Climate implications of water-free dyeing of biofibers (ClimaDYE)

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A Climate-KIC funded project for the *Sustainable Production Systems* theme

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Climate-KIC

The images at the cover of this document comes from DyeCoo's website: http://www.dyecoo.com/

Contents

Short description of the contents of this document

This document illustrates the project outputs of the Climate-KIC funded project “ClimaDYE”. The purpose of the project is to estimate environmental and in particular climate implications of a water-free dyeing technology using supercritical CO_2 ($scCO_2$) and to evaluate the business case for it.

The outputs of the ClimaDYE project are three:

1. an economic and environmental evaluation of $scCO_2$ dyeing of polyester (PES) fabric against two alternative dyeing technologies
2. an estimation of environmental impact of $scCO_2$ dyeing of biofibers, to be confirmed by future physical tests on biofibers
3. a list of business opportunities for PES and biofibers dyeing with $scCO_2$, to be confirmed by future physical tests on biofibers

As a result, this deliverable is to be considered as a blend of a feasibility study and a comparative study.

This document contains the main analyses being done to obtain the project outputs mentioned above, and the project results in relation to the three outputs.

Executive Summary

Average per capita world fiber consumption in the year 2016 was 13.4 kg. What does this imply for Earth's ecological systems which provide resources to the textile industry and bear the burden of related emissions?

In 2015, greenhouse gas (GHG) emissions from textiles production totaled 1.2 billion tonnes of CO_2 equivalent, which is more than those of all international flights and maritime shipping combined.

Water is one of the most significant inputs of wet processes (pre-treatment, dyeing and finishing) in textile industry. The world uses 5 trillion liters (l) of water each year for fabric dyeing alone, enough to fill 2 million Olympic-sized swimming pools. If the per capita world fiber demand will maintain today's patterns, the outlook of global and local ecological systems looks worrisome when considering that the world population accounts for 7.6 billion now (close to the end of 2017) and will reach 8.0 billion in 2020-2024.

Can research and development in innovative dyes and dyeing technologies help tackle this problem? Can carbon dioxide be part of the solution rather than being part of the problem only? This research project named "ClimaDYE" explores if and how well this scenario might happen.

First, captured carbon dioxide emitted by fossil fuel power plants and other industries can be "compressed" and serve other different industrial processes, by replacing "conventional input materials" of these processes rather than being geo-sequestrated, for instance in deep geological formations, or in the form of mineral carbonates. Supercritical fluids are highly compressed matter at high temperature that have properties of both a liquid and gas. Supercritical CO_2 acts as both a solvent and a solute in dyeing processes, by completely replacing water as dyeing medium. $scCO_2$ dyeing was launched by the Dutch company DyeCoo and has been operating for a decade. Apparel companies like Nike, Adidas and Mizuno, among other renowned names, adopt polyester (PES) fabrics dyed through $scCO_2$ in order to bring the water footprint of some of their products remarkably down and save operational costs. However, the potential of $scCO_2$ dyeing of being adopted by more and more companies in the textile industry is still untapped. The main reasons for this are: high investment costs for equipment purchase (from 2.5 to 4 million USD[1]), which make the technology inaccessible for Small and Medium Enterprises (SMEs), and the possibility so far to successfully dye synthetic fibers only. On the other hand, the technology involves less operative costs than conventional dyeing and require neither water nor process chemicals, with consequent cost savings and reduced environmental impact in terms of water footprint and aquatic pollution.

[1] From here on in this report "$"stands for USD.

As remarkable savings are achievable in terms of water, an interesting question then becomes: what are the *climate* implications of scCO_2 dyeing? The purpose of ClimaDYE is indeed to estimate environmental and in particular climate implications scCO_2 dyeing and to evaluate when the business case for the use of this technology exists. In order to do so, there is the need to assess the current state of the technology for the case of PES, and use the knowledge and the figures at hand to draw an educated estimation of the economic and climate impacts of cotton and other biofibers dyeing with scCO_2.

The benchmark used for the technology evaluation compares scCO_2 dyeing with two alternative water dyeing technologies, provided data availability: jet dyeing with low-liquor ratio (so far the most widespread in the market) and dyeing with zero-liquid discharge (ZLD). When no data is available, a comparison has been done with "traditional" water-based dyeing, although it is being phased out nowadays.

