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Emerging Textile Production Technologies
Sustainability and feasibility assessment and process LCA of supercritical CO_2 dyeing

Master's thesis within the Industrial Ecology programme

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Department of Energy and Environment
Division of Environmental Systems Analysis
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Abstract

The textile industry is a large industrial sector and the production of textiles and clothing is expected to increase due to the economic growth in many developing countries as well as an increasing population. The main environmental concerns for the textile industry are: large use of water, energy, chemicals and emissions to water. A lot of focus has been on new fibres instead of new production technologies. The purpose of this master thesis is therefore to review emerging textile production technologies for wet processing that are claimed to be environmental beneficial and set up sustainability and feasibility criteria for assessing these emerging technologies. Furthermore, this study aims to deliver knowledge of the environmental performance of one of the emerging technologies, namely, supercritical CO_2 (SC-CO_2) dyeing compared to conventional dyeing. This review is based on scientific literature and on interviews and for the environmental evaluation a Life Cycle Assessment (LCA) was performed.

This study identified plasma technology, spin-dyeing, SC CO_2 dyeing, digital printing, ozone bleaching, enzymatic treatments, electrochemical dyeing and ultrasonic treatment as emerging technologies for textile wet processing. Furthermore, this study developed seven sustainability and feasibility criteria for emerging textile production technologies, namely, cost, technical quality, flexibility, interest, technology readiness level (TRL), resource availability and environmental potential. Based on the developed criteria, SC-CO_2 dyeing was chosen for further evaluation of its environmental performance. The study investigated four scenarios, two for conventional dyeing and two for SC-CO_2 dyeing. Two different electricity mixes were used and an optimisation of the CO_2 losses from 18% to 5% was also studied. The LCA result from the study indicates that SC-CO_2 dyeing can be environmentally beneficial, given that the process is optimised regarding energy use and CO_2 losses and a greener electricity mix is used. This study also shows that the production of the electricity causes the main contribution.

The result from this master thesis should be seen as a first screening of the environmental performance of SC-CO_2 dyeing. Future studies with further validation of process data are needed to determine if SC-CO_2 dyeing can improve the environmental performance of the textile industry.

Keywords: Emerging technologies, Wet processing, Supercritical CO_2, Criteria, Life Cycle Assessment.

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Cecilia Johannesson

Abbreviations

CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalents
COD	Chemical oxygen demand
BOD	Biochemical oxygen demand
FU	Functional unit
GHG	Greenhouse gas
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
NaOH	Sodium hydroxide
O_3	Ozone
PA	Polyamide
PES	Polyester
PET	Polyethylene terephthalate
PU	Polyurethane
SC-CO_2	Supercritical CO_2
TRL	Technology Readiness Level
VOC	Volatile organic compounds

Contents

1 Introduction

The textile and clothing industry is one of the largest industrial sectors with a total share of 4.3% in world merchandise trade in 2014 (WTO, 2015). The leading exporters of textiles are China, the European Union, India, United States and Turkey. The global export of clothing and textiles grew in 2014 to 797 billion US dollar. In 2011, the global production of all fibres was 84.1 million tons which was an increase of 4.4% compared to previous year, 2010 (Aizenshtein, 2012). Cotton is today one of the most important global textile fibres and represents 40% of the total global consumption (Bevilacqua et al., 2014). Consumption and production of textiles and clothing are expected to increase due to an increasing population as well as the current economic growth in many developing countries and the environmental impact from the textile industry is therefore of high concern (Hasanbeigi & Price, 2015).

Cultivation and processing of cotton require large amounts of water (Bevilacqua et al., 2014). Besides high water consumption, it has been estimated that cultivation of cotton is responsible for 11% of the global consumption of pesticides and cotton is therefore associated with severe environmental impacts on ecosystems and freshwater resources. The textile industry is also responsible for the use of large amounts of fuels, electricity and chemicals, which in turn causes greenhouse gas (GHG) emissions and contaminated waste water (Hasanbeigi & Price, 2015). The environmental issues related to the industry are caused by the whole supply and production chain, from fibre production to finishing processes of textiles (Parisi et al., 2015). However, wet processing in textile production, which includes pretreatment, dyeing, printing and finishing, to create colour, pattern and special characteristics, is particularly of high concern due to its adverse environmental impact (Chen & Burns, 2006).

The growing demand for textile products and the adverse environmental impact set requirements on the industry to become more sustainable. In this context, a lot of focus have been on finding new fibres that are better from an environmental perspective. However, according to Roos et al. (2015) the main concern is not related to the fibre production step in textile production. Furthermore, according to Nieminen et al. (2006), emerging technologies for textile production have a key position and are of high importance in order for the textile industry to become more sustainable. This study will therefore focus on alternative textile production technologies for textile wet processing in order to investigate how this can promote a sustainable textile industry.

No guidelines for assessing the sustainability and feasibility of emerging textile production technologies exist. This has inspired this study to investigate which criteria that should be set up for emerging textile production technologies. Finally, this study will also contribute to the Mistra Future Fashion Research program, described below.

1.1 Mistra Future Fashion

Founded by Mistra, the Swedish Foundation for strategic environmental research, the Mistra Future Fashion research program started in 2011. The purpose of the program is to generate insights and to improve the environmental performance of the Swedish fashion industry as well as to create a national research platform for sustainable fashion. The program involves stakeholders in the whole textile product chain (Mistra Future Fashion, 2016).

During the first phase (2011-2015), the research program ran eight projects with various foci and the program has now continued into a second phase that will last until 2019. This master thesis project will contribute to knowledge within the Mistra Future Research program and has been conducted within one of its four themes, which is called the supply chain theme.

1.2 Purpose

The purpose of this master thesis project is to review emerging technologies within the textile production with a focus on wet processing technologies and set up criteria for assessing the sustainability and feasibility of emerging textile production technologies. Furthermore, this thesis aims to deliver detailed knowledge of the environmental performance of one emerging technology for textile production. The following research questions are addressed in this master thesis project:

- Which technologies are the currently most important "emerging textile production technologies"?
- Which criteria for assessing the feasibility and sustainability of emerging textile production technologies should be set up?
- What is the environmental performance of one emerging technology compared to existing technology?

1.3 Delimitations

This study only focuses on fashion, which means that processes only applied for home textiles, technical textiles and high performance textiles (outdoor and work-wear textiles) are not included in this study. The main focus of this thesis are environmental aspects of sustainability. Other aspects such as socio-economic aspects are therefore not in focus in this thesis.

Furthermore, this thesis focuses on technologies for wet processing that can be used for cotton, elastane, polyester (PES) and polyamide (PA) (figure 1). This study has conducted a literature review of some sources which means that the list of emerging technologies is not exhaustive. Finally, due to time constraints, only one technology that scored highly on the developed sustainability and feasibility criteria was further investigated in this thesis.

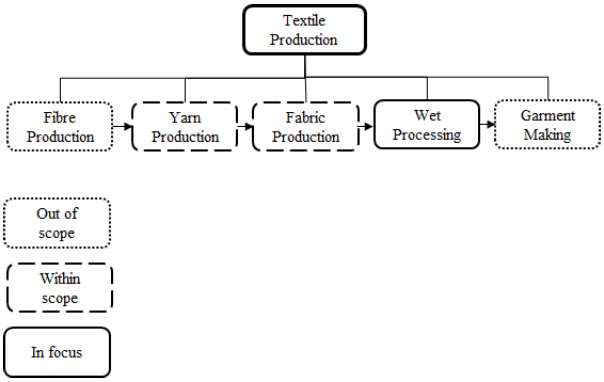


Figure 1: Production areas in focus of this study.

1.4 Outline of the thesis

This report is divided into 8 chapters. First, chapter 2 presents a theoretical background regarding textile production.

Chapter 3 describes the methodology regarding how this thesis was performed. In chapter 4, a review of emerging technologies for textile wet processing is presented, which includes eight technologies.

In chapter 5 sustainability and feasibility criteria for assessing emerging textile production technologies are developed. Based on these, SC-CO_2 dyeing was selected for further study.

Chapter 6 presents a LCA study of SC-CO_2 dyeing and conventional dyeing of PES fabric in order to investigate the difference in environmental impact.

Finally, chapter 7 discusses the results from this study and conclusions are presented in chapter 8.

2 Textile production

This chapter presents the theoretical and the practical background of textile production. The different stages in the manufacturing chain are described together with a description of existing conventional technologies as well as the environmental concern related to these technologies.

The textile industry has a complicated industrial chain due to the variety of fibres, processes and finishing steps (pretreatment, dyeing, printing, chemical and mechanical finishing and coating) (Hasanbeigi, 2010). The main steps in production of textiles are: fibre production, yarn production, fabric production, wet processing and garment making. A general flowchart that describes the production steps of textiles is presented in figure 2. Important to notice is that all process steps do not always take place in the same facility and which processes that are needed depend on the fibre used as well as the end-use of the textile product.

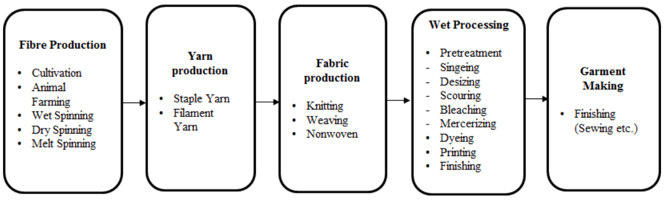


Figure 2: Textile production flowchart.

2.1 Fibre production

Fibres are the smallest component of textile fabrics and the two main types of fibres are natural and manufactured fibres (Humphries, 2009). Natural fibres are fibres that can be found in nature and the main sources are plants (i.e. cellulose based) and animals (i.e. protein based). The most important natural fibres are cotton and wool (Schönberger & Schäfer, 2003). Natural cellulose-based fibres can further be divided into seed (e.g. cotton), bast (e.g. hemp) or leaf (e.g. sisal) depending on which part of the plant the fibre comes from (Sinclair, 2015). The most important manufactured fibres are PES, PA, polyacrylonitrile, polypropylene, acetate and regenerated cellulose (viscose) (Schönberger & Schäfer, 2003). Manufactured fibres are made from either natural polymers, synthetic polymers or inorganic material. Figure 3 illustrates the different categories for fibres as well as some examples.

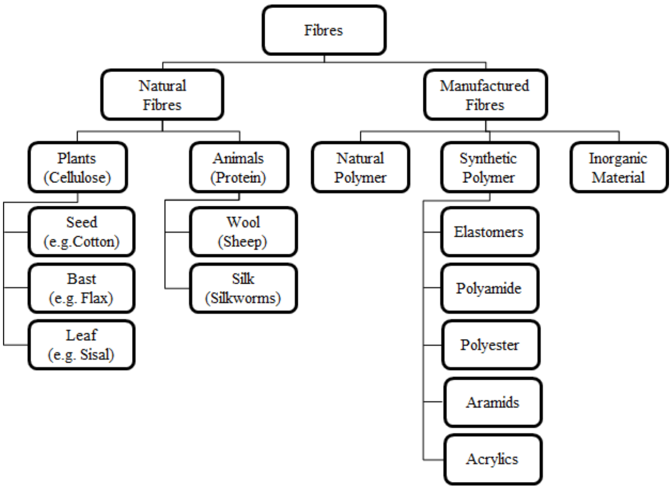


Figure 3: Typology of textile fibres (Humphries, 2009; Sinclair, 2015).

Fibres have a broad range of physical, chemical and mechanical properties (Sinclair, 2015). Length, shape, colour, strength, flexibility, abrasion resistance and moisture absorbance are some important mechanical and physical properties of fibres. Important chemical properties includes chemical reactivity, resistance and antimicrobial properties. Moreover, textile fibres can be classified as either staple or filament fibres (Humphries, 2009). Most of the natural fibres are staple fibres which are short and measured in millimetres compared to filament fibres which are longer, measured in meters. All manufactured fibres are filament fibres but can be cut to staple fibres. This study focuses on cotton, PES, PA and elastane, shortly described in the following subsections.

2.1.1 Cotton

Cotton is one of the most important apparel fibres (Karthik & Gopalakrishnan, 2015). Cotton consists mainly out of cellulose and some other compounds like waxes and pectins in varying composition (Schönberger & Schäfer, 2003). Cotton has a variety of application in textiles due to the beneficial properties of cotton, that is absorbent, comfortable, good static resistance and that the fibre withstands machine wash and drying (Humphries, 2009). There are many types of cotton with different characteristics, however, cotton is usually divided into three groups, depending on the length of the staple fibre (Yu, 2015). Cotton is cultivated mainly in North and South America, Asia and Africa. After harvesting, the cotton seed is transported to a ginning plant where the fibre is separated from the seed and other plant matter. The main environmental concern related to cultivation of cotton are high water use, land use and use of pesticides (Karthik & Gopalakrishnan, 2015).

2.1.2 Polyester

PES fibres are the most widely used synthetic manufactured fibres due to favourable properties and because the manufacturing process is less expensive compared to PA (Humphries, 2009). The properties can appear similar to PA fibres, but PES conducts moisture away from the skin better than PA fibres and dries faster. PES is a good fibre regarding strength and abrasion resistance. There are several types of PES, but the one that was first developed is called polyethylene terephthalate (PET). PES fibres are based on terephthalic acid with different glycols such as butane diol or propylene glycol, with the most common being ethylene glycol (European commission, 2007). PET can be produced by two methods, either by using dimethyl terephthalate or with terephthalic acid (Deopura & Padaki, 2015). PES fibres for textiles are mainly produced from dimethyl terephthalate and ethylene glycol in a batch polycondensation process (Roos et al., 2015).

2.1.3 Polyamide

PA, also known as nylon, was the first synthetic fibre to be produced and is used for its strength, abrasion resistance and heat settability (Humphries, 2009). PA is chemically characterised by a macromolecular structure with an amide group (-NH-CO-) (European commission, 2007). There are two types of PA, PA 6, made from caprolactam and PA 66 that is made from hexamethylene diamine and adipic acid (nylon salt) (Plastics Europe, 2016). The raw material for producing PA 6 and PA 66 are derived from refinery products from the petrochemical industry such as benzene, cyclohexane and p-xylene. PA 6 is the most used PA, mainly due to the availability of raw material and several application possibilities (European commission, 2007). PA 6 can be produced both by batch and continuous polymerisation and the main process steps are: polymerisation, cutting, extraction, drying and extract water processing. PA 66 can be manufactured through a batch or continuous polymerisation of nylon salt in solution.

2.1.4 Elastane

Elastane is a synthetic manufactured fibre that is produced from an elastomer that contains at least 85% of polyurethane (PU) (European Commission, 2003). Elastane also known as spandex or lycra, consists of both hard and elastic polymer segments (Humphries, 2009). Elastane is the most expansive of all synthetic fibres and the most important characteristic of elastane fibre is the elasticity. Elastane fibres are used in a combination with other fibres with an amount of 3-50%.

2.2 Yarn production

Yarn is a continuous thread of fibres or filaments that can be knitted or woven to fabric (Humphries, 2009). There are two types of yarn: filament yarn and staple yarn. These two yarn production methods are described in the following chapters.

2.2.1 Filament Yarn

To produce yarn from manufactured polymers, the polymers have to be spun, using a spinning method. There are several spinning methods applied for manufactured fibres, the most used are melt spinning, dry spinning and wet spinning (Alagirusamy & Das, 2015). In melt spinning, used for thermoplastic polymers (e.g. PES and PA), the polymer granulates from the polymerisation process are melted and extruded from a nozzle (Schönberger & Schäfer, 2003). The nozzle can be of different sizes and after the polymer is extruded the fibres are cooled and stretched to create orientation of the polymer chain, finally, the filaments are collected on a take-up wheel (Alagirusamy & Das, 2015). The process temperature for melt spinning for PES is 280-300^{o}C and 280^{o}C for PA (Lawrence, 2015).

In both dry spinning and wet spinning the polymer is dissolved in an appropriate solvent (Schönberger & Schäfer, 2003). Dry spinning is used for polymers that cannot be spun by melt spinning due to safety and environmental concerns, for example elastane (Alagirusamy & Das, 2015). After the polymer has been dissolved in a volatile solvent, the solution is pumped through a spinneret and before the fibres are collected on a take-up wheel, air or inert gas is used to evaporate the solvent from the fibre. Wet spinning is the oldest spinning method and is used for acrylic fibres. In wet spinning, the viscous solution of polymer and solvent is extruded into a bath containing a second solution called the spin bath (Lawrence, 2015). The spin bath precipitates the polymer and coagulates the chain into continuous filaments. The continuous filaments are then drawn out from the spin bath, washed, stretched and dried.

2.2.2 Staple Yarn

As mentioned before, staple fibres are of short length and needs to be twisted together to produce yarn (Elhawary, 2015). Staple fibres require processing before yarn can be produced and specially cotton needs to proceed with several process steps (i.e. cleaning, blending, carding, combing, drawing and roving). After preparation processes the fibres are spun to yarn. Staple yarn is formed in spinning mills and there are several spinning technologies for spinning of staple fibres. Most of the staple fibres are spun by either ring spinning (70%) or rotor spinning (23%) (Elhawary, 2015).

During the spinning process, spinning lubricants and conditioning agents are applied, which contribute to notable environmental impact since these auxiliaries needs to be removed before the dyeing (European Commission, 2003). Auxiliaries used in the spinning process contribute to both air pollution as well as the organic load in effluent. Spinning lubricants may also lead to emissions of hazardous chemicals like polyaromatic hydrocarbons and biocides.

2.3 Fabric production

There are several methods to produce textile fabric from yarn. The three most important processes for fabric production are knitting, weaving and nonwoven (Hasanbeigi, 2010). These three processes are described briefly below.

2.3.1 Weaving

Weaving is a widely used method for fabric production and can be used to give a variety of textile structure (Humphries, 2009). Weaving is obtained by a process by which yarn is assembled together on a loom (weaving machine) (European Commission, 2003). Before the weaving process, most of the staple yarns and some of the filament yarns have to be sized (Schönberger & Schäfer, 2003). Sizing is done in special machines and is used to protect the yarn from damage during the weaving process. The process itself only requires electricity, however, lubricants and oils are needed for the loom (European Commission, 2003).

