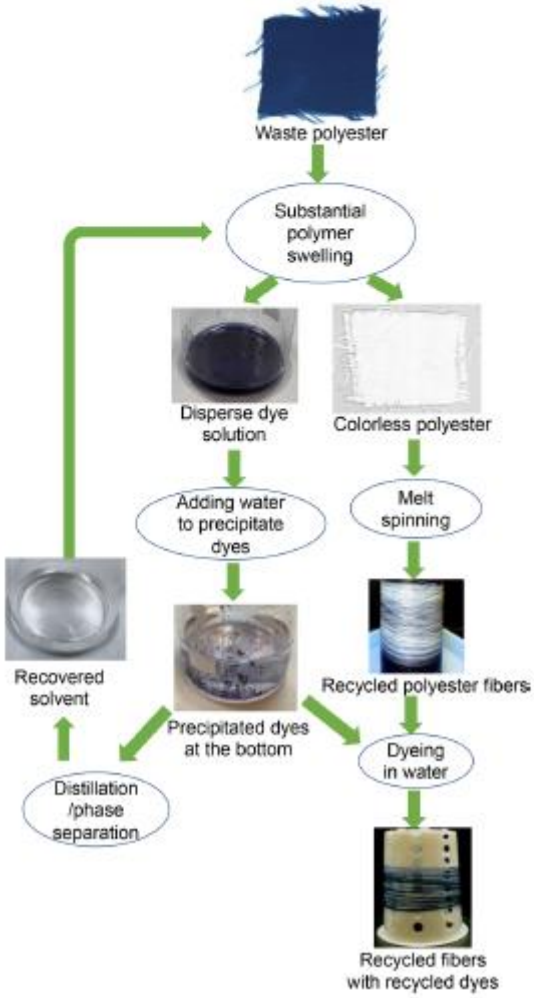

Figure 16: Recycling of PET and disperse dyes from waste textiles, Mu et al. (2023)

Mu et al. analyzed the performances of their process according to different aspects. First of all, the quality of the PET recycled fibers was similar to the one of virgin fibers. The dye used for the tests was Disperse Blue 79. The process showed complete removal of the dye and the recycled dye displayed almost identical properties as the virgin Blue 79. Moreover, the solvent was able to be reused without damaging. The recycled PET fibers showed excellent dyeability. Costs calculations proved this fiber-to-fiber process to be effective, less than 20% of the estimated costs of virgin PET fiber production. In terms of resource consumption, the production of 1 ton of recycled PET consumed less than 17% of the energy needed for the same amount of virgin PET production, and contributed to water savings, although they were not quantified in terms of percentages. Mu et al. acknowledge one drawback: up to 5% of the solvent (benzyl alcohol) may be discharged with the water because of the strong affinity between this solvent and PET. However, benzyl alcohol only has a minimal impact on the environment and is not harmful to human health.

Overall, this fiber-to-fiber process for PET recycling with non-destructive dye removal proved to be sustainable, cost effective and shows great potential for industrial applications. One question remains regarding the efficiency of the process towards other dyes than the Disperse Blue 79 for which the process was tested. Indeed, PET fibers may come with a variety of dyes and the process might need to be effective for more than one dye for industrial implementation.

6.4.3 Challenges of fibers recycling

Post-consumer textile waste management has been widely studied in the literature as one of the main issues of textile production. Although textile and fibers valorization have a beneficial impact in terms of sustainability, circular economy practices are facing obstacles for high scale implementation. From their review of solid textile waste valorization, Subramanian et al. (2021) emphasize some challenging aspects of the current processes.

One of the first obstacles is textile waste collection and separation. As Sandin et al. (2018) also mention, Subramanian et al. (2021) see this stage as one of the most hindering issues when aiming at effective recycling of textile waste. Because of the diversity of garments, textiles styles, and fabrics, separation of blended textile wastes require extensive knowledge and workforce. According to Subramanian et al. there is currently no commercially viable implementation for textile waste collection and separation. From a financial point of view, industry-wide recycling can only happen if there is an efficient system supporting the distribution of textile waste.

Another challenge lies in the variations in structures and properties of the fibers. This is particularly challenging for PET fiber production, since it might lead to quality degradation The goal with recycled fibers is to produce fibers with similar quality and properties as the virgin ones, so that the lifecycle of the recycled product is not reduced. Some processes of PET fiber regeneration include PET chips from plastic bottles to produce fibers with similar quality to virgin ones, which raises a questioning of the sustainability of the process. Subramanian et al. note that efforts to improve the quality of recycled PET fibers is limited to research scale for analytic purposes.