The outputs of ClimaDYE will be indicated hereby with O1 (output 1), O2 (output 2) and O3 (output 3). They are:

- O1: an economic and environmental evaluation of scCO_2 dyeing of PES compared to alternative water-based dyeing technologies
- O2: an estimation of environmental impact of scCO_2 dyeing of biofibers, to be confirmed by future physical tests on biofibers
- O3: a map of the business opportunities for PES and biofiber dyeing with scCO_2

The economic impacts were calculated in operational costs (machine operating costs) compared to the ones of alternative water-based technologies. However, these costs strongly depend on the location of the dyeing factory, how the factory is being managed and the customer companies. These factors determine the cost of the energy (e.g., fuel used for electricity generation) used by the dyeing factory, the manpower's salary, the types of dyes, the order sizes and the transport costs for supplying the scCO_2 to the factory. Nevertheless, it was possible to present percentage variations of costs and illustrate specific examples helpful to compare scCO_2 dyeing with other competitor technologies.

The climate impacts were calculated in terms of kg of CO_2 emissions and global warming potential (GWP), measured in kg of CO_2 emissions equivalents. GWP is an indicator that measures the potential and the extent of the warming effect of greenhouse gases (GHGs) to world's climate. Even in this case, specific examples were used to compare climate impacts of scCO_2 dyeing.

The results of the project related to each output are synthetized as follows:

O1: Economic evaluation – PES case

It was found that scCO_2 dyeing reduces machine operating costs normally to 20% in comparison to water-based dyeing. There are different reasons that explain lesser operational costs achievable through scCO_2 dyeing. scCO_2 utilizes pure dyes and their cost ranges from 0.76$ to 1.37$ per kg of dyed PES fabric, which are always less than the costs of dyes for traditional, water-based dyeing. The reason is two-fold: absence of chemicals needed for $scCO_2$ dyeing and 1% of the amount of dyes waste in the process against a 10% of dyes dispersed in water with conventional dyeing. By switching to $scCO_2$ instead of water as dyeing medium, a peer-reviewed study based in China calculated a saving of 0.32$ per kg of fabric. In fact, cost for specific CO_2 intake appeared to be only 13% of the cost that would be spent otherwise for specific water intake (water and steam use and treatment). This sounds sensible, if considering that the range of water usage for traditional dyeing goes from 100 l/kg to 150 l/kg. scCO2 dyeing benefits also from reduced dyeing times. Full operational times for scCO2 dyeing are lesser than the ones in competing technologies such as regular jet machines: 2-3 hours against 3-4 hours, respectively. The range is determined by the depth of the color (lower-boundary time for light colors and upper-boundary time for dark colors).

From a mid and long-term perspective, the costs that have been examined are those due to processes or events that happen beyond the boundaries of the dyeing factory.
First, the advantage of not being reliant on water allows freedom of location of the factories, which as a result can be located close to the customer. This possibility can bring about savings in transport costs, directly related to the proximity of the customers.
Another cost saving comes from the opportunity cost of avoiding a sudden closure of the factory ordered by the authorities when environmental regulations are not respected, even though this example refers to the case of companies that do not tend to follow regulations as legally demanded. In China, factories have been shut down for several months after the authorities discovered wastewater discharged from hidden pipes and untreated pollutants discharged in lakes and rivers.
All these advantages, when converted in cost savings over the life time of the equipment (20-30 years) and discounted by time and risk factors, can make the payback time of the equipment shorter than presently estimated (4-5 years).

O1: Climate evaluation – PES case

Many of the aforementioned savings translate into savings in kg CO_2 emissions and therefore less impactful dyeing processes from a GWP standpoint.
The main driver for savings in CO_2 emissions and consequent GWP is the reduction of energy consumed from the dyeing process, which ranges from 20% to 40% if compared to other water-based technology. Dyeing with ZLD did not appear to outperform $scCO_2$ dyeing and jet dyeing. Dyeing with ZLD aims to reduce water pollution and decreases water use, but the technology is constrained by high cost and intensive energy consumption, that is still hard to reduce. It was understood that the main reasons for less energy consumptions were lesser dyeing times, the avoidance of steam usage during the dyeing process and the avoidance of a following drying phase. In DyeCoo's machines, $scCO_2$ is used as dyeing medium and normally 90%-95% is recycled in a closed-loop system and the rest ends up as CO_2 gas exhausts. It is important to remark that such a closed-loop system does not imply reduced CO_2 exhausts in comparison to the CO_2 used as input material. In fact, this simply means that at the 10^{th} batch, all the $scCO_2$ employed for the