2.3.2 Knitting

Knitting is one of the most used methods to produce textile fabric out of yarn. The fabric structure is constructed from a series of intermeshing loops (Power, 2015). Modern machine knitting is divided into two types, weft knit and warp knit (Humphries, 2009). Compared to woven fabrics, knitted fabrics are lighter, more porous and have comfort stretch. However, knitted fabrics are less stable than woven (Power, 2015). To protect the yarn from mechanical stresses during knitting, the yarn is normally waxed or lubricated before (European Commission, 2003). Oil and waxes stay on the fabric until the finishing processes when the fabric is washed.

2.3.3 Nonwoven

Nonwovens are fabric that are made directly from fibres without yarn processing (Schönberger & Schäfer, 2003). Nonwovens are normally produced as sheet material from filaments or fibres according to two stages (Mao & Russell, 2015). Firstly, a web of fibres are constructed and secondly, these webs are bonded together using a web bonding technology. There are several methods for web bonding such as mechanical, thermal and chemical bonding (Humphries, 2009). In the production of nonwoven fabrics, the main environmental impact is due to the emissions of gases from the chemical and thermal web bonding technologies (European Commission, 2003).

2.4 Wet processing

Wet processing in textile production involves different process steps. The main processes in wet processing are: pretreatment, dyeing, printing and finishing. Depending on the end-use and the required properties of the textile, all or only some of the processes described below are employed. Wet processing is one of the major energy consuming stages due to the use of thermal energy for steam and heat (Hasanbeigi & Price, 2012).

2.4.1 Pretreatment

Pretreatment of textiles consists of several process steps and is important for removal of natural impurities (Schönberger & Schäfer, 2003). Pretreatment is also important in order to improve the properties of the fibre and to increase the quality of downstream processes such as dyeing. Typical pretreatment processes for cotton are shortly described in the following subsections.

Singeing

Singeing is done to give a smooth surface for high-quality cotton cloths (Humphries, 2009). It can also be used for PES to prevent pilling and the process is executed by passing the fabric quickly over a gas flame which burns of fibres that stick out. After the fabric has been passed over the gas flame, the fabric is put into a quench bath to cool the fabric (European Commission, 2003). The quench bath often contains a solution for desizing and singeing can therefore be combined with desizing. The process can be used for both yarn and fabrics and is most common for cotton, cotton/PA and cotton/PES blends. Singeing is specially important if the fabric should be printed, since that requires a smooth surface (Schönberger & Schäfer, 2003). The main environmental problems related to singeing are dust and volatile organic compounds (VOC) during the process.

Desizing

Desizing is used to remove size material from fibres and is often used as a pretreatment process for woven fabrics that are produced from cotton or cotton blends (Schönberger & Schäfer, 2003). Desizing is also needed for manufactured fibres that contain sizes and is often the first step in pretreatment of fabrics if singeing is not needed (European Commission, 2003). There are several different desizing techniques depending on which type of sizing agent that should be removed. Enzymatic desizing is the most used technique for removal of starch-based sizes. It is common in the industry to try to minimize the number of process steps in pretreatment. One opportunity to combine desizing and bleaching is to use oxidative desizing where the fabric is placed in a bath containing hydrogen peroxide, sodium hydroxide (NaOH), stabilisers and complexing agents. However, oxidative desizing is difficult to control, which means that the cellulose can be damaged in the process (Schönberger & Schäfer, 2003). Manufactured fibres contain water-soluble sizes, which are removed with hot water and sodium carbonate. This desizing process is carried out in an industrial washing machine (European Commission, 2003).

Scouring

Scouring is a cleaning process to extract natural impurities (i.e. waxes, pectin, proteins and metal salts) (European Commission, 2003). The process is used for cotton and their blends as well as for other natural fibres. During the process the fibres are treated with hot alkali and it can both be a continuous or a discontinuous process. Usually the alkali treatment used consists of NaOH (Grancari et al., 2006). Besides NaOH, surfactants and complexing agents are used in the process (Schönberger & Schäfer, 2003). Scouring involves use of large amounts of water, high energy requirement and waste water containing NaOH (Grancari et al., 2006). Scouring leads to high COD load (chemical oxygen demand) due to the removal of organic impurities. The COD-concentration is typically 2,000-6,000 mg O_2/l (Schönberger & Schäfer, 2003).

Bleaching

To improve the whiteness, the absorbency and in order to remove impurities and natural colouring compounds, bleaching is employed (Arooj et al., 2014). Only natural fibres require bleaching, since synthetic fibres can be manufactured to be transparent (Hauser, 2015). Cotton is often bleached with hydrogen peroxide. Such bleaching with hydrogen peroxide requires alkaline conditions and stabilizer (e.g. sodium silicate) to control the reaction. Other auxiliaries used are surfactants with emulsifying, dispersing and wetting properties (European Commission, 2003). Conventional bleaching process requires high temperature (100-130°C) and extensive use of chemicals (Arooj et al., 2014). A rinsing step is also required in order to remove residuals of NaOH that is used as bleaching agent.

Mercerising

Mercerising is used for cotton in order to increase the tensile strength and the lustre of the fabric (European Commission, 2003). An improvement of dye uptake can also be accomplished with mercerising and the consumption of dyestuff can be reduced by 30-50%. During mercerising the fabric is treated with a solution containing NaOH and the fabric is usually held under tension during the treatment (Humphries, 2009). The concentration of NaOH varies between 20-30%, however, the main environmental concern with mercerising is the NaOH residual (Schönberger & Schäfer, 2003). The process is performed in the following process steps: padding of the textile with NaOH, drafting of the textile, washing and finally, acidifying and rinsing. Mercerising can also be done with NaOH without tension of the fabric (European Commission, 2003). The process is carried out in 20-30°C with 145-190 g NaOH per litre of water. Mercerising can be performed on yarn, woven or knitted fabrics.

2.4.2 Dyeing

Dyeing is the process where colour is applied to the textile material (Hasanbeigi, 2010). The process is usually executed in water but other methods can be used as well, like solvent and molten metal dyeing (Humphries, 2009). Dyestuff, chemicals (e.g. salts and acids) and auxiliaries (e.g. surfactants and dispersing agents) are used in dyeing of textiles (Schönberger & Schäfer, 2003). The process, amount of dyestuff, chemicals and auxiliaries depend on the fibre and the quality required. Nine different classes of dyes are presented in table 1 together with an indication whether they are commercially applied for cotton, elastane, PES and PA.

Table 1: Classes of dyes and whether they are commercially applied dye for cotton, elastane, PA and PES (Richards, 2015).

Type of dye	**Cotton**	**Elastane**	**PES**	**PA**
Direct	✓			
Reactive	✓			✓
Vat	✓		✓	
Sulphur	✓			
Azoic	✓			
Acid			✓	
Metal-complex			✓	
Mordant			✓	
Disperse		✓	✓	✓

Textiles can be dyed in several of the stages in textile manufacturing (i.e. fibres, yarn, fabric and garment). Dyeing can be performed in both batch or continuous/semi-continuous process. The choice between the two options depends on cost, available equipment and the dyes (European Commission, 2003). Both the batch and continuous dyeing process involve the following steps: preparation of the dye, dyeing, fixation and finally, washing and drying.

Several pollutants are related to dyeing of textiles (Karthik & Gopalakrishnan, 2014). Both the dyestuff and chemicals used during the dyeing process, cleaning and maintenance of the equipment contribute to the environmental impact. It has been reported that dyeing consumes 5% of the water use and causes 7% of the BOD (biochemical oxygen demand) in a finishing process for cotton (Karthik & Gopalakrishnan, 2014).

Batch dyeing

In batch dyeing an amount of fabric is put into a dyeing machine containing dye and auxiliaries (European Commission, 2003). The colourant is absorbed to the fibre and the fixation is increased with chemicals and controlled temperature. After the dyeing process, the dye bath is drained and the textile material is washed and dried.

Continuous dyeing

In continuous dyeing the dye solution is applied by impregnation or by other application systems (European Commission, 2003). The most common process for continuous dyeing of textiles are continuous feeding of textiles into a dip with dye. After the dip, the textile material is fed through rollers that control the uptake of dye. Finally, heat and chemicals are used for fixation of the dye and the textile material is then washed and dried.

2.4.3 Printing

Dyeing is preferred for adding colour and simple patterns while printing is used for more complex patterns (Hasanbeigi, 2010). Another difference between printing and dyeing is that printing involves adding pattern to the surface whereas dyeing is a process that includes penetration of the fabric (Humphries, 2009). The printing process involves the use of colour, often in the form of a paste (Hasanbeigi, 2010). The printing process is followed by drying and steaming in order to fix the colour onto the fabric (Schönberger & Schäfer, 2003). A washing step and an additional drying step are also needed except for when pigment dye is used in the printing process. The main environmental impact from printing of textiles is due to the waste water from washing as well as cleaning of the equipment (Schönberger & Schäfer, 2003). Similar to dyeing, printing causes high amounts of pollutants as well as high BOD and COD load (Karthik & Gopalakrishnan, 2014).

There are several techniques for printing of textiles, but the most common are: roller printing, rotary screen printing and heat transfer printing (Humphries, 2009). Roller printing is a quite inexpensive fast method and has been an important method for a long time. Today, roller printing has become a less used technology since preparing the rollers takes long time and is expensive. Fabrics produced today are also too wide for roller printing. The most used printing method is rotary screen printing, which accounts for almost half of all printing (Humphries, 2009). Rotary screen printing is performed with metal foil, so called "screens", in cylinder form. The printing paste is placed in the center and pushed through the screens using electrostatic power. Transfer printing is mainly used for fabrics made from PES and the pattern in transfer printing is created by applying heat to a paper, which transfers the pattern from the paper to the fabric (Schönberger & Schäfer, 2003).

Finishing

Finishing relates to treatment processes that are used for improving properties of the textile (European Commission, 2003). Finishing treatments can be mechanical, thermal or chemical processes to change properties related to visual effects or certain characteristics of the textile depending on the end-use of the product. Some examples of finishing processes are, easy-care finishing for cotton and antistatic treatment for synthetic fibre. Chemical finishing processes are of higher environmental concern than mechanical due to the higher pollution potential. The main environmental concern related to finishing processes are emissions to air together with solid and liquid waste (Karthik & Gopalakrishnan, 2014).

2.5 Garment making

Garment making include various processes in order to finalise the product to a garment. Processes for completing the garment include sewing, steaming etc.

3 Methodology

This chapter describes how this thesis was performed, methods used and important choices made during the study. The work progress of this thesis was divided into three phases, review, screening sustainability and feasibility assessment and process LCA, see figure 4.

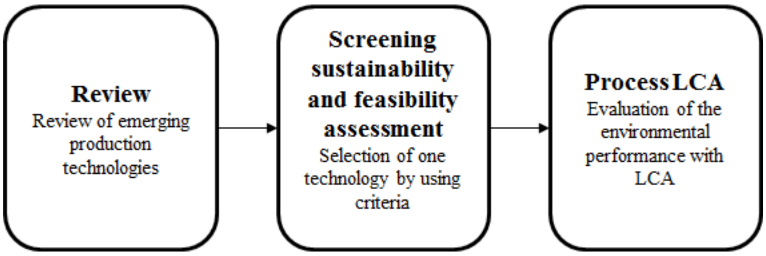


Figure 4: Phases for execution of this master thesis.

The project started with a review phase with focus on technologies with the possibility to substitute the environmentally problematic wet processes used in the production of textiles. The aim with the review phase was to get an overview of new emerging technologies for textile production, in order to later do a selection of one technology with the highest priority for this study, using developed sustainability and feasibility criteria. The screening phase was conducted using literature studies and semi-structured interviews. The literature study and semi-structured interviews are further described in sections 3.1-3.2. After the review phase, sustainability and feasibility criteria were developed in order to select one technology for further evaluation of the process potential to improve the sustainability. Finally, the environmental performance was evaluated in more detailed by an LCA described in chapter 4.

3.1 Literature study

Several literature sources were used in this study for both the background as well as the review phase. Most of the literature was collected from articles in scientific journals (e.g. Journal of Cleaner Production and Textile Research Journal) and books, although, some web pages were used as well. The literature sources were selected based on the relevance for this study as well as publishing date since more recently published literature is of higher interest in order to get updated information in this field of research. Moreover, the business journal Ecotextile News was studied in order to be informed of news in the textile industry. As mentioned above, several literature sources were used in this study, but, three main sources that can be highlighted in this study are: European Commission (2003) (a reference document for best available technologies with pollution prevention and control), Hasanbeigi & Price (2015) and Schönberger & Schäfer (2003).

3.2 Semi-Structured interviews

The interviews were conducted using semi-structured interview as methodology. Semi-structured interview is an interview methodology where a pre-set interview protocol is prepared beforehand in order to guide the interviewees with a set of questions or subjects for discussion (Reed et al., 2009). Semi-structured interviews also allow flexibility since the questions can be asked in or out of sequence and interviewers can ask additional questions. Semi-structured interviews are useful when information regarding a specific topic is fragmented and was therefore chosen as methodology for this study.

Before each interview, an interview template was sent out, see appendix A, with a project description and some questions to be discussed. Notes were taken during each interview and the interviews were also recorded. All interviewees were asked for recommendations of other persons that could be of interest to interview in this study, so called snowball sampling (Reed et al., 2009). Interviews for this study were conducted with researchers at the Swedish School of Textiles at Borås as well as stakeholders in the fashion industry.

3.3 Life Cycle Assessment

LCA stands for Life Cycle Assessment and has been brought forward as an important tool for analysing the environmental impact from products and services. The whole life cycle of a product or service from the production and extraction of raw material to the use phase and disposal can be included in an LCA study (Baumann & Tillman, 2004). LCA can be used for decision making, learning and communication.

There are international standards for LCA, ISO 14040,14044 (Baumann & Tillman, 2004). The procedure of an LCA study is divided into four phases, see figure 5. In the first step, the goal and scope definition, the purpose and the product of the study are defined. The second step is the life cycle inventory analysis (LCI) where a system model and system boundaries of the technical system is defined. Furthermore, inventory analysis also include mass and energy balances and data collection for all activities in the system. The life cycle impact assessment (LCIA) aims to assess the impact from the environmental load calculated in the inventory analysis. Finally, interpretation is important in order to identify the significant issues, evaluate the result and draw conclusions from the study.

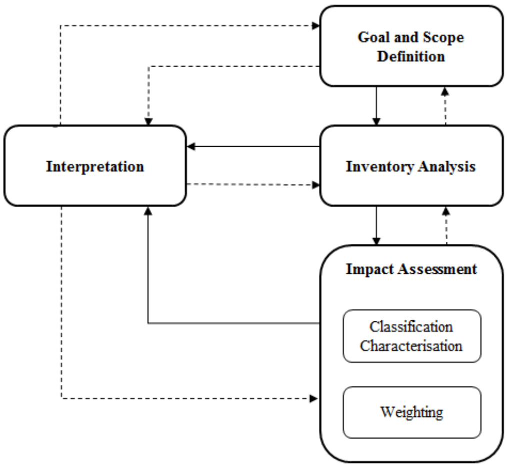


Figure 5: LCA procedure based on Baumann & Tillman (2004). The arrows show the procedural order and the broken arrows indicate possible iterations.

The LCA software tool SimaPro version 8.1.0.60 was used for this LCA study. The details of how the LCA was conducted can be found in chapter 6.

4 Emerging technologies for textile wet processing

This chapter presents a review of some emerging technologies for wet processing in the textile industry. None of the technologies presented are fully commercialized, however, it is claimed that they have environmental benefits such as reduced amount of energy, water and chemicals used. The technologies that are presented in this chapter are: plasma technology, spin-dyeing, supercritical CO_2 dyeing, digital printing, enzymatic treatments, electrochemical dyeing and ultrasonic treatment. This chapter ends with a table that summaries the main information of the presented technologies.

4.1 Plasma technology

Plasma can be described as a mixture of partially ionized gases, where atoms, radicals, ions and electrons can be found, sometimes referred to as the fourth state of matter (European Commission, 2003). Plasma used in the textile industry consists of gases such as oxygen, air, nitrogen argon, helium or fluorine (Samanta et al., 2014). Plasma can be produced in both the industry and in the laboratory (Zille et al., 2014).

There are several types of plasma that can be divided into two categories: non-thermal and thermal plasma. The temperature in thermal plasma is very high and is therefore not used for textile material, which often consists of heat sensitive material. Non-thermal plasma, also known as cold plasma, is more suitable to use in the textile industry (Morent et al., 2008). Non-thermal plasma can further be divided into atmospheric and low pressure plasma (Zille et al., 2014). The most used and established plasma is corona plasma, which is a type of atmospheric plasma (Jelil, 2015). Table 2, lists some properties of corona and low pressure plasma. Corona plasma is generated through low frequency and high voltage between two electrodes during atmospheric pressure (Zille et al., 2014). The process of low pressure plasma technology is easier to control, which make the results reproducible (Jelil, 2015). Low pressure plasma contains high concentration of reactive species compared to atmospheric plasma (Samanta et al., 2014). The disadvantages with low pressure plasma are longer process time and that only batch processes can be performed.

Table 2: Comparison between corona and low-pressure plasma (Schönberger & Schäfer, 2003).

	Corona plasma	**Low pressure plasma**
Generation of plasma	High voltage between coated electrodes	Direct current or high frequency
Pressure	Atmospheric pressure (1 bar)	Low pressure (1 mbar)
Continuous process	Easy	Difficult

Area of application

Plasma technology can be used for both natural and manufactured fibres (Schönberger & Schäfer, 2003). The technology is used for surface modification in order to increase the efficiency of several treatments and processes. According to Samanta et al. (2014) plasma technology is one of the most promising emerging technologies for surface modification in the textile industry. The physical and chemical changes on the fibres are obtained by activation, cleaning, oxidation, polymerisation, radical formation and creation of nano-structure caused by the plasma. The wide range of application areas for plasma technology includes pretreatment (desizing), change of wettability, pretreatment for printing and dyeing (increased affinity for dyestuff), antibacterial finishing, improvement of efficiency of wet finishing processes and influence of the physical properties (Schönberger & Schäfer, 2003; Morent et al., 2008).