There is a dilemma between rentability of the recycling process and the use of clean technologies. Some of the textile waste recycling techniques involve hazardous chemicals like acids that may be harmful to the environment. Treatment, purification and recycling of textile waste also has an impact on the environment as some of the processes require fossil fuels or water supply. Researchers have been focusing on implementing cleaner processes, but reaching high product yields remains challenging.

The economic viability of textile valorization can be challenging. The processes that have been brought forward often involve reduced-scale production. As we have seen, recycling processes must be cost-efficient but at the same time sustainable. Regeneration of solvents, chemicals, acids, water and other components used in the process is mandatory to achieve cost efficiency. The risk of recycling costs surpassing production costs must be reckoned with. Moreover, incentives from governments and regulatory authorities may be needed to promote a deep change in business models and to foster cooperation between textile and non-textile industries for waste recycling.

7. Conclusions

7.1 General conclusions

In this report, state of the art literature of the last decade about clean textile production processes has been analyzed and systematized. Three main axes of research emerge from the scientific community: wastewater treatment, water management and waste management. Toxic effluents are produced at various stages of the textile production chain. Water pollution from textile wastewater is a major concern for environmental and safety issues. Wastewaters must be properly treated before being reintroduced in the system or dumped into water sources. After analyzing the merits and demerits of the different technologies for water treatment, it appears that hybrid processes involving physico-chemical and biological methods are the most promising solutions for achieving cleaner wastewater treatment.
Reducing the water consumption is another pressing issue regarding sustainability of the textile industry. While some managerial efforts can be made in order to reduce water perdition from leaking or damaged equipment, new processes are emerging with the aim of reduced or zero water discharge. Alternative technologies, like plasma treatment or aerosol technology, are being developed for processes like bleaching or finishing.
This report also highlights the question of using natural dyes with respect to synthetic ones, because of the toxic production processes of the later. However, the literature accounts for the complexity of natural dyes production and their limited properties compared to their synthetic counterpart. While the environmental impact is positive, the economic sustainability of natural colorants has for now a deterring effect on their industry-wide adoption.
Textile wastes is one of the major sources of pollution in the world. Discarded textile and wastes from production are often burned or dumped in landfills. The academic community calls for a revised approach of textile products lifecycle, with the implementation of circular economy practices. On the one hand, pre-consumer wastes can be reduced by implementing new design methods. Cutting is the production phase mainly responsible for waste generation. Zero waste pattern cutting aims at producing garments without waste, following creative cutting techniques. Because of the limited design possibilities and a called-out lack of aesthetic, these techniques are still difficult to implement in high scale textile companies. On the other end, post-consumer textile waste can be reduced with closed-loop systems. Upcycling and downcycling aims at revalorizing textile fibers into textile or non-textile products, through innovative processes. Again, textile recycling is facing some challenges due to the lack of efficient textile collecting and sorting processes, the difficulty to implement industry-wide recycling processes, and financial viability of recycling compared to production.

7.2 Limitations and future research

This report was done by analyzing scientific publications on the topic of clean production processes from the last decade. A larger and more exhaustive systematic review might highlight other processes from the years before. Additionally, enlarging the selection of keywords to specific processes like bleaching, cutting, or finishing might lead to a wider range of papers. While the innovative processes presented in the different papers show promising results within the boundaries of the experiments performed, the lack of applications at industry scale raises legitimate doubts on their feasibility.
Furthermore, although mentioned in various papers, additional research can be done on the energy management for cleaner processes, involving cleaner sources of energy and innovative processes for energy conservation within the textile production system.

7.3 Managerial implications

Current climatic issues have contributed to raise awareness on the environmental impact of the textile, and especially the fashion industry. Consumers place increasing importance in the sustainability of the fashion product they buy, and fashion companies cannot ignore the eco-responsibility of their supply-chain anymore. Manager can address this by shifting the production processes of their companies towards cleaner alternatives that have been studied in this report. While transitioning towards sustainable textile production is hard, this report emphasizes different axes that can be explored by managers for reducing the environmental impact of the textile production. Promoting cleaner practices and innovative design approaches can help managers lead their companies to eco-conscious audiences, especially the younger generations.

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