dyeing process gets released in the atmosphere. Ultimately, since less climate impacts in $scCO_2$ dyeing are linked to reduced energy consumption only, the type of fuel burnt in the factory to supply energy in the factory determines the value of the GWP of the dyeing processes.
Yeh Group publicly reported that $scCO_2$ dyeing allowed a reduction of 50% of energy consumption. In this example, assuming that the factory burns hard coal to produce energy, the GWP of the dyeing operations would be 20.82 kg of CO_2 eq./kg fabric, which would be reduced of 6 percentage points if adopting hydro power instead (19.48 kg of CO_2 eq./kg fabric).
As laboratory tests on cotton and other biofibers (e.g., coming from forestry resources) were not in the scope of ClimaDYE, qualitative estimations have been drawn during the project workshop at DyeCoo. These estimations are based on the extensive experience from experiments at DyeCoo on cotton dyeing in scCO2. Today several limitations impede getting satisfactory results from a product quality standpoint.

O2: Economic estimation – biofibers case

No cost increase has been forecasted in comparison to the existing costs for PES dyeing.
The dyeing time of cotton with $scCO_2$ was estimated to be 2 hours for light-color dyes and 3 hours for dark-color dyes, similarly to the PES case. It was estimated a range of prices between 10 €/ kg to 30 €/ kg of dye, against average prices of 5 €/ kg to 25 €/ kg of the dyes currently employed for PES.

O2: Climate estimation – biofibers case

The amount of energy savings and reduced GWP from $scCO_2$ dyeing compared to competing technologies will be maintained because cotton dyeing takes the same time and same energy consumed in comparison to the PES case. However, it is unknown whether finishing treatments will require further energy.

From a systemic point of view, an interesting argument is that if the market recognizes the benefits of $scCO_2$ dyeing, more plants to realize $scCO_2$ dyeing will be built. This would in turns incentivize sells of carbon captured by CSS plants from fossil fuels power plants, which would help reduce GWP from energy generated by fossil fuels. This would not result in a reduction of GWP on a global scale though, if the increased amount of captured carbon would rather be used by industries whose products are less impactful in their GWP than those in the textile industry (demands and volumes being equal).

O3: Business opportunities and limitations

Opportunities for dyeing houses:

- Reduced industrial costs and environmental impacts (water footprint and GWP) of the dyeing processes, including pre and post dyeing treatments

- Increased likelihood of compliance with environmental regulatory agencies and continuity of operations
- Freedom of location, which opens up new geographical markets and reduces transports of dyed fabrics to customers
- Active participation in climate mitigation strategies by using CO_2 captured in CCS plants

Opportunities for apparel and furniture companies:

- Demonstrable commitment towards some of the Sustainable Development Goals like "Responsible Production and Consumption", and "Life below water".
- Increased market share for products appealing to environmentally-conscious customers
- Improved company reputation.

Limitations:

- Higher investment costs that for the case of SMEs do not seem to be so far justified by higher opportunities and potential future benefits by investors in the textile industry (e.g., top management of apparel and furniture companies, venture capitalists)
- Poor dyeability of biofibres in $scCO_2$ due to poor solubility of polar dyes in $scCO_2$. More R&D is needed in order to achieve efficient $scCO_2$ dyeing of biofibres.

In the light of the project results, we ultimately recommend:

- Disseminating knowledge about the economic and environmental benefits of $scCO_2$ dyeing by workshops, talks, and campaigns
- Spreading further awareness on the enormous impact that dyeing has on aquatic toxicity, as it would encourage customers to pay a premium price for a water-free dyed piece of cloth and help $scCO_2$ dyeing reduce fixed costs over time
- Having the proven economic and environmental benefits properly accounted for in investment evaluation models
- Funding research to achieve $scCO_2$ dyeing on cotton, either through adjustments on the dyeing technology or, more promisingly, through the synthesis of reactive dyes that successfully absorb pure pigments via $scCO_2$. Interesting applications like anti-fungal and anti-bacterial treatments on cotton could be made via $scCO_2$ dyeing, opening up new markets such as the healthcare care sector for $scCO_2$ dyeing houses.

1. Background

1.1. Carbon and water footprint of the textile industry

The textile industry has a huge ecological footprint from a global standpoint. In 2015, greenhouse gas (GHG) emissions from textiles production totaled 1.2 billion tonnes of CO_2 equivalent [1] which is more than those of all international flights and maritime shipping combined ([2] cited in [3]).
According to the estimations and assumptions made by [4], the impact of one polyester t-shirt to be 3.8 kg CO_2 equivalents (eq.) if the fabric is knit and 7.1 kg CO_2 eq. if the fabric is woven, which is roughly equal to the carbon footprint of driving a passenger car for 5 miles (a bit more than 8 km).