Future status

According to Samanta et al. (2014), plasma technology has the potential to be commercialized for the textile processing of home, apparel and technical textiles at lower cost compared to existing processes. Low pressure plasma has been extensively studied, but has not been commercialized due to technical and economical limitations. Atmospheric plasma can overcome the limitations of low pressure plasma and is investigated for several applications. Furthermore, low pressure has been difficult to up-scale for continuous processes and batch processing limits the commercial application (Jelil, 2015). According to Jelil (2015) the textile industry, today, manages the coating and finishing steps with existing equipment, which often consists of very simple methods. Substitution of the existing methods with the more expensive plasma technology is therefore difficult.

According to Morent et al. (2008), there are several possible reasons for the slow development of plasma technology in the textile industry such as limited information regarding optimal treatment conditions, the variety of plasma sources, the lack of scientific reports regarding the use in industrial reactors and the use of plasma effect characterisation tools that are not adapted for textiles. According to Radetic et al. (2007), plasma technology can not replace all processes in textile wet processing, but, it can be a viable pretreatment technology with environmental and economic benefits. Furthermore, according to Jelil (2015), plasma technology can be used for new surface characteristics, that can not be performed with existing wet processing. Plasma technology can therefore be important for innovation of new products.

4.2 Spin-dyeing

Almost all fabrics are dyed, which increases the environmental impact from the industry and actions for reducing the environmental load from the dyeing process are therefore important. According to We are spindye (2016), which is a Swedish company working with spin-dye technology, the spin-dye process is a dyeing process that takes the water out of the process. Spin-dyeing is a process simplification where the dyeing agents are added to the spinning solution (Shuster et al., 2014). In contrast, the conventional dyeing process, dyes the woven or knitted fabric. The spin-dye process combines spinning and dyeing, which reduces the number of process steps.

Area of application

The technology can be used to receive any colour, today, the technology is only used for colours with large market volumes (i.e. black, brown, red and dark blue). The process is successful for cellulosic and non-cellulosic fibres (Schuster et al., 2014).

Future status

Two LCA studies (Schuster et al. (2014) and Manda et al. (2014)) show that spin-dyeing is environmentally beneficial compared to conventional dyeing process. The spin-dyeing process is used in the textile industry and due to the environmental advantages, it can be expected that the technology will be further adapted in the textile industry.

4.3 Supercritical CO_2 dyeing

Supercritical fluids are materials that are above the critical pressure and temperature of the material (European Commission, 2003). The critical point for carbon dioxide (CO_2) occurs at a pressure of 73.8 bar and at a temperature of 31.1^{o}C (Ahmed & El-Shishtawy, 2010). Figure 6 shows the phase diagram for CO_2 including the critical point.

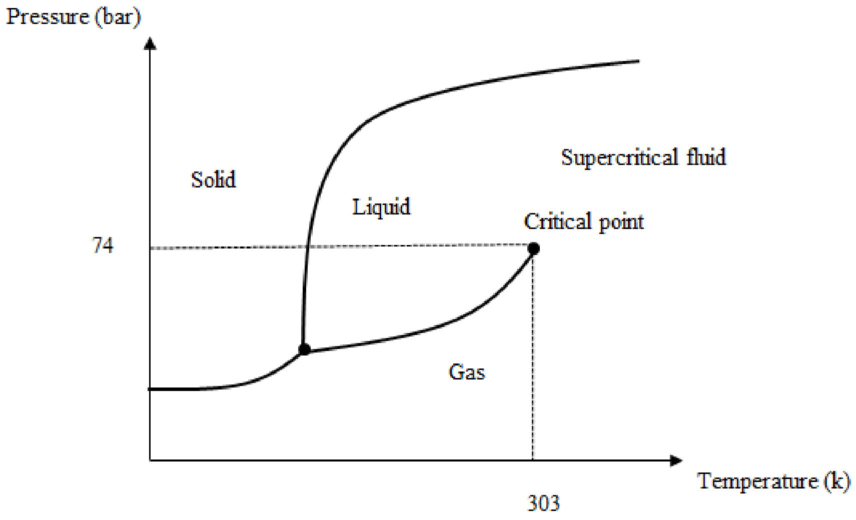


Figure 6: Phase diagram of CO_2 based on Ahmed & El-Shishtawy (2010).

CO_2 is produced commercially and is often used as a solvent since CO_2 is non-toxic, non-hazardous and a non-corrosive gas. Supercritical fluids can dissolve organic molecules that are hydrophobic, such as disperse dyestuff. SC-CO_2 can therefore be used as a dyeing medium for dyeing of textiles (Nieminen et al., 2006). SC-CO_2 has two functions in the dyeing process, heating the substrate and transporting the dye (Hasanbeigi & Price, 2015). The critical point of SC-CO_2 gives CO_2 the properties of both a gas and liquid (Bach et al., 2002). This means that, SC-CO_2 has the density of a liquid, which is advantageous for dissolving hydrophobic dyes and low viscosity and diffusion properties of gases, which reduces the dyeing time.

The SC-CO_2 dyeing process compared to conventional water dyeing is illustrated in figure 7 (Bach et al., 2002). No drying step is required in SC-CO_2 dyeing since CO_2 is released in gaseous state.

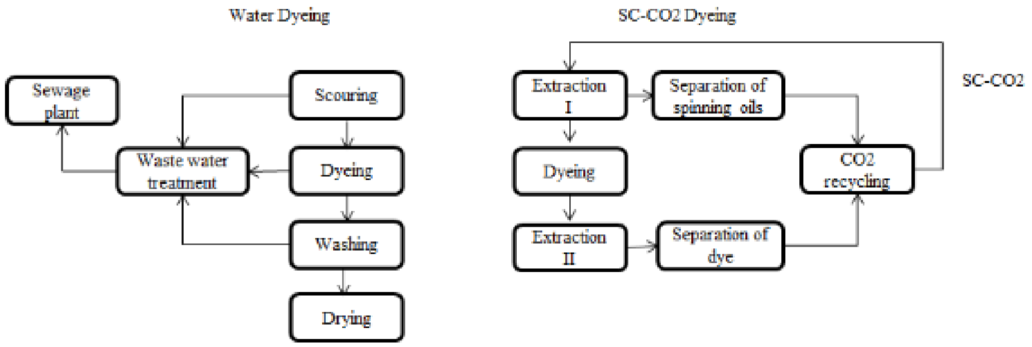


Figure 7: SC-CO_2 dyeing process for PES compared to conventional water dyeing process based on Bach et al. (2002).

Area of application

SC-CO_2 can be used for dyeing of PES and polypropylene fibres (European Commission, 2003; Bach et al., 2002). Dyeing of PES and polypropylene fibres with SC-CO_2 is performed under isothermal and isobaric conditions (120°C and 300 bar) (Schönberger & Schäfer, 2003). SC-CO_2 dyeing of polar fibres like cotton and wool are problematic due to the polarity of the dyestuff used in the dyeing of these fibres (European Commission, 2003; Bach et al., 2002). To be able to use the technology for cotton is of high interest since cotton stands for a large market share (Bach et al., 2002). Different methods have therefore been investigated (e.g. use of co-solvents and fibre modification) in order to overcome the problems. However, the methods that have been studied lose the main advantage of being water-free dyeing processes compared to conventional water dyeing. Other concepts need to be developed for the future in order to use the technology for cotton.

Future status

SC-CO_2 is under investigation for further industrial applications (Bach et al., 2002). An important breakthrough for the technology would be if the technology could be applied for cotton, which requires further research. Another important thing for the further development of the technology is cooperation with dye producers, to make sure that dyes for SC-CO_2 dyeing are commercial available. According to Hendrix

(2001), research and development related to SC-CO_2 dyeing has increased during the past decade as well as the number of publications. This together with an increase in the number of patents, indicate that the interest in commercialization of SC-CO_2 dyeing has increased during the last decade.

4.4 Digital printing

About 10% of all produced textiles are printed (Gupta, 2001). Conventional printing technologies are polluting and cost intensive and in context to this, new technologies for printing of textiles have emerged, such as digital printing. Digital printing, also known as ink-jet printing can be compared to an office printer (Schönberger & Schäfer, 2003). The technology of digital printing provides high flexibility for printing and two technologies for digital printing exist, drop on demand and continuous flow. The difference between the two technologies is that in drop on demand the ink drops are generated on demand through electrochemical impulses, compared to continuous flow where the drops are generated continuously. The digital image is obtained by ink drops which are pressed out of printing nozzles onto the fabric (Hasanbeigi & Price, 2015).

Before digital printing, the fabric often has to be pretreated, dried and after the printing, the fabric is often washed and steamed (Schönberger & Schäfer, 2003). Washing is needed since the uptake of dye never is 100% complete and steaming is used to open up the fibres in the fabric, which is important in order for the dyes to be fixed to the fabric (Tyler, 2005).

Area of application

Digital printing was first applied for carpets, flags banners and other niche products (Tyler, 2005). During the last five years it has been a drastic development of digital printing, which has resulted in an increase of commercial machines and improvements of inks (Tyler, 2005). Today, digital printing has broader application in the textile industry. Despite the recent development there are some obstacles for digital printing to reach a wider market.

Digital printing can be used for different types of fibres, however, different types of dyes need to be used depending on the fibre (Tyler, 2005). There are four types of dyes: reactive dyes for cellulosic fibres, disperse dyes for PES, acid dyes for protein fibres and PA and pigments that can be used for all fibre types. As mentioned before, most fabric needs pretreatment before being digitally printed. The degree of pretreatment needed depends on the dye used. Plasma pretreatment has been investigated as an alternative method for pretreatment for pigment printed textiles (Zille et al., 2014). Studies, investigating atmospheric plasma as a pretreatment method for pigment printed cotton textiles have shown good result regarding colour fastness and colour yield. Digital printing with pigment is one of the most used and the main advantage is that no washing is needed, which means that waste water and residues can be avoided and the process has also a higher productivity (European Commission, 2003). Digital printing with pigment can therefore be a viable alternative to conventional technology.

Future status

According to European Commission (2003), the production speed of digital printing is very low, which affects and prevents digital printing from replacing existing printing technology. This is also confirmed by Gupta (2001), who claims that the technology is limited due to the low speed as well as the low availability of fast and low viscosity dyes and small size of colour cartridges.

Between 1998-2003 it has been a clear growth of digital printing installations and the increase is expected to continue in the future (Gupta, 2001). Even though digital printing is a promising technology for the future, it is unlikely to replace conventional printing technologies according to Gupta (2001). However, digital printing will be an important technology for production of smaller batches and according to Gupta (2001), digital printing will stand for 10% of all printed textiles. On the other hand, according to Dehghani et al. (2004), the application of digital printing is increasing rapidly and is foreseen to replace conventional rotary and screen printing in the future.

4.5 Ozone bleaching

To prevent environmental pollution from pretreatment processes used for cotton fabrics, new emerging technologies such as ozone bleaching have emerged (Perincek et al., 2009). Ozone (O_3) is for technical purposes produced by an ozone generator (Arooj et al., 2014). In the generator, air or oxygen pass through a strong electrical field which splits the oxygen molecule into two unstable atoms that can react with oxygen molecules and produce ozone. Ozone is a strong oxidation agent and has an oxidation potential of 2.07 electron-volts (eV), which can be compared to 1.77 eV for hydrogen peroxide (Eren & Ozturk, 2011).

Ozone is thermodynamically unstable, which means that ozone will spontaneously convert back to oxygen (Perincek et al., 2007). The fact that ozone is chemically unstable is an advantage compared to other bleaching agents, since no secondary derivatives remain in the bleached fabric (Ben Hmida & Ladhari, 2015).

Area of application

Ozone has a wide range of applications in the industry and was first used as a bleaching agent in the pulp and paper industry (Perincek et al., 2007). Ozone has also been shown to be efficient for decolourisation of effluent to remove colour and improve biodegradability. Ozone has therefore been used for waste water treatment in the textile industry (Arooj et al., 2014; Eren & Ozturk, 2011). Ozone bleaching has been investigated in many studies and has been shown to be efficient for different types of fibres (Piccoli et al., 2015). Moreover, ozone has been used for bleaching of cotton and jute and treatment of nylon and silk (Eren & Ozturk, 2011).

Future status

Ozone is today used for bleaching of paper and treatment of effluent from the textile industry (Arooj et al., 2014). Although ozone bleaching for textiles has shown several environmental advantages compared to conventional development such as energy savings, reduction of water consumption and chemicals, the technology is still under development (Hasanbegi & Price, 2015).

4.6 Enzymatic treatments

Enzymes are proteins that work as catalysts, which activate and accelerate reactions (European Commission, 2003). Enzymes are macromolecules with high molecular weight and more than 3,000 enzymes have been classified (Roy Choudhury, 2014). To date, 10% of all industrial applied enzymes are used in the textile industry.

Enzymes are obtained from animal tissue, plants and microbes, however, enzymes used in the industry are produced by a process called fermentation (Roy Choudhury, 2014). Enzymes work in moderate conditions regarding temperature and pH and both the energy and the water use are therefore reduced. Existing machines can be used for enzymatic pretreatment processes (Schönberger & Schäfer, 2003). The main advantage with enzymes is their high substrate selectivity, which allows mild process conditions compared to conventional processes (European Commission, 2003).

Area of application

Enzymes can be applied in several steps in the wet processing of textiles such as desizing, scouring, bleaching and treatment of textiles effluent (Roy Choudhury, 2014). Enzymes are investigated and used in pretreatment and finishing processes for natural fibres, and research has been conducted to investigate the possibility to use enzymes for synthetic fibres (European Commission, 2003; Nieminen et al., 2006). Different enzymes and their application are presented in table 3.

Table 3: Different enzymes and application area (Kirk et al., 2002; Roy Choudhury, 2014).

Enzyme	Application
Cellulase	Denim finishing, Cotton softening
Amylase, Lipase	Desizing
Pectinase, Cellulase, Cutinase	Scouring
Laccase, Oxidoreductase, Xylanase	Bleaching
Oxidoreductase	Dyeing
Cellulase, Lipase, Oxidoreductase	Finishing

One of the most important applications of enzymes is during scouring. As mentioned in the textile production theory, scouring is a cleaning process to remove waxes, pectines and to make the material hydrophilic before dyeing (Roy Choudhury, 2014). Enzymatic scouring can be applied for cellulosic fibres as well as fibre blends in both continuous and batch processes (Schönberger & Schäfer, 2003). The temperature conditions are much lower compared to conventional scouring, between 40-60^{o}C (Roy Choudhury, 2014).

Another important application of enzymes in the textile industry, is in removal of hydrogen peroxide residues. Fabrics made from natural fibres are often bleached with hydrogen peroxide before dyeing, and peroxide residuals left on the bleached fabric can affect the dyeing process and needs to be removed (Roy Choudhury, 2014). Hydroperoxidase (catalase) is an enzyme that degrades hydroxide peroxide to water and oxygen at pH 3-9 and in a temperature around 30-80^{o}C. The conventional process for removal of extent hydrogen peroxide includes reducing agents and several rinsing steps with water (Schönberger & Schäfer, 2003). The use of enzymes in the process reduces the number of rinsing steps required and the process is today applied in textile finishing mills.

Future status

Enzymes have during the last five years been investigated and used in the textile industry for several process steps (Roy Choudhury, 2014). The potential of enzymes is high and the application of enzymes in the industry is therefore expected to increase. The productivity and the efficiency are expected to be improved and enzymatic treatments can therefore be economically beneficial compared to conventional treatments. According to Chen et al. (2007), it is evident that application of biotechnology in the textile industry results in cleaner processes that produce less waste, use less water and energy. Enzymatic treatments are therefore important for both pollution prevention and cost reduction.

4.7 Electrochemical dyeing

Vat dyes and sulfur dyes are the most common used dyestuff for cellulosic fibres, together they represent 31% of the dyestuff market (Schönberger & Schäfer, 2003; Ahmed & El-Shishtawy, 2010). Both vat dyes and sulfur dyes include complicated procedure steps which involves reduction with reducing agents and fixation using oxidation agents. These types of dyes have to be reduced to water-soluble form to be absorbed to the fibre and then re-oxidized to the water-insoluble form to be fixed to the fibre (Ahmed & El-Shishtawy, 2010). In order to reduce the dye, reducing agents need to be used. For vat dyes, the most used reducing agent is sodium dithionite (Kulandainathan et al., 2007). Sodium dithionite is very unstable and decomposes into several by-products. Several of the by-products produced are sulfur compounds which cause air pollution by formation of H_2S. Reducing agents that contain sulfur are also of concern for the environment due to water toxicity. They also cause higher COD and the reducing agents and the dye bath cannot be reused since the reducing power of the agents cannot be regained (Hasanbeigi & Price, 2015).

Vat dyes and sulfur dyes are expected to continue to have large shares of the market since vat dyes yield dyed fibres with great fastness to light and washing and sulfur dyes are important for inexpensive fibres, that have average requirement for fastness (Ahmed & El-Shishtawy, 2010).

Area of application

As described above, a conventional reducing agents result in by-products that remain in the dye bath (Kulandainathan et al., 2003). An alternative method to reduce and oxidize dyes is to use electrochemical dyeing, where electrons from the electric current are used (Hasanbeigi & Price, 2015; Kulandainathan et al., 2007). Electrochemical dyeing can be indirect or direct (Kulandainathan et al., 2007). Vat dyes are reduced with indirect electrolysis and sulfur dyes are reduced with direct electrolysis (European Commission, 2003). In direct electrolysis, the dye is reduced at the surface of the cathode, while, in indirect electrolysis, the reducing agent is continuously regenerated at the cathode, which makes it possible to reuse the dye bath as well as the reducing agent.

Future status

Some problems exist regarding indirect electrochemical dyeing technology (Kulandainathan et al., 2003). The reduction of the dye should be conducted in a separate cell, the design of the electrochemical cell should be so that the cathode has maximum surface area available and an electrochemical cell with minimum area of separator that separates the anolyte and catholyte is important for the cost and the electrochemical reaction.

4.8 Ultrasonic treatment

Ultrasonic waves have a frequency of 16 kilohertz and have been investigated as a solution for the textile industry to optimize cost, reduce the environmental impact and meet the quality requests (Ahmed & El-Shishtawy, 2010; Hasanbeigi & Price, 2015). When ultrasonic energy is used in a liquid it cause two things: heating and cavitation (Wang et al., 2012). Cavitation is a phenomenon of formation and collapse of bubbles and ultrasound, can be used for improvement of transport of molecules to the surface of the fibre, which also increase the reaction rate. A major benefit with ultrasonic treatment is that the equipment can be installed within existing machines (Hasanbeigi, 2010).

Area of application

Experimental studies have been performed during the last 20 years to investigate the use of ultrasonic energy for washing and dyeing of both natural and manufactured fibres (Hasanbeigi & Price, 2015). Ultrasonic energy has also been studied as an alternative for conventional methods to accelerate mass transfer in desizing, scouring, bleaching, mercerizing and dyeing of cotton fabrics (Wang et al., 2012). Several studies, like Yachmenev et al. (1998) have also investigated the use of ultrasonic energy in enzymatic pretreatment processes of textiles.

Future status

As described above, ultrasonic treatment has been investigated in several studies to increase the efficiency of textile wet processes (Vouters et al., 2004). Although studies on laboratory scale for finishing processes have shown good result, the technology has not been implemented in industrial scale (Moholkar & Warmoeskerken, 2004). Two factors for this lack of implementation are: lack of knowledge regarding the physical mechanism of the ultrasonic enhancement of the ultrasonic mass transfer in textiles and the disadvantages with the ultrasonic processors. According to Ahmed & El-Shishtawy (2010), the interest in ultrasonic assisted dyeing will increase especially for the use in small-scale enterprises.

4.9 Summary

A summary of the described emerging technologies based on the literature review is presented in table 4.

Table 4: Summary of emerging technologies in wet processing.

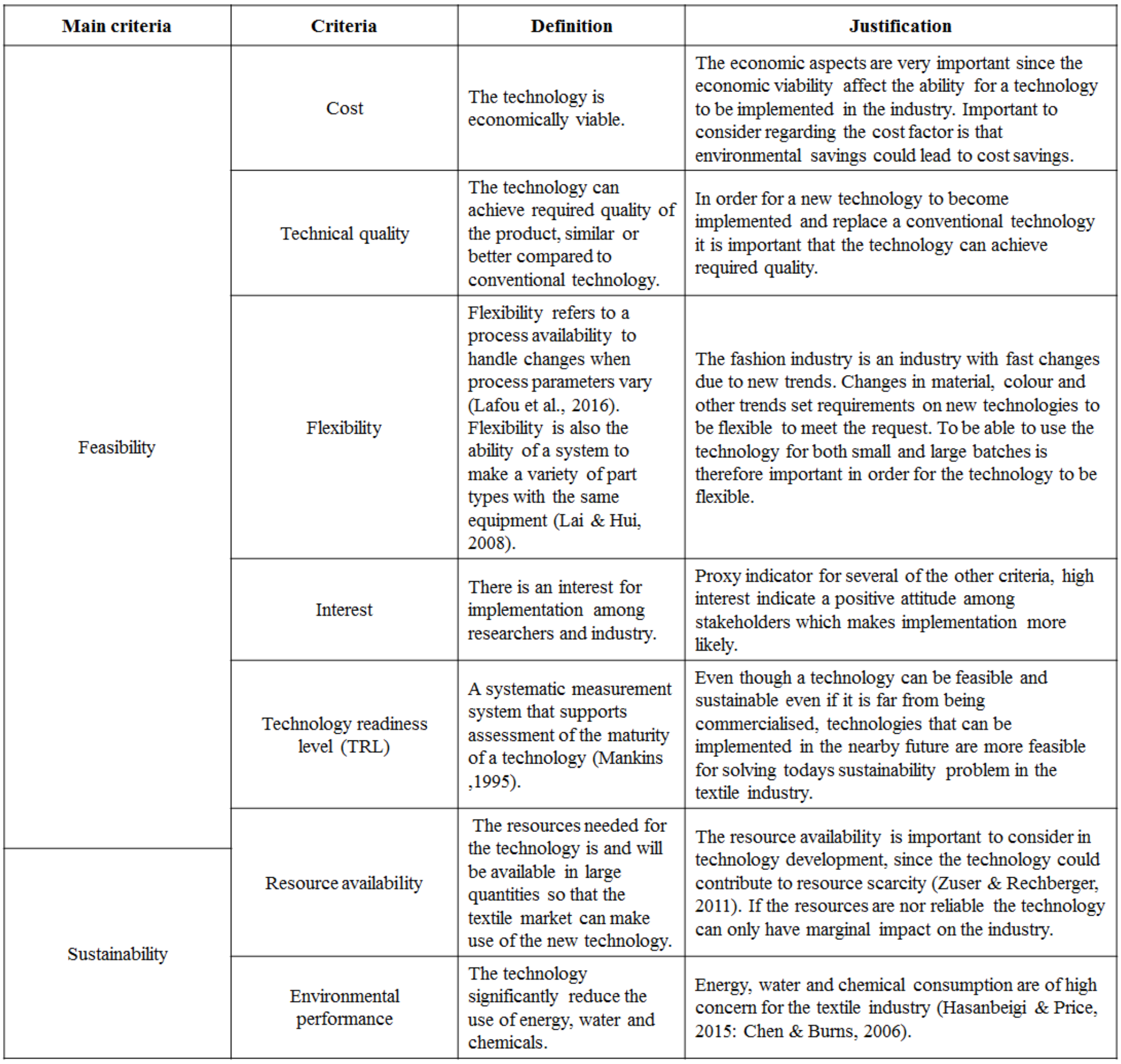
Technology	**Area of Application**
Plasma technology	Pretreatment, Finishing
Spin-dyeing	Dyeing
SC-CO_2 dyeing	Dyeing
Digital printing	Printing
Ozone bleaching	Bleaching
Enzymatic treatment	Scouring, Desizing, Dyeing, Finishing
Electrochemical dyeing	Dyeing
Ultrasonic treatment	Dyeing, Bleaching, Scouring, Desizing, Mercerizing

5 Sustainability and feasibility criteria

Since no criteria for assessing the sustainability and feasibility of emerging textile production technologies exist, this study investigated sustainability and feasibility criteria for emerging technologies. A further definition and justification of each criterion are presented in the subsection 5.1 and the screening sustainability and feasibility assessment is presented in subsection 5.2.

5.1 Definition of criteria

The following subsection include a figure of the definition and justification with the different criteria, see figure 8.



Main criteria	Criteria	Definition	Justification
Feasibility	Cost	The technology is economically viable.	The economic aspects are very important since the economic viability affect the ability for a technology to be implemented in the industry. Important to consider regarding the cost factor is that environmental savings could lead to cost savings.
	Technical quality	The technology can achieve required quality of the product, similar or better compared to conventional technology.	In order for a new technology to become implemented and replace a conventional technology it is important that the technology can achieve required quality.
	Flexibility	Flexibility refers to a process availability to handle changes when process parameters vary (Lafou et al., 2016). Flexibility is also the ability of a system to make a variety of part types with the same equipment (Lai & Hui, 2008).	The fashion industry is an industry with fast changes due to new trends. Changes in material, colour and other trends set requirements on new technologies to be flexible to meet the request. To be able to use the technology for both small and large batches is therefore important in order for the technology to be flexible.
	Interest	There is an interest for implementation among researchers and industry.	Proxy indicator for several of the other criteria, high interest indicate a positive attitude among stakeholders which makes implementation more likely.
	Technology readiness level (TRL)	A systematic measurement system that supports assessment of the maturity of a technology (Mankins ,1995).	Even though a technology can be feasible and sustainable even if it is far from being commercialised, technologies that can be implemented in the nearby future are more feasible for solving todays sustainability problem in the textile industry.
Sustainability	Resource availability	The resources needed for the technology is and will be available in large quantities so that the textile market can make use of the new technology.	The resource availability is important to consider in technology development, since the technology could contribute to resource scarcity (Zuser & Rechberger, 2011). If the resources are nor reliable the technology can only have marginal impact on the industry.
	Environmental performance	The technology significantly reduce the use of energy, water and chemicals.	Energy, water and chemical consumption are of high concern for the textile industry (Hasanbeigi & Price, 2015: Chen & Burns, 2006).

Figure 8: Definition and justification of sustainability and feasibility criteria.

5.2 Screening sustainability and feasibility assessment

This chapter presents the screening sustainability and feasibility assessment for plasma technology, spin-dyeing, SC-CO_2 dyeing, digital printing, ozone bleaching, enzymatic treatments, electrochemical dyeing and ultrasonic treatment. The resource availability criteria is not discussed in detail, since no particularly scarce raw materials have been identified for any of the technologies. Due to lack of information, flexibility is not discussed, except for digital printing. This chapter ends with a final table where the technologies and criteria are assessed.

5.2.1 Plasma technology

This section presents the assessment for plasma technology.

Cost

Due to lower process time and temperature than conventional technology, plasma technology is a cost-effective technology (Samanta et al., 2014). Less resources for treatment of effluent will also lead to a reduction of cost (Morent et al., 2008). The main advantages with corona plasma technology compared to low pressure plasma technology are easier construction and operation (Schönberger & Schäfer, 2003).

The main advantages with atmospheric plasma compared to low pressure plasma are that expensive vacuum equipment is not needed and that the process can be continuous, which makes atmospheric plasma cost-competitive (Jia et al., 2011). Due to the expensive vacuum equipment, low pressure plasma has both higher capital and running cost compared to atmospheric plasma (Jelil, 2015). Finally, according to Radetic et al. (2007), implementation of plasma technology involves higher investment cost.

Technical quality

According to a literature review regarding non-thermal plasma technology written by Morent et al. (2008), plasma technology can obtain good results even with industrial scale reactors for several applications. Plasma pretreatment has been shown to improve the dyeing of cotton and other fibres (Samanta et al., 2014). The improvement in hydrophilic property leads to faster dye exhaustion, reduction of dyeing time and temperature. Furthermore, according to Morent et al. (2008), plasma technology used for dyeing also improves the dyeing homogeneity and improved dyeing properties have been reported for all fibre types. A study by Sun & Stylios (2004) (cited by Jelil, 2015) reported that low pressure oxygen plasma increased the dyeing rate of cotton. A study written by Bae et al. (2006) (also cited by Jelil, 2015) showed that oxygen plasma treatment efficiently removed sizing agents from PET fabrics.

Interest

Plasma technology is one of the technologies that is frequently mentioned in Ecotextile News and during the interviews.

TRL

The development of plasma technology for the textile industry has been very slow and plasma technology has therefore not had a large uptake in the textile industry (Jelil, 2015; Morent et al., 2008). Up to date, plasma technology is adopted for niche applications, however, in the context of increasing environmental concerns, it is predicted that adoption of plasma technology will start to become used industrially according to Jelil (2015).

Environmental potential

According to European Commission (2003), the main advantages with plasma technology are the short treatment time, low application temperature which means that energy, water and solvent can be avoided and less or no chemicals are required for the technology. Furthermore, according to Schönberger & Schäfer (2003) an additional advantage with plasma technology compared to conventional technologies is saving of energy due to avoidance of drying steps after plasma finishing. Additionally, plasma technology reduces the COD/BOD of effluents as well as increases the exhaustion of chemicals from the bath (Radetic et al., 2007; Jelil, 2015). According to Zille et al. (2014), atmospheric plasma technology is promising for the future within the textile industry due to the environmental benefits and Jelil (2015) describes plasma technology as a technology that has great attention in the textile industry since the technology is both economically and environmentally promising.

5.2.2 Spin-dyeing

This section presents the assessment for spin-dyeing.

Cost

According to the study by Schuster et al. (2014), savings in production cost such as raw material cost and capital cost as well as labour cost are enabled by implementing spin-dyeing due to the lower input of chemicals and energy and lower amount of waste water.

Technical quality

Fibres that are dyed with spin-dyeing show good fastness properties and there is almost no pigment lost (Schuster et al., 2014). Although the colour range is limited, the process requires less pigment and the entire body of the fibre is coloured compared to conventional dyeing where only the surface of the fibre is dyed.

Interest

Spin-dyeing was only mentioned in one of the interviews and two times in Ecotextile News.

TRL

Compared to conventional dyeing, the use of spin-dyeing is very small, at industrial scale it has been estimated that less than 5% of the total production is dyed using spin-dyeing (Schuster et al., 2014).

Environmental potential

According to a study written by Schuster et al. (2014), which compares conventional dyeing and spin-dyeing of modal (i.e. semi-synthetic cellulose fibres made by spinning reconstituted cellulose), spun-dyed modal fabrics have 50% lower energy use, 60% lower carbon footprint and requires 50% less water than conventional dyed modal fabric. It was also found that across all impact categories the spun-dyed fabric causes half to one third of the environmental impacts compared to conventional dyed fabric. In addition, it is also expected that spun-dyed fabric causes less toxicity due to lower amount of pigment (20% less pigment). An LCA study written by Manda et al. (2014) confirms the results from the study written by Schuster et al (2014).

5.2.3 Supercritical CO_2 dyeing

This section presents the assessment for SC-CO_2 dyeing.

Cost

The main disadvantage with the technology is the high investment cost for the equipment, which especially is a drawback for low-price fibres such as PES (Bach, 2002; European Commission, 2003). Energy and water cost differ a lot between countries and it is therefore difficult to compare SC-CO_2 dyeing with conventional water dyeing (Bach et al., 2002). However, according to Hendrix (2001), SC-CO_2 dyeing is economically beneficial due to reduction in energy, no drying step and eliminating of water discharge compared to conventional dyeing.

A study written by Walle et al. (1998) (cited by Bach et al., (2002)) investigated the cost of dyeing PET fibres in SC-CO_2 in three different capacities of dyeing vessel (300, 2,000 and 6,000 l). The result from the study showed that the cost for dyeing PET fibres were 5.51 EUR/kg (300 l vessel) and 2.01 EUR (2,000 l vessel). This could be compared with water dyeing of yarn or fabric in Europe that is between 1.07 and 3.07 EUR/kg PET fibres.

Technical quality

In order to use SC-CO_2 dyeing technology commercially, it is important that the properties of the fibres are not damaged in the process since it affects the quality and dye uptake of the fibre (Bach et al., 2002). Studies show that synthetic fibres are not damaged in SC-CO_2 dyeing if optimum conditions for the dyeing process are used. According to a study written by Hou et al. (2010) that investigated dyeing of PES with SC-CO_2 in a pilot plant, the result showed that the fibres had good fastness and physical properties.

The uptake of dye to the fibre and the fastness characteristics are similar to conventional water dyeing (European Commission, 2003). This is also confirmed by a study written by Rita de Giorgi et al. (2000) that studied dyeing of PES with SC-CO_2 and the results showed that it was possible to get the same result with SC-CO_2 dyeing in 80^oC compared to using water as dyeing medium. A study regarding dyeing of PES with SC-CO_2 written by Hendrix (2001) showed that the dyed yarn had the same properties as water dyed yarn. Moreover, some auxiliaries that are used in conventional dyeing affect the release of dye in SC-CO_2 dyeing and therefore only dyes with certain additives can be used (Schönberger & Schäfer, 2003).

Interest

SC-CO_2 dying was the technology that was most mentioned in the interviews and in Ecotextile News.

TRL

SC-CO_2 is used in industrial scale for dyeing of PES and polypropylene fibres (European Commission, 2003; Bach et al., 2002).

Environmental potential

Many studies have shown the advantages of SC-CO_2 compared to water as dyeing medium (Bach et al., 2002). The main advantages with SC-CO_2 dyeing include almost zero water consumption, no drying step after dyeing, CO_2 can be recycled and therefore low gas emission during the process, dispersing agents are not needed or only in very small amounts and the dyestuff residues can be reused (European Commission, 2003; Hou et al., 2010).

According to the Dutch company Dyecoo that produced the first commercial dyeing machine for SC-CO_2 dyeing, the process has low operation cost, no water, no emissions of process chemicals and therefore no waste water treatment is necessary. Furthermore, Dyecoo claims that the uptake of dye is 98% and that 95% of the CO_2 is recycled in a closed loop system. According to Dyecoo, the technology is energy efficient since the process is dry which eliminates the need of evaporate water and enables short time batches (Dyecoo, 2016).

5.2.4 Digital printing

This section presents the assessment for digital printing.

Cost

Today, digital printing exists for smaller batches where the technology also is economically beneficial (European Commission, 2003; Tyler, 2005). For long lengths, conventional printing technology such as rotary printing is fast, continuous and profitable (Gupta, 2001). However, for smaller runs conventional printing technology is non economic due to high waste of fabrics and inks and high cost of labour, colour matching, sampling and design etc. According to a study by Dehghani et al. (2004), digital printing can have major cost reductions on the printing industry of textiles. Furthermore, the existing rotary screen printing is related to high capital and investment cost. To implement digital printing, which is smaller and more flexible, will then result in cost savings.

Technical quality

Compared to conventional printing technologies (i.e. screen and roller printing), digital printing has shown good properties e.g. pattern quality and colour fastness (Zille et al., 2014; Humphries, 2009).

Flexibility

Digital printing of textiles is a flexible technology due to the fact that small batches can be produced and that there is a freedom regarding design options (Tyler, 2005). Digital printing can be used for different types of fibres.

Interest

Digital printing is one of the most mentioned in Ecotextile News and in some interviews.

TRL

The method of digital printing did not have commercial importance until 2001 when the technology was used for production runs and not only samples (Humphries, 2009). Today, the status of digital printing is commercial with low adoption rate (Tyler, 2005).

Environmental potential

Digital printing is considered to be cleaner compared to conventional technologies for printing (Tyler, 2005). The main advantages with digital printing include higher fixation rate of dye, reduced energy consumption, cleaning and washing of the equipment is not necessary and the water consumption is therefore reduced, high flexibility in the production and no wasted inks and dyes (Hasanbeigi & Price, 2015; Tyler, 2005).

5.2.5 Ozone bleaching

This section presents the assessment for ozone bleaching.

Cost

From an economic point of view application of ozone bleaching saves energy, chemicals, water and expenses for waste water treatment and is therefore an economically viable alternative to conventional bleaching (Arooj et al., 2014). Furthermore, ozone is a less expensive bleaching chemical compared to e.g. chlorine dioxide (Perincek et al., 2007).

Technical quality

According to Hasanbeigi & Price (2015,) several studies have shown that the quality of the bleached fabric in terms of whiteness were comparable to conventional bleaching with greater decreases in polymerization degrees. A study from Eren & Ozturk (2011) showed that ozone bleaching of cotton fabric reached a comparable whiteness level as fabric that was bleached with hydrogen peroxide. Moreover, Eren et al. 2014 conclude that bleaching of cotton with ozone in combination with ultrasound result in equal values of whiteness as for conventional peroxide bleaching.

A study written by Arooj et al. (2014) showed that cotton can be bleached with ozone successfully if optimal process conditions are applied in the process. The study also showed that the same water bath can be used several times and that the best results were achieved at pH 5, 45 min and at room temperature. However, the ozone bleached fabric showed less whiteness and higher fibre damage, but the quality was sufficient for dyeing of medium to dark shades.

Interest

Ozone bleaching was not mentioned in the interviews and not so often in Ecotextile News.

TRL

The technology is still under development and has not yet reached commercialization (Hasanbeigi & Price, 2015).

Environmental potential

Ozone bleaching for cotton has been developed as a solution to conventional bleaching which consumes large amount of water, energy and chemicals that causes polluted waste water (Eren & Ozturk, 2011). Ozone bleaching requires lower amounts of water than conventional bleaching and can be performed at room temperature under short time which means that no energy is needed for either cooling or heating (Perincek et al., 2007). A study regarding ozone bleaching in combination with ultrasound written by Eren et al. (2014) showed that dramatically less COD load in the effluent compared to conventional bleaching with hydrogen peroxide.

5.2.6 Enzymatic treatments

This section presents the assessment for enzymatic treatments.

Cost

Savings of energy, water, time and chemicals/auxiliaries will also lead to cost savings (Schönberger & Schäfer, 2003). Since enzymatic pretreatment can be applied in existing machines, high investment cost for new machines is not required. Furthermore, according to Preša & Tavčer (2009), savings by using enzymatic bleaching and scouring instead of conventional processes can be achieved since enzymatic pretreatment can be performed under neutral pH and no neutralization is therefore required.

Technical quality

Regarding the technical quality, enzymatic scouring of cotton leads to reduced fibre damage, soft texture and increased colour yield (Schönberger & Schäfer, 2003). The use of catalase for elimination of peroxide improves the dyeing process and increases the colour yield (Roy Choudhury, 2014). Further, a study written by Hartzell & Hsieh

(1998) showed that enzymatic scouring with a combination of pectinase and cellulase improved the wetting and retention properties, similar to conventional scouring for cotton fabrics. Amylase is a commercial enzyme for desizing for cotton fabric and is preferred due to the high efficiency in removing the size without any damage to the fibre (Araujo et al., 2008).

Interest

Enzymatic treatments were not mentioned in any of the interviews and infrequently mentioned in Ecotextile News.

TRL

Some enzymes such as amylase for desizing and laccase for denim finishing are today commercially successful in the textile industry (Araujo et al., 2008).

Environmental potential

There are several advantages with using enzymes in the textile industry for different processes. NaOH used in conventional scouring is not necessary in enzymatic scouring (European Commission, 2003). Enzymatic scouring reduces the consumption of water, BOD and COD load by approximately 20% (European Commission, 2003). The water consumption is reduced due to the neutral pH and energy requirements are reduced due to lower process temperature (40-60^{o}C) (Roy Choudhury, 2014; European Commission, 2003). It is also claimed that enzymatic scoured fabric leads to better bleachability with reduced requirements of chemicals and auxiliaries (European Commission, 2003). The use of catalase for elimination of peroxide after bleaching reduces the number of rinsing steps since it can be added directly in the dye bath (Roy Choudhury, 2014).

A study written by Siddiquee et al. (2014) compared conventional scouring and bleaching with enzymatic pretreatment. The study showed that enzymatic treatment was an environmentally beneficial technology since the process could occur in neutral pH and reduce the amount of COD compared to conventional process. Moreover, another study by Preša & Tavčer (2009) concluded that enzymatic scouring and bleaching reduced the amount of water and energy compared to conventional processes and the bath was biodegradable. Furthermore, according to Chen et al. (2007,) biotechnology in the textile industry can reduce the water and energy demand for bleaching by 9-14% and 17-18% respectively. Water consumption for scouring can be reduced by 30-50%.

5.2.7 Electrochemical dyeing

This section presents the assessment for electrochemical dyeing.

Cost

Cost savings will be achieved due to the significant reduction in water and chemicals (Schönberger & Schäfer, 2003). Božič & Kokol (2008) describes the technology as economically beneficial due to reduction of chemicals and effluent load which are also environmental advantages.

Technical quality

Experiments with electrochemical dyeing for vat dyes have shown similar results as conventional vat dyeing with sodium dithionite (Kulandainathan et al., 2007). Experiments with electrochemical dyeing have also shown good reproducibility.

Interest

Electrochemical dyeing was not mentioned in the interviews and not so often in Ecotextile News.

TRL

Electrochemical dyeing is still in development in laboratory scale, but can be a technology for vat and sulfur dyes in the future (Kulandainathan et al., 2003).

Environmental potential

The main advantages with electrochemical dyeing are reduction of chemicals used and minimized effluent load (Ahmed & El-Shishtawy, 2010). This is also confirmed by a study written by Božič & Kokol (2008) which concludes that electrochemical dyeing methods have environmental benefits due to the reduction of chemicals and effluent load. Furthermore, a study by Bechtold & Turcano (2009), which investigated the use of electrochemical reduction in vat dyeing, showed substantial reduction of chemicals and contaminated waste water during the dyeing process. The study also showed that the chemicals can be reduced by 50% by regeneration. Finally, if sodium dithionite can be avoided as reducing agent, it will lead to no toxic sulfur compounds in the waste water, which improves the aquatic life (Hasanbeigi & Price, 2015).

5.2.8 Ultrasonic treatment

This section presents the assessment for ultrasonic treatment.

Cost

It is predicted that implementation of ultrasonic energy for several applications in the textile industry will lead to economically benefits due to the reduction of energy, process time, auxiliaries and dyestuff. This is also described by Yachmenev (1998), who writes that implementation of ultrasonic energy in enzymatic pretreatment of cotton will provide significant economic savings due to lower process time and less concentration of chemicals.

Technical quality

A pioneer study written by Thakore (1988) (cited by Ahmed & El-Shishtawy, 2010) showed that cotton fabric can be dyed ultrasonically with direct dye. The result from the study also showed that ultrasonic energy reduced the dyeing time, temperature, concentration of dye and electrolytes in the dye bath. Furthermore, a study by Öner et al. (1995), also cited by Ahmed & El-Shishtawy (2010), compared conventional dyeing with dyeing where ultrasonic technique was used. The result indicated that dyeing with ultrasonic energy improved the dye fixation and the percentage exhaustion. However, the result obtained from the study did not show improvements in dye fastness of the dyed material.

According to Hasanbeigi (2010), ultrasonic treatment increases the efficiency in the processes without damaging the properties of the treated material. According to research at laboratory scale by Yachmenev et al. (1998), ultrasonic energy used in enzymatic treatment of cotton fabrics showed improvement in enzyme efficiency without decreasing the tensile strength of the cotton fabric. It also appears that ultrasound does not affect the activity of the enzyme molecules. Finally, according to a report by Schönberger & Schäfer (2003), dyeing of wool, wool/PES blends, PA and cotton results in higher levelling properties and bath exhaustion.

Interest

Ultrasonic treatment was not mentioned in either the interviews or in Ecotextile News.

TRL

Up to date, ultrasound technology is only used at an industrial scale for cleaning of textiles and not for other processes (Vouters et al., 2004).

Environmental potential

Benefits of using ultrasonic treatment for textile finishing processes are reduction of consumption of auxiliaries and reduction of energy due to lower temperature and shorter process time (European Commission, 2003). Reduction of auxiliaries is obtained by the increased dispersion of dyestuff which also leads to a reduction in process time (Nieminen et al., 2006). A study regarding the use of ultrasonic energy in the enzymatic desizing of cotton fabric written by Wang et al. (2012) showed that the process saved time, compared to conventional enzymatic process of cotton, the ultrasonic process can save half of the process time and the desizing efficiency was increased with 5%. Moreover, Vouters et al. (2004) write in a study regarding ultrasound that the technology reduces chemicals and dyestuff used, which can reduce the amount of effluent with 20-30% and reduce the water consumption (20%) and energy (30%) due to increased efficiency in washing and rinsing.

5.3 Results from criteria

Based on the screening sustainability and feasibility assessment, table 5 was constructed. All identified emerging technologies are claimed to be environmental beneficial and scored high on the environmental potential criteria. Due to cost savings related to the high environmental potential of all technologies, all eight technologies scored low on the cost criterion. The resource availability were also identified as high for all technologies since the technologies are used for the most common fibres like cotton and PES, which do not rely on any scarce particularly resource. The two technologies that scored highest were SC-CO_2 dyeing and digital printing. Based on the assessment in table 5 and process data availability, SC-CO_2 dyeing was selected for further evaluation with LCA, presented in chapter 6.

Table 5: Evaluation of the technologies for each criteria.

	Cost	Technical quality	Flexib-ility	Interest	TRL	Resource availability	Environmental potential
Plasma technology	Low	High	n/a	High	Low	High	High
Spin-dyeing	Low	High	n/a	Low	High	High	High
SC-CO_2 dyeing	Low	High	n/a	High	High	High	High
Digital printing	Low	High	High	High	High	High	High
Ozone bleaching	Low	High	n/a	Low	Low	High	High
Enzymatic treatments	Low	High	n/a	Low	High	High	High
Electrochemical dyeing	Low	High	n/a	Low	Low	High	High
Ultrasonic treatment	Low	High	n/a	Low	Low	High	High

6 Life Cycle Assessment

To further investigate the environmental performance of SC-CO_2 dyeing of PES fabric, an LCA was performed and is presented in this chapter.

6.1 Goal and Scope definition

This section presents the goal and scope definition of the LCA which includes the goal of the study, scenarios to model, functional unit, system boundaries, data quality and assumptions and limitations.

6.1.1 Goal of the study

The goal of this LCA is to estimate the environmental performance of SC-CO_2 dyed PES fabric and conventional dyed PES fabric. The aim is to compare these two processes in order to study the environmental influence of replacing conventional dyeing process with SC-CO_2 dyeing.

This LCA study has a process based approach and the background data are attributional since consequential data would involve more uncertainties. In this study, a set of impact categories according to the ILCD 2011 midpoint method, which was published by the European Commission in 2012 was used. The environmental impact is presented in terms of climate change, water resource depletion and human toxicity, cancer effects. In addition, the energy use was also investigated with the cumulative energy demand impact assessment method which is described by Arvidsson et al. (2012) as an indicator which focuses on the limited access to energy resources in a broader sense than just fossil energy. These impact categories were chosen since they represent categories of high concern for the textile industry, as mentioned earlier in this report.

6.1.2 Scenarios to model

This study investigates two processes for dyeing of PES fabric. The first one is conventional dyeing of PES fabric with water as dyeing medium in a jet-dyeing machine. The second process is SC-CO_2 dyeing with SC-CO_2 as dyeing medium. Moreover, this study investigates four different scenarios, two for conventional dyeing and two for SC-CO_2 dyeing based on two different electricity mixes as well as a reduction of the CO_2 losses in one of the SC-CO_2 dyeing scenario. The first electricity mix modelled is based on electricity from China, Bangladesh and Turkey. The second is a greener electricity mix from Sweden. The following scenarios are investigated in this LCA:

- Conventional dyeing
- Conventional dyeing with greener electricity mix
- SC-CO_2 dyeing (18% CO_2 losses)

- SC-CO_2 dyeing with greener electricity mix (5% CO_2 losses)

The dyeing options as well as the electricity mixes are more extensively described in the inventory analysis.

6.1.3 Functional unit

The two processes are used for dyeing of PES fabric and the function is to apply colour to the fabric. The functional unit (FU) has to be chosen so that the two processes can be compared and the FU is therefore 1 kg of dyed PES fabric in this study.

6.1.4 System boundaries

System boundaries include temporal boundaries, boundaries in relation to the natural system and within the technical system as well as geographical boundaries.

Temporal boundary

This study investigates the environmental difference of replacing conventional dyeing with SC-CO_2 dyeing. Possible difference in lifespan of the dyed fabric and technical quality are not considered in this study.

Boundaries in relation to natural system and within the technical system

Boundaries in relation to the natural system define where the life cycle begins and ends as well as the boundary between the natural system and the technical system. This study is a process LCA, which means that this study only includes processes related to the dyeing process and not the whole life cycle of the dyed fabric (i.e. neither cradle to grave nor cradle to gate). Capital goods such as machinery used during the manufacturing and the maintenance of these goods are not considered in this study.

Geographical boundaries

The dyeing processes are modelled with inputs from the technosphere (i.e. materials and fuels) from all over the world and one of the electricity mixes was set to a electricity mix from China, Bangladesh and Turkey, which makes the geographical boundaries global.

6.1.5 Data quality

Several data sources were used in order to perform this LCA study. For the conventional dyeing process of PES fabric a Mistra Future Fashion report written by Roos et al. (2015) was used. Regarding the SC-CO_2, studies written by Bach & Schollmeyer (2007) and Bach et al. (2002) were used. Furthermore, databases such as Ecoinvent 3 provided in SimaPro and Future Fashion provided by Swerea IVF was also used as data source for this LCA study.

6.1.6 Assumptions and limitations

Some assumptions were made in this study in order to reduce the complexity of the problem. The following main assumptions were made in this study:

- The same disperse dyestuff was assumed for the two dyeing processes.
- No after-wash, softening and drying step were assumed to be used after the SC-CO_2 dyeing process.
- The waste from the spinning oils and dyestuff in SC-CO_2 dying are assumed to be similar to waste treatment of mineral oil respective paint.

Following limitations are related to this study:

- Economic and social impacts related to the four scenarios are not included in this study.
- Process data for the SC-CO_2 dyeing are based on estimated data from a pilot plant and have therefore not been measured at site.
- No transports of inputs to the dyeing plant are included in this study.
- Cleaning of the dyeing equipment after the process is not included in this study.

6.2 Inventory Analysis

This chapter presents the inventory analysis of the study which includes a more detailed description of the technical system with flow charts as well as life cycle inventory (LCI) data for the processes. The following chapter describes electricity production, heat production and system description of conventional water dyeing and SC-CO_2 dyeing. The most relevant LCI data for this study are presented in appendix D and the processes used in SimaPro are presented in appendix E.

6.2.1 Electricity production

The electricity mix called MiFuFa electricity mix was used for two of the scenarios in this study. It is based on the electricity used in the report by Roos et al. (2015). The electricity is modelled based on the electricity mix from three countries, China (65%), Bangladesh (23%) and Turkey (12%). The share is based on the countries contribution to import of textiles to Sweden. More detailed information regarding how the electricity mix for each country is modelled is given in appendix B.

For two of the scenarios, a greener electricity mix from Sweden was used. The electricity mix is based on wind power (4.4%), hydro power (48.5%), thermal power (9.5%) and nuclear power (37.8%).

6.2.2 Heat production

The same process for heat production was used for both dyeing processes. The heat production was modelled from the Ecoinvent process ”Heat light fuel oil, at boiler 10 kW, non-modulating/CH”.

6.2.3 Conventional water dyeing

As mentioned before, LCI data for a conventional dyeing process was taken from a Mistra Future Fashion report written by Roos et al. (2015). The conventional dyeing process consists of several process steps. First the fabric is pre-washed with detergent, soda and sequestering agent at 95°C for 20 min. After the pre-wash, the fabric is rinsed with water at 50°C for 10 min. The fabric is then dyed with dye, dispergent agent, ammonium sulfat, reduction protection agent, wetting agent and acetic or formic acid. The dyeing step occur at 135°C for 40 min.

After the dyeing, the fabric is rinsed and washed again with soda, soaping agent and NaOH at 70°C for 20 min. Finally, after the second wash, the bath is neutralized with acid and a softening agent is added. The process ends with a drying step. A flowchart of how the process was modelled in SimaPro is presented below, see figure 9. A table of chemicals and auxiliaries needed for conventional dyeing of PES fabric is presented in table 6.

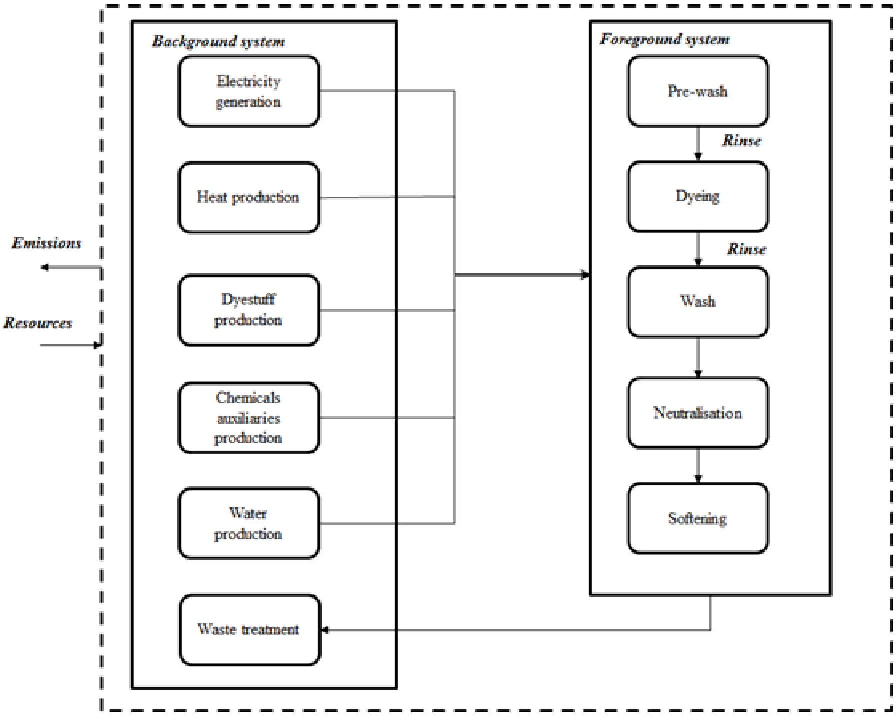


Figure 9: Flowchart for conventional dyeing.

Table 6: Chemicals and auxiliaries for conventional dyeing (Roos et al., 2015).

Chemicals and auxiliaries
Detergent/Wetting agent
Sequestering agent
Antifoaming agent
Base (alkali) (Na_2CO_3)
Acid (formic acid)
Wetting/Penetration agent (synhetic)
Dispergent
Decalcifier ((NH_4)2SO_4)
Antireduction agent (H_2O_2)
Base (alkali) (NaOH)
Reducing agent
Soda ($CaCO_3$)
Softener

6.2.4 SC-CO_2 dyeing

Process data for the SC-CO_2 dyeing were taken from a study written Bach et al. (2004), cited by Bach and Schollmeyer (2007). The study presents estimated process data for an up-scaled plant for SC-CO_2 dyeing based on the experience from a technical plant, called the Uhde plant. The plant is estimated for dyeing of 120 kg of PES fabric per batch with a volume of 600 l of the dyeing autoclave (Bach & Schollmeyer, 2007). The dyeing process includes several process steps as presented in figure 7 (see subsection 4.3). The process starts with an extraction and separation of spinning oils. After the first extraction, the dyeing process is performed and the process ends with extraction and separation of the dyestuff. The extracted spinning oils and dyestuff are precipitated in a separator. After the dyeing process, the CO_2 in the tank is depressurized to liquid CO_2 and stored in a tank. Process conditions for the dyeing process are presented in table 7.

Table 7: Process conditions Bach & Schollmeyer (2007).

Parameter	**Setting**
Temperature	100-140^{o}C
Pressure	250-350 bar
Time	2 h

An illustration of the process is presented in appendix C. The uptake of dye is estimated to 98%, which means that 2% goes to waste together with the extracted spinning oils (Bach & Schollmeyer, 2007). Most of the CO_2 can be recycled. However, the total loss of CO_2 during one batch was estimated to 140 kg without including losses from the separator since emptying of the separator is not needed every time. The losses correspond to 18%. However, according to Dyecoo (2016) the loss of CO_2 is 5% and one of the scenarios for SC-CO_2 dyeing was therefore modelled with a loss of 5% together with the greener electricity mix. A table of LCI data regarding the process (i.e. electricity and heat) can be found in appendix D. A flowchart of the process is presented in figure 10. The waste from the extracted dyestuff and spinning oils were modelled as paint and mineral oil, respectively. The CO_2 liquid needed for the process was modelled based on the Ecoinvent process “carbon dioxide liquid, at plant” which uses CO_2 from ammonia production and processes this to liquid CO_2.

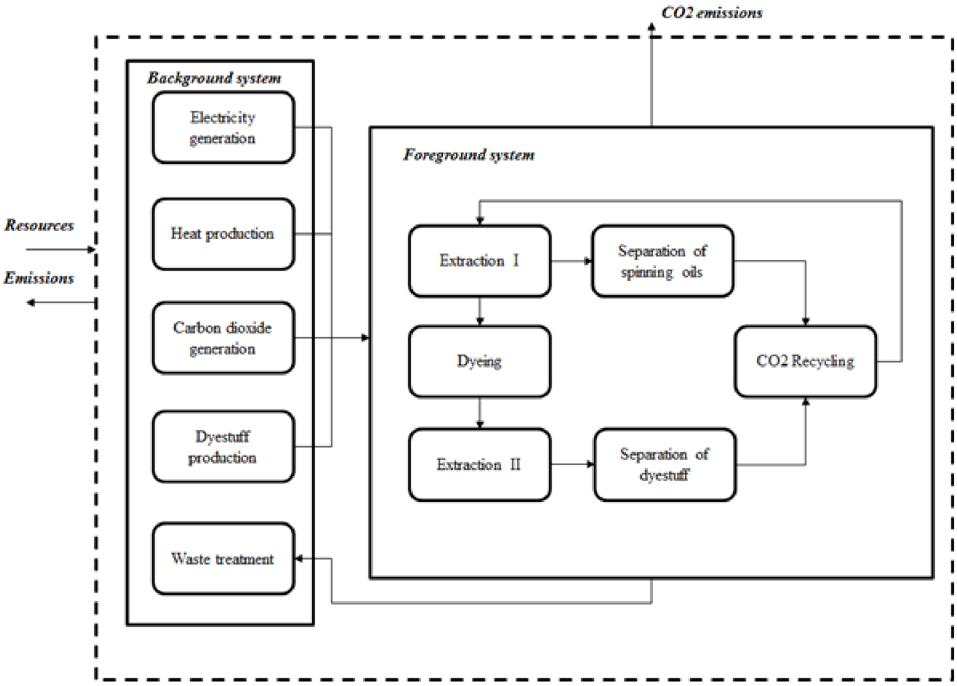


Figure 10: Flowchart for SC-CO_2 Dyeing.

6.3 Impact Assessment

This chapter presents the result of the study, both individual results for each dyeing process as well as comparisons between the four scenarios. The results are presented in terms of climate change, water resource depletion, human toxicity (cancer effects) and cumulative energy demand. In section 6.8, the normalisation results are presented, which also includes, human toxicity non-cancer, particulate matter, photochemical ozone formation and freshwater ecotoxicity. Cumulative energy demand is not included there since no normalisation factors are provided for this method. Normalisations factors for the ILCD 2011 midpoint impact assessment method are presented in appendix F. Detailed result tables from the impact assessment are found in appendix G.

6.3.1 Climate change

The environmental impact related to climate change for the two scenarios for SC-CO_2 dyeing and the two scenarios for conventional dyeing are presented in figure 11 and 12. The result is divided into different processes related to the dyeing process. The highest impacts for SC-CO_2 dyeing are related to the electricity and the CO_2 supply needed for the dyeing process as well as the losses of CO_2 in the process. The electricity stands for 50% of the total impact for the worst case. The use of the greener electricity mix results in a considerable total reduction of the climate change impact for both dyeing processes.

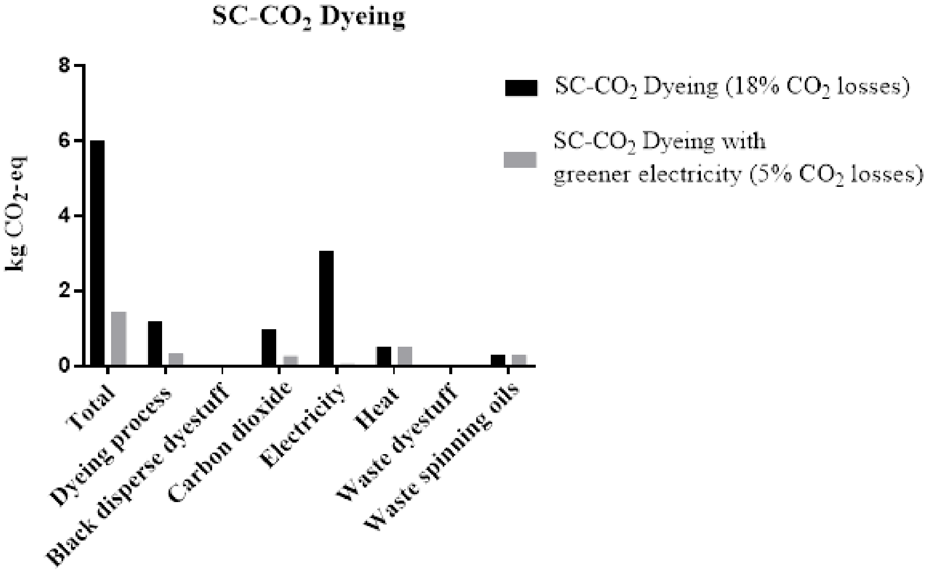


Figure 11: Climate change for the two scenarios of SC-CO_2 dyeing.

The conventional dyeing process without the greener electricity mix has more than 50% less climate impact compared to the worst scenario of SC-CO_2 dyeing. However, for the two other scenarios with greener electricity mix the processes have similar impact (1 kg CO_2-eq/FU). Similar as for the SC-CO_2 dyeing, the main contribution is due to the electricity used for the dyeing process. Furthermore, chemicals and auxiliaries used in the dyeing process do also contribute to a significant part of the climate change impact. The main contribution here is from the softener (see appendix G).

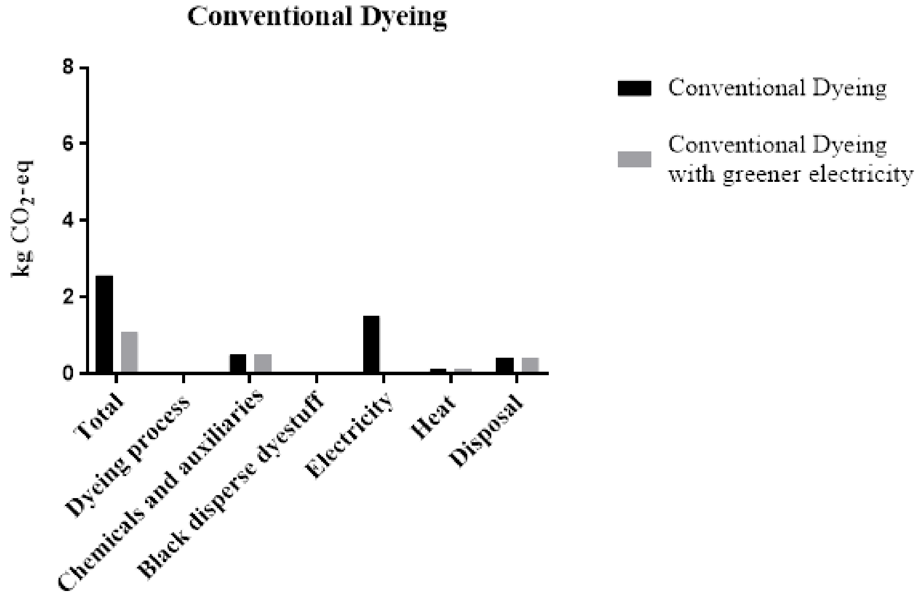


Figure 12: Climate change for the two scenarios of conventional dyeing.

6.3.2 Water resource depletion

Water resource depletion for the four scenarios are presented in figure 13 for SC-CO_2 dyeing and in figure 14 for conventional dyeing. Since no water is needed for SC-CO_2 dyeing process, the impact from the process itself is zero. However, the electricity needed for the dyeing process relates to almost all of the total impact from this category. Since the electricity mix differs between the two scenarios, the result regarding this category differs while the other results are the same (i.e. for the heat).

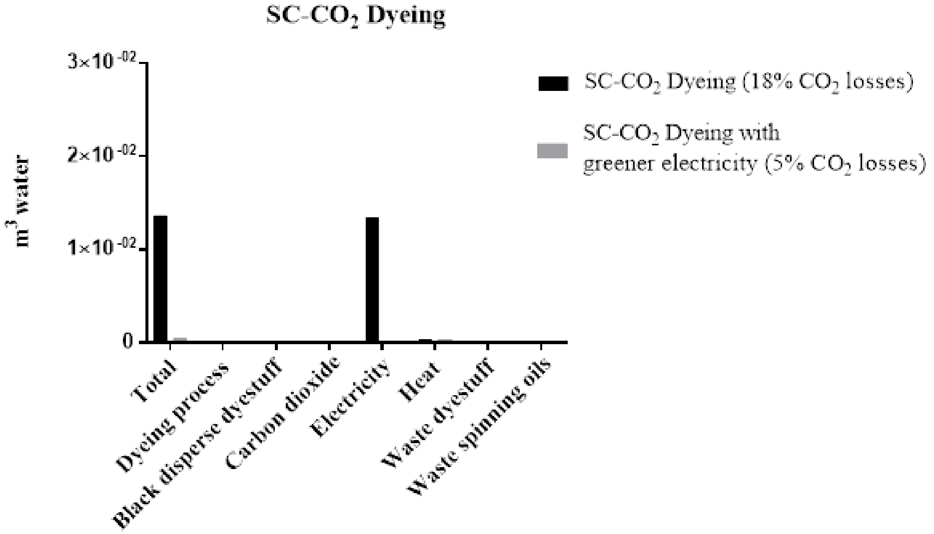


Figure 13: Water resource depletion for the two scenarios of SC-CO_2 dyeing.

The conventional dyeing process requires a high amount of water, which explains the high impact from the dyeing process. The high amount of water used in the conventional dyeing process also lead to the fact that conventional dyeing has a higher impact in this category for both scenarios compared to SC-CO_2 dyeing. SC-CO_2 dyeing with the greener electricity mix result has the lowest impact, $4.5x10^{-3}$ m^3 water per FU, which can be compared to 0.025 m^3 per FU for the worst case of conventional dyeing.

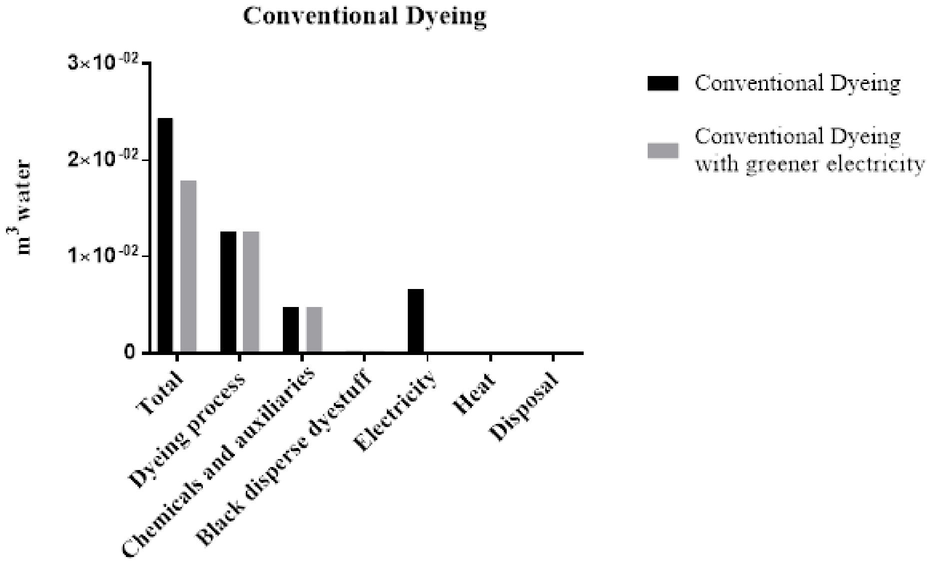


Figure 14: Water resource depletion for the two scenarios of conventional dyeing.

6.3.3 Human toxicity, cancer effects

The human toxicity, cancer effects characterisation results for the four scenarios are presented in figure 15 for SC-CO_2 dyeing and in figure 16 for conventional dyeing below. The highest impact for SC-CO_2 dyeing is related to the electricity (approximately 60% of the total impact) in the dyeing process and as can be seen in figure 15 the use of the greener electricity mix and a reduction of CO_2 losses to only 5% can reduce the total impact of human toxicity with more than one third.

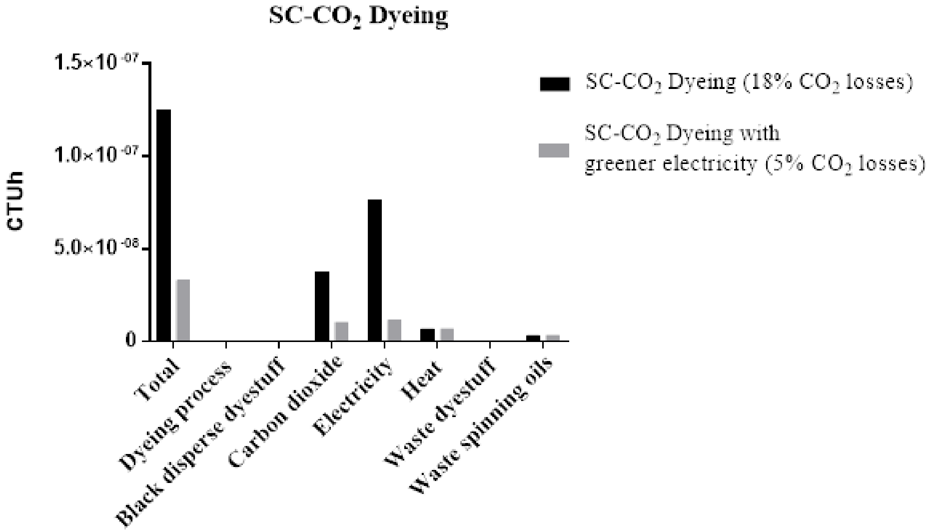


Figure 15: Human toxicity, cancer effects for the two scenarios of SC-CO_2 dyeing.

The highest impacts for the conventional dyeing process are due to the electricity and the chemicals and auxiliaries used in the dyeing process. The main contribution related to the chemicals and auxiliaries are from the softener and the anti-reduction agent, see appendix G. SC-CO_2 dyeing with the greener electricity mix has the lowest total impact for this category compared to conventional dyeing, however, it is important to notice that the differences are not that large.

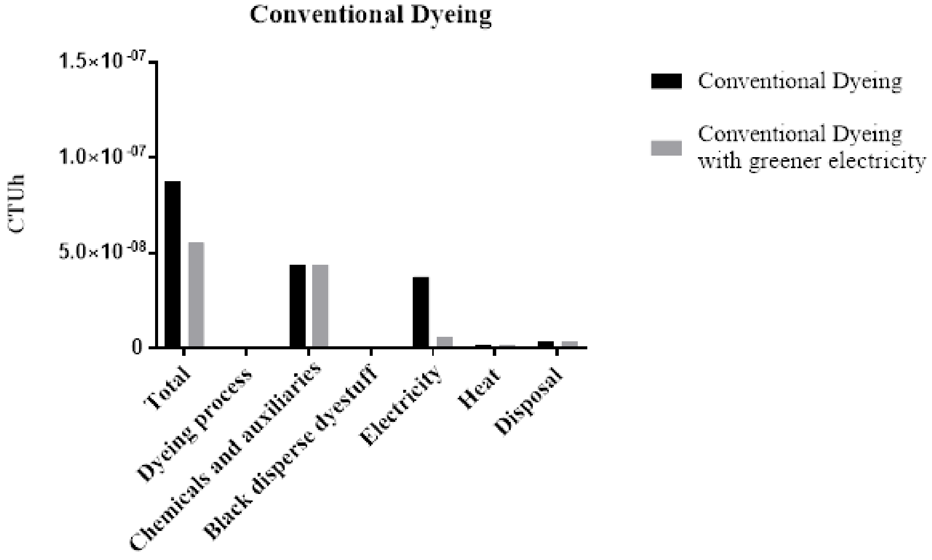


Figure 16: Human toxicity, cancer effects for the two scenarios of conventional dyeing.

6.3.4 Cumulative energy demand

The result of the cumulative energy demand presented in this subsection includes both renewable (i.e. solar, wind, water, geothermal, biomass) and non-renewable energy (i.e. fossil, nuclear, biomass) and the result is presented in MJ. The result for SC-CO_2 dyeing is presented in figure 17 and figure 18 for conventional dyeing. The electricity mix is also here the main contributor (more than 50%) to this impact category for SC-CO_2 dyeing.

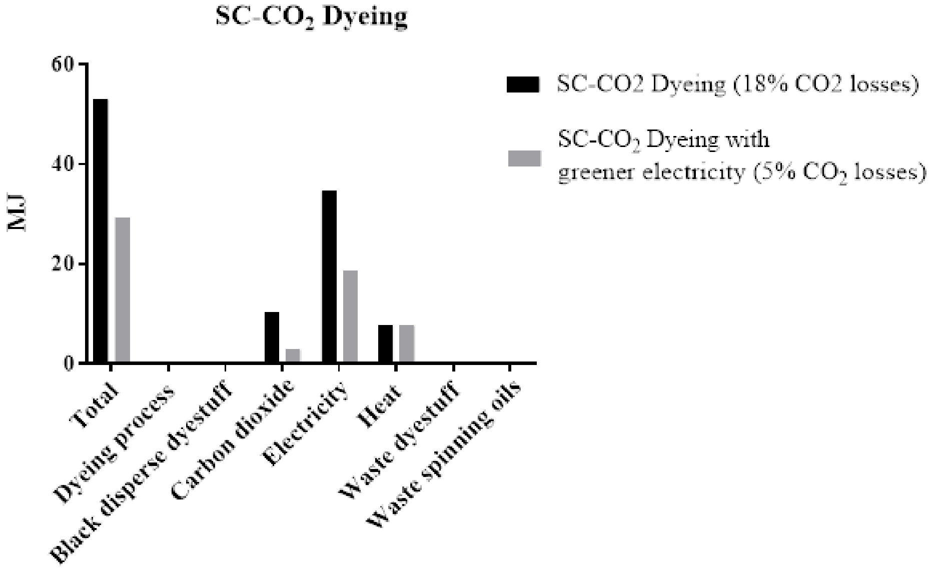


Figure 17: Cumulative energy demand for the two scenarios of SC-CO_2 dyeing.

Conventional dyeing process has lower energy demand compared to SC-CO_2 dyeing due to the lower amount of electricity use. Note, however, that the best-case scenario for the SC-CO_2 dyeing is of approximately the same magnitude as the conventional dyeing.

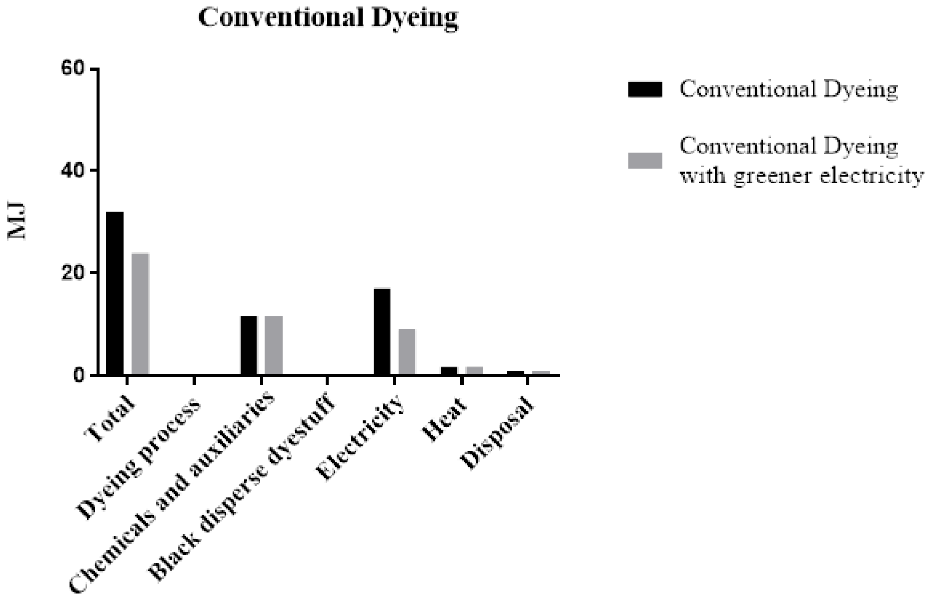


Figure 18: Cumulative energy demand for the two scenarios of conventional dyeing.

6.3.5 Normalisation

In order to compare the four scenarios and the impact categories, figure 19 presents the normalisation result regarding several impact categories for the four scenarios. The normalisation result is based on normalisation factors for the ILCD 2011 midpoint impact assessment method presented in appendix F. The highest impact category from the dyeing processes is from human toxicity, cancer effects. SC-CO_2 dyeing with 18% CO_2 losses has the highest impact for all categories except for water resource depletion. However, SC-CO_2 dyeing with green electricity mix and 5% CO_2 losses has the lowest impact for several impact categories.

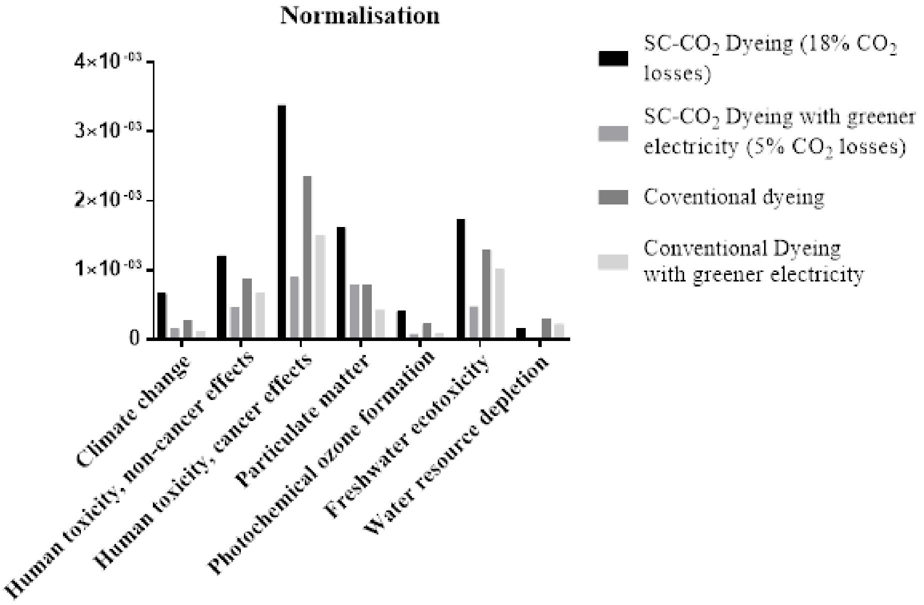


Figure 19: Normalisation result regarding several impact categories for the four scenarios.

7 Discussion

This chapter discusses the obtained results for the three main part of this study, review of emerging technologies, sustainability and feasibility criteria and the LCA study. The chapter ends with a discussion regarding further studies based on the result from this report.

7.1 Emerging technologies

This study identified eight emerging technologies for textile wet processing that are claimed to be environmental beneficial. The list of technologies presented in this report is not exhaustive, which is important to consider. However, the most relevant emerging technologies within the wet processing of the textile sector are probably covered in this study. As mentioned in the methodology (chapter 3), three main literature sources were used, which had identified almost the same technologies. Furthermore, no additional technologies were mentioned in the interviews, which indicates that this study has covered relevant technologies.

7.2 Sustainability and feasibility criteria

Since no criteria for assessing the sustainability and feasibility of emerging technologies could be found, this study presents a list of criteria that were identified. The criteria identified in this study are not exhaustive, which means that other criteria could be useful as well. Scalability was discussed as an additional criteria for this study. However, due to difficulties to find a clear definition, which for example is described by Hill (1990), and the fact that scalability is a proxy indicator for several of the other criteria, scalability was excluded from this study. Further development of the criteria identified in this study and to include other aspects, such as social aspects, could be of interest. The developed criteria were an important part in this study, in order to screen which technology that should be selected for further study. Since there is a lack of data regarding emerging technologies, it is important to notice that the assessment was a screening assessment and is not a detailed evaluation of the feasibility and sustainability. Besides being used to assess the sustainability and feasibility of emerging technologies, the criteria could also be seen as a list of guidelines for technology development of regarding emerging technologies in the textile industry.

7.3 LCA study

This subsection discusses the results from the LCA study and includes representativeness, a discussion regarding the contribution from the electricity production and if SC-CO_2 dyeing is or could be an sustainable alternative for the industry.

7.3.1 Representativeness

Several assumptions and limitations were made, which affect the representativeness of the result. Uncertainties related to the data used for this study also affect the representativeness of the result. As mentioned before, the modelling of SC-CO_2 dyeing scenarios is based on estimated data and this is probably the main uncertainty of this study. It is important to consider that the process data used are based on a non-optimised process, which means that the process data for the SC-CO_2 dyeing machine that Dyecoo uses can be different.

Optimisation of the CO_2 losses from 18% to 5% according to Dyecoo were tested in this study. Reducing the CO_2 losses to 5% leads to some environmental improvement related to climate change and human toxicity due to a reduction in CO_2 production and emission during the process, even though the electricity production contributed to the most. According to Bach & Schollmeyer (2007), it might be possible to keep constant temperature in the autoclave and dyestuff vessel during the whole process, which would reduce the energy consumption. Since no estimation of how much the energy consumption could be reduced was found, this was not investigated in this study. The result shows that from a life cycle perspective, SC-CO_2 dyeing reduces the water use, which was also claimed by several literature sources (e.g. Hasanbeigi & Price, 2015; European Commission, 2003).

Moreover, no washing, softening and drying step were included in the SC-CO_2 dyeing process in this study. These steps are probably used after the dyeing process and it is therefore important to consider this in the comparison between the two dyeing processes since it is included for the conventional dyeing process. In this study, the input of CO_2 for the dyeing process was modelled as processing of CO_2 from ammonia production. How the CO_2 in the dyeing process is produced is something that may affect the result.

7.3.2 Electricity production

The production of electricity for the dyeing processes accounts for the main contribution to all impact categories investigated in this study. Two different electricity mixes were therefore investigated in this study, one called the MiFuFa electricity mix based on country electricity mix from China, Bangladesh and Turkey and the other option was a greener electricity from Sweden based on wind, hydro, thermal and nuclear power. Two of the dyeing scenarios were modelled with the greener electricity and two with the other electricity. The result shows that the choice of electricity mix has a large impact on all impact categories. The greener electricity mix has considerable lower impact compared to the MiFuFa electricity mix.

The country electricity mix from China causes the largest impact due to a large share in the MiFuFa electricity mix compared to Bangladesh and Turkey, but also due to a large amount of electricity produced from coal and peat. The result from this LCA study shows that it is not the foreground system that is most important in this case. Instead, processes in the background system, in particular the electricity production, are most important to consider.

7.3.3 SC-CO_2 dyeing as a sustainable alternative

This study investigated the environmental performance of SC-CO_2 dyeing compared to conventional dyeing. As mentioned above, the choice of electricity mix has considerable impact on the result. It can therefore be discussed whether a new dyeing technology will solve the environmental issues from the textile industry, given that the electricity is based on non-renewable energy sources.

If the SC-CO_2 dyeing process is optimised in terms of energy use and CO_2 losses, the results indicates that the technology can be a sustainable alternative, even though further studies are required. It is also important to notice that water in many countries is a scarce resource, which makes SC-CO_2 dyeing beneficial. Moreover, as seen from the result, the production of chemicals and auxiliaries contributes considerably to the environmental load, which is also important to consider. The result should be seen as a first screening of the environmental performance of SC-CO_2 dyeing. Further studies are needed to determine how environmental beneficial SC-CO_2 dyeing is for the industry.

7.4 Future studies

Based on the result from this study several further studies are of interest. As mentioned before, data for the SC-CO_2 dyeing are very uncertain and process data from Dyecoo could be interesting for further study. Moreover, process data for new technologies are difficult to obtain since most of them are under development. Even though there is a lack of LCA studies regarding emerging textile production technologies, many environmental claims exist, which motivates further investigations.

This study chose to evaluate the environmental performance of SC-CO_2 dyeing, however, to evaluate the environmental performance of the other presented technologies is interesting for further studies. In this case, the focus should be on technologies that scored high in the sustainability and feasibility criteria, such as digital printing.

8 Conclusion

The aim of this master thesis was to review emerging sustainable textile production technologies for wet processing, set up sustainability and feasibility criteria for assessing emerging technologies and finally, evaluate the environmental performance of one technology based on the developed criteria.

This study presents eight emerging technologies for textile wet processing, namely, plasma technology, spin-dyeing, SC-CO_2 dyeing, digital printing, ozone bleaching, enzymatic treatment, electrochemical dyeing and ultrasonic treatment. All identified technologies are claimed to have environmental advantages compared to conventional technologies. Moreover, several of the identified technologies have been under development during a long time which indicates that implementation of new technologies in the textile industry is complex.

Furthermore, this study identified seven sustainability and feasibility criteria for emerging textile production technologies namely, cost, technical quality, flexibility, interest, TRL, resource availability and environmental potential. Based on these developed criteria, SC-CO_2 dyeing was selected for further environmental evaluation and the environmental performance was evaluated with LCA.

The results from the LCA study indicates that SC-CO_2 dyeing can be a sustainable alternative to conventional water dyeing given that the process is optimised regarding CO_2 losses and energy use and if the electricity is produced from renewable energy sources. However, even though this study shows that SC-CO_2 dyeing can be a beneficial alternative, the result from this study also shows that background systems such as the electricity production cause the main contribution. It can therefore be questioned whether new technologies can solve the environmental concerns related to the textile industry, if a greener electricity is not used.

The results from the LCA study regarding SC-CO_2 dyeing as a sustainable alternative for the industry motivate further environmental investigations with further validation of process data. Further studies regarding some of the other technologies identified in this study would also be of interest. In this case, the focus should be on technologies that scored high on the sustainability and feasibility criteria developed in this study. Finally, the result from this master thesis should be seen as a first screening of the environmental performance of SC-CO_2 dyeing. Future studies are needed to determine if SC-CO_2 dyeing improves the environmental performance of the textile industry.

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Appendices

Appendix A -Interview template

1. What do you think are the main concerns/issues for the textile industry?

- Are new sustainable production technologies something that can be an important solution for the industry?
- Are new sustainable technologies something that is in focus in the textile industry?
- Where in the textile production is it important to make an effort in order to become more sustainable?

2. Which new “promising” technologies have you heard about?

- Is there some technology that sounds more promising and if so, why?
- Why are these technologies seen as promising for the industry?
- What do you know about these technologies?
- What timeline do you see for implementation: existing now / will be on the market in 1-5 years / probably more than 5 years ahead?

3. What is expected of a new technology?

- Is there some trend or main focus in the development of new technologies?

4. Is there some process/technology that is important to replace in the wet processing stage of textile manufacturing?

5 Which criteria should be set up in order to select among these technologies?

- Why are these criteria important?
- Which are the most important criteria, why?

6. Do you know someone that can contribute to knowledge for this master thesis and could be important for me to interview?

Appendix B -Electricity production

B.1 MiFuFa Electricity mix

MiFuFa Electricity mix

Input	Share
Electricty mix China	65%
Electricty mix Bangladesh	23%
Electricty mix Turkey	12%

B.2 Electricity mix China

Electricity mix China

Input	Ecoinvent process	Share
Chinas electricity mix	CN: electricity, medium voltage, at grid	100%

B.3 Electricity mix Bangladesh

Electricity mix Bangladesh

Input	Ecoinvent process	Share
Electricity from natural gas	GLO: electricity, natural gas, at turbine, 10MW	91.50%
Electricity from oil	UCTE: electricity, oil, at power plant	4.80%
Electricity from hydro power	RER: electricity, hydro power, at reservoir power plant, non alpine regions	2.00%
Electricity from coal and peat	CN: electricity, hard coal, at power plant	1.80%
Losses		10.3%

B.4 Electricity mix Turkey

Electrical mix Turkey

Input	Ecoinvent process	Share
Electricity from natural gas	GLO: electricity, natural gas, at turbine, 10MW	45.80%
Electricity from coal and peat	UCTE: electricity, hard coal, at power plant	29.10%
Electricity from hydro power	RER: electricity, hydropower, at reservoir power plant, non alpine regions	23.00%
Electricity from wind power	Electricity from wind power	2.10%
Losses		14.20%

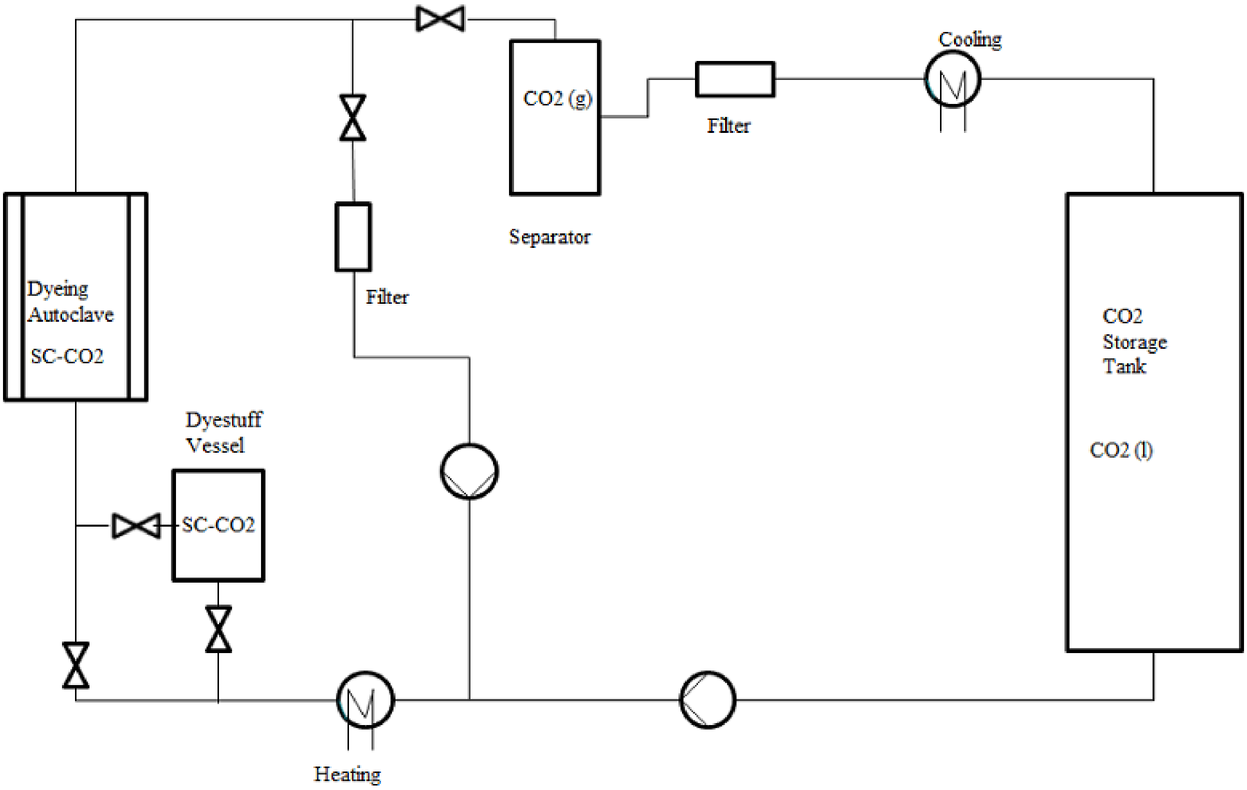
B.5 Greener Electricity Sweden

Green Electricity mix

Input	Share
Wind power	4.4%
Water power	48.3%
Thermal power	9.5%
Nuclear power	37.8%

Appendix C -SC-CO_2 process chart

Process figure of the dyeing plant based on Bach & Schollmeyer (2007).



Appendix D -LCI Data

D.1 Conventional dyeing

(Roos et al., 2015)

Input/Output type	Amount/FU	Unit
Resources		
Water	78	l
Materials/fuels		
Detergent/Wetting agent	0.075	kg
Sequestering agent	0.02	kg
Antifoaming agent	0.0015	kg
Base (alkali) (Na_2CO_3)	0.0025	kg
Acid (formic acid)	0.015	kg
Wetting/Penetration agent (synthetic)	0.01	kg
Dispergent	0.015	kg
Decalcifier ($(NH_4)_2SO_4$)	0.01	kg
Antireduction agent (H_2O_2)	0.015	kg
Black disperse dyestuff	0.005	kg
Base (alkali) (NaOH)	0.005	kg
Reducing agent	0.005	kg
Soda ($CaCO_3$)	20	kg
Detergent/Wetting agent, BAT	0.02	kg
Softener	0.2	kg
Electricity/heat		
Electricity	1.47	kWh
Heat	0.35	kWh
Emissions to air		
from 1 kg Detergent/Wetting agent	0.15	kg
from 1 kg Sequestering agent	0.04	kg
from 1 kg Acid (formic acid)	0.03	kg
Emissions to water		
from 1 kg Detergent	0.15	kg
from 1 kg Sequestering agent	0.04	kg
from 1 kg Antifoaming agent	0.003	kg
from 1 kg Base (NaOH)	0.005	kg
from 1 kg Acid (formic acid)	0.03	kg
from 1 kg Wetting/Penetration agent (synthetic)	0.015	kg
from 1 kg Soda ($CaCO_3$)	0.02	kg
from 1 kg Black disperse dyestuff	0.0005	kg
COD, Chemical Oxygen Demand	0.0002	kg
Waste to treatment		
Disposal	0.5	kg

D.2 SC-CO_2 dyeing

(1)-Bach & Schollmeyer, 2007 (2)-European Comission, 2003

Input/Output type	**Amount/FU**	**Unit**	**Reference**
materials/fuels			
Carbon dioxide	1.17	kg	(1)
Black disperse dyestuff	0.002	kg	(1)
Electricity/Heat			
Electricity	3.0	kWh	(1)
Heat	1.5	kWh	(1)
Emissions to air			
Carbon dioxide (18%/5% - losses)	1.17/0.325	kg	(1)
Waste and emissions to treatment			
Waste paint	0.0004	kg	(1)
Waste mineral oil, treatment of hazardous waste incineration	0.1	kg	(2)

Appendix E -Processes SimaPro

E.1 Conventional dyeing

Resources
Water, river
Materials/fuels
Detergent/Wetting agent, average
Sequestering agent, average
Antifoaming agent, average
Base (alkali) (Na_2CO_3), average
Acid (formic acid), average
Wetting/Penetration agent (synthetic), average
Dispergent, average
Decalcifier ($(NH_4)2SO_4$), average
Antireduction agent (H_2O_2), average
Black disperse dyestuff PA, BAT
Base (alkali) (NaOH), average
Reducing agent, average
Soda ($CaCO_3$), average
Detergent/Wetting agent, BAT
Softener, average
Electricity/heat
MiFuFa electricity mix
Electricity, medium voltage, GREEN at grid/SE System
Heat, light fuel oil, at boiler 10kW, non-modulating/CH S
Waste to treatment
Disposal, sludge from pulp and paper production, 25% water, to sanitary landfill/CH

E.2 SC-CO_2 dyeing

Materials/fuels
Black disperse dyestuff PA, BAT
Carbon dioxide, liquid (RoW)— market for — Alloc Def, S
Electricity/heat
MiFuFa electricity mix
Electricity, medium voltage, GREEN at grid/SE System
Heat, light fuel oil, at boiler 10kW, non-modulating/CH S
Waste to treatment
Waste paint (GLO)— market for — Alloc Def, S
Waste mineral oil RoW— treatment of, hazardous waste incineration — Alloc Def, S

Appendix F -Normalisation factors

Normalisation	
Climate change	0.00011
Ozone depletion	46.3
Human toxicity, non-cancer effects	1876
Human toxicity, cancer effects	27100
Particulate matter	0.263
Ionizing radiation HH	0.000885
Ionizing radiation E (interim)	0
Photochemical ozone formation	0.0315
Acidification	0.0211
Terrestrial eutrophication	0.00568
Freshwater eutrophication	0.676
Marine eutrophication	0.0592
Freshwater ecotoxicity	0.000114
Land use	1.34E-05
Water resource depletion	0.0123
Mineral, fossil & ren resource depletion	9.9

Appendix G -Impact assessment data

G.1 Normalisation result

Impact category	SC-CO_2 dyeing (18% CO_2 losses)	SC-CO_2 dyeing greener electricity (5% CO_2 losses)	Conventional dyeing	Conventional dyeing greener electricity
Climate change	6.60E-04	1.60E-04	2.83E-04	1.20E-04
Ozone depletion	1.01E-05	4.17E-06	5.49E-06	3.27E-06
Human toxicity, non-cancer	1.21E-03	4.66E-04	8.83E-04	6.73E-04
Human toxicity, cancer	3.39E-03	8.98E-04	2.37E-03	1.50E-03
Particulate matter	1.62E-03	7.82E-04	7.78E-04	4.28E-04
Ionizing radiation HH	1.48E-04	5.60E-05	1.71E-04	1.53E-04
Ionizing radiation E	0	0	0	0
Photochemical ozone	4.12E-04	7.71E-05	2.25E-04	8.40E-05
Acidification	7.37E-04	7.93E-05	3.76E-04	9.21E-05
Terrestrial eutrophication	2.53E-04	4.74E-05	1.33E-04	4.51E-05
Freshwater eutrophication	4.46E-04	9.83E-05	3.65E-04	2.55E-04
Marine eutrophication	2.72E-04	5.21E-05	7.73E-04	6.87E-04
Freshwater ecotoxicity	1.74E-03	4.74E-04	1.29E-03	1.02E-03
Land use	5.60E-05	2.33E-05	2.71E-05	1.47E-05
Water resource depletion	1.68E-04	5.58E-06	3.00E-04	2.20E-04
Mineral, fossil & ren resource depletion	5.70E-04	1.83E-04	1.10E-04	1.11E-04

G.2 SC-CO_2 dyeing (18% CO_2 losses)

Impact category Unit	Climate change kg CO2-eq	Water resource depletion m^3 water	Human toxicity, non cancer CTUh
Total	6.00	1.36E-02	1.25E-07
Dyeing process	1.17	0	0
Black disperse dyestuff	9.76E-03	6.29E-05	3.61E-10
Carbon dioxide	9.71E-01	-1.16E-04	3.75E-08
Electricity	3.06	1.34E-02	7.64E-08
Heat	5.11E-01	2.94E-04	6.86E-09
Waste dyestuff	9.58E-04	6.87E-09	5.32E-10
Waste spinning oils	2.85E-01	1.27E-05	3.41E-09

Impact category Unit	Total cumulative energy demand MJ	Non-renewable MJ	Renewable MJ
Total	5.30E+01	5.03E+01	2.72
Dyeing process	0	0	0
Black disperse dyestuff	1.79E-01	1.76E-01	2.69E-03
Carbon dioxide	1.04E+01	9.65	7.46E-01
Electricity	3.47E+01	3.28E+01	1.91
Heat	7.66	7.61	5.25E-02
Waste dyestuff	1.03E-04	1.00E-04	2.85E-06
Waste spinning oils	3.22E-02	3.08E-02	1.37E-03

G.3 SC-CO_2 dyeing with greener electricity (5% CO_2 losses)

Impact category Unit	Climate change kg CO_2-eq	Water resource depletion m^3 water	Human toxicity, non cancer CTUh
Total	1.45	4.54E-04	3.31E-08
Dyeing process	3.25E-01	0	0
Black disperse dyestuff	9.76E-03	6.29E-05	3.61E-10
Carbon dioxide	2.70E-01	-3.22E-05	1.04E-08
Electricity	5.03E-02	1.16E-04	1.16E-08
Heat	5.11E-01	2.94E-04	6.86E-09
Waste dyestuff	9.58E-04	6.87E-09	5.32E-10
Waste spinning oils	2.85E-01	1.27E-05	3.41E-09

Impact category Unit	Total cumulative energy demand MJ	Non-renewable MJ	Renewable MJ
Total	2.93E+01	1.10E+01	1.83E+01
Dyeing process	0	0	0
Black disperse dyestuff	1.79E-01	1.76E-01	2.69E-03
Carbon dioxide	2.89	2.68	2.07E-01
Electricity	1.86E+01	5.48E-01	1.80E+01
Heat	7.66	7.61	5.25E-02
Waste dyestuff	1.03E-04	1.00E-04	2.85E-06
Waste spinning oils	3.22E-02	3.08E-02	1.37E-03

G.4 Conventional dyeing

Impact category Unit	Climate change kg CO_2-eq	Water resource depletion m^3 water	Human toxicity cancer effects CTUh
Total	2.57	2.44E-02	8.73E-08
Dyeing process	0	1.26E-02	8.65E-13
Black disperse dyestuff	2.44E-02	1.57E-04	9.03E-10
Electricity	1.50	6.58E-03	3.76E-08
Heat	1.20E-01	6.90E-05	1.61E-09
Disposal	4.33E-01	1.48E-04	3.19E-09
Detergent/Wetting agent	9.11E-02	4.34E-04	3.56E-09
Sequestering agent	8.51E-03	1.60E-04	9.30E-09
Antifoaming agent	2.37E-04	2.49E-06	1.54E-11
Base (alkali) (Na_2CO_3)	2.63E-03	2.07E-05	1.65E-10
Acid (formic acid)	3.72E-02	8.31E-04	1.58E-09
Wetting/Penetration agent	7.07E-03	3.33E-05	3.01E-10
Dispergent	3.16E-02	1.78E-04	1.43E-09
Decalcifier ($(NH_4)_2SO_4$)	5.65E-03	5.85E-06	2.66E-10
Antireduction agent (H_2O_2)	3.37E-02	9.55E-04	1.06E-08
Base (alkali) (NaOH)	1.10E-02	1.88E-04	1.08E-09
Reducing agent	1.64E-02	1.80E-04	1.60E-09
Soda ($CaCO_3$)	1.71E-02	2.16E-04	1.25E-09
Detergent/Wetting agent, BAT	1.50E-02	6.25E-05	5.79E-10
Softener	2.14E-01	1.54E-03	1.23E-08

Impact category Unit	Total cumulative energy MJ	Non-renewable MJ	Renewable MJ
Total	3.19E+01	3.06E+01	1.32
Dyeing process	0	0	0
Black disperse dyestuff	4.47E-01	4.40E-01	6.73E-03
Electricity	1.71E+01	1.61E+01	9.41E-01
Heat	1.80	1.78	1.23E-02
Disposal	9.06E-01	8.06E-01	1.00E-01
Detergent/Wetting agent	2.90	2.87	3.11E-02
Sequestering agent	1.26E-01	1.20E-01	6.21E-03
Antifoaming agent	6.25E-03	6.07E-03	1.82E-04
Base (alkali) (Na_2CO3)	4.81E-02	4.65E-02	1.62E-03
Acid (formic acid)	9.75E-01	9.54E-01	2.03E-02
Wetting/Penetration agent	2.29E-01	2.27E-01	2.70E-03
Dispergent	1.00	9.89E-01	1.40E-02
Decalcifier ($(NH_4)_2SO_4$)	9.51E-02	9.34E-02	1.77E-03
Antireduction agent (H_2O_2)	6.83E-01	6.65E-01	1.83E-02
Base (alkali) (NaOH)	2.28E-01	2.14E-01	1.45E-02
Reducing agent	3.30E-01	3.10E-01	2.07E-02
Soda ($CaCO_3$)	2.19E-01	2.06E-01	1.29E-02
Detergent/Wetting agent, BAT	4.48E-01	4.43E-01	5.48E-03
Softener	4.43	4.32	1.06E-01

G.5 Conventional dyeing with greener electricity

Impact category	Climate change	Water resource depletion	Human toxicity, cancer effects
Unit	kg CO_2-eq	m^3 water	CTUh
Total	1.09	1.79E-02	5.54E-08
Dyeing process	0	1.26E-02	8.65E-13
Black disperse dyestuff	2.44E-02	1.57E-04	9.03E-10
Electricity	2.47E-02	5.70E-05	5.68E-09
Heat	1.20E-01	6.90E-05	1.61E-09
Disposal	4.33E-01	1.48E-04	3.19E-09
Detergent/Wetting agent	9.11E-02	4.34E-04	3.56E-09
Sequestering agent	8.51E-03	1.60E-04	9.30E-09
Antifoaming agent	2.37E-04	2.49E-06	1.54E-11
Base (alkali) (Na_2CO_3)	2.63E-03	2.07E-05	1.65E-10
Acid (formic acid)	3.72E-02	8.31E-04	1.58E-09
Wetting/Penetration agent	7.07E-03	3.33E-05	3.01E-10
Dispergent	3.16E-02	1.78E-04	1.43E-09
Decalcifier ($(NH_4)_2SO_4$)	5.65E-03	5.85E-06	2.66E-10
Antireduction agent (H_2O_2)	3.37E-02	9.55E-04	1.06E-08
Base (alkali) (NaOH)	1.10E-02	1.88E-04	1.08E-09
Reducing agent	1.64E-02	1.80E-04	1.60E-09
Soda ($CaCO_3$)	1.71E-02	2.16E-04	1.25E-09
Detergent/Wetting agent, BAT	1.50E-02	6.25E-05	5.79E-10
Softener	2.14E-01	1.54E-03	1.23E-08

Impact category Unit	Total cumulative energy MJ	Non-renewable MJ	Renewable MJ
Total	2.40E+01	1.48E+01	9.23
Dyeing process	0	0	0
Black disperse dyestuff	4.47E-01	4.40E-01	6.73E-03
Electricity	9.12	2.69E-01	8.85
Heat	1.80	1.78	1.23E-02
Disposal	9.06E-01	8.06E-01	1.00E-01
Detergent/Wetting agent	2.90	2.87	3.11E-02
Sequestering agent	1.26E-01	1.20E-01	6.21E-03
Antifoaming agent	6.25E-03	6.07E-03	1.82E-04
Base (alkali) (Na_2CO_3)	4.81E-02	4.65E-02	1.62E-03
Acid (formic acid)	9.75E-01	9.54E-01	2.03E-02
Wetting/Penetration agent	2.29E-01	2.27E-01	2.70E-03
Dispergent	1.00	9.89E-01	1.40E-02
Decalcifier ($(NH_4)_2SO_4$)	9.51E-02	9.34E-02	1.77E-03
Antireduction agent (H_2O_2)	6.83E-01	6.65E-01	1.83E-02
Base (alkali) (NaOH)	2.28E-01	2.14E-01	1.45E-02
Reducing agent	3.30E-01	3.10E-01	2.07E-02
Soda ($CaCO_3$)	2.19E-01	2.06E-01	1.29E-02
Detergent/Wetting agent, BAT	4.48E-01	4.43E-01	5.48E-03
Softener	4.43	4.32	1.06E-01