It is important to consider that the most significant hotspot in greenhouse gas (GHG) emissions is related to the amount and weight of fabric used in the t-shirt. However, this should not be taken as a pretext to disregard the environmental impacts of production processes: yarn production, dyeing, weaving and knitting, namely. In fact, many novel technological opportunities as well as incremental room of improvements exist for these processes to reduce their ecological footprint [1].

In addition to the global problem of climate change triggered by man-made GHG emissions, the industry also has local impacts resulting from the textile production processes. Naturally, the level of impacts varies significantly based on the region where the production activities occurred [5], such the type of fuel and the energy mix being used by dyeing houses and textile factories mainly, followed by the mileage of the transports of supplied materials and products among the textile supply chain.

Water is one of the most significant inputs of wet processes (pre-treatment, dyeing and finishing) in textile industry. It is relevant to specify what these processes are meant for:

Dyeing is the aqueous application of color to the textile substrates, mainly using synthetic organic dyes and frequently at elevated temperatures and pressures. Figure 1 (next page) shows tanks containing dyed fabrics coming from a dyeing vessel.

Figure 1: A water-based jet dyeing machine with external winch, dyeing fabrics in yellow. Source: http://textilelearner.blogspot.se/2011/12/dyeing-process-process-of-dyeing.html

Finishing involves treatments with chemical compounds aimed at improving the quality of the fabric. Permanent press treatments, water proofing, softening, antistatic protection, soil resistance, stain release and microbial/fungal protection are all examples of fabric treatments applied in the finishing process [6].

A review done by [7] reported that the IPPC Textile BAT (Best Available Technology) Reference (BREF) indicated a specific water consumption ranging from 92 l/kg to 162 l/kg in mills employing cotton and PES fabric finishing-dyeing from European-based data of 2003. Moreover, the world uses 5 trillion liters (1.3 trillion gallons) of water each year for fabric dyeing alone, enough to fill 2 million Olympic-sized swimming pools [8].

The environmental problem brought by conventional fabric dyeing does not involve water consumption only, but also water pollution: 20% of industrial water pollution globally is attributable to the dyeing and treatment of textiles [9] because of chemicals used in dyeing and finishing processes and following mismanagement of wastewater. Figure 2 (next page) shows an instance of water pollution caused by fabric dyeing. Recalcitrant organic, colored, and toxicant, surfactant and chlorinated compounds and salts are the main pollutants in textile effluents [10].

Figure 2: Polluted rivers around Tirupur, India, with runoff from nearby factories. Source: Newsweek : http://www.newsweek.com/2015/08/21/environmental-crisis-your-closet-362409.html

The facts and figures aforementioned call for urgent reduction of the ecological footprint of the textile industry, due to the volumes of clothes and other textile products being produced and demanded by the end consumers. Average per capita world fiber consumption in the year 2016 was 13.4 kg [11]. This is worrisome when considering that the 2017 UN world population prospects indicates that the world population is 7.6 billion as of mid-2017 and will reach 8.0 billion in 2020-2024 [12].

Further, the textile dyeing industry contributes large output value for highly-populated, fast-growing developing countries such as China [13] and India, the two largest producers of clothes [5]. Just by looking at China, dyeing enterprises produced more than 53.674 billion meters in 2014, completing $19.0 billion exports in 2015, according to the textile dyeing data of China [14].

Another compelling reason to urgently reduce the environmental impact of the textile industry stems from the figures about the available amount of freshwater and the need to urgently reduce GHG emissions and capture the existing ones already in the atmosphere (climate mitigation). In particular:

- GHG emissions associated with Representative Concentration Pathway RCP2.6 could limit global warming to around or below a 2 °C increase since pre-industrial times. According to the Shared Socioeconomic Pathways (SSP), in order for this to happen,

global CO_2 emissions need to decline rapidly and cross zero emissions after 2050 [15]. The textile industry, being part of the problem, needs to be part of the solution as well.
- Freshwater makes up a very small fraction of all water on the planet. While nearly 70% of the world is covered by water, only 2.5% of it is fresh. The rest is saline and ocean-based [16]. Moreover, 3 in 10 people worldwide, or 2.1 billion, lack access to safe, readily available water at home [17].
- By 2030, the world is projected to face a 40% global water deficit under the business-as-usual climate scenario. Moreover, climate change will exacerbate the risks associated with variations in the distribution and availability of water resources [18].

1.2. Aim, scope and outputs of the project

The production phase that mainly concerns the research project "ClimaDYE" is the dyeing phase. ClimaDYE aims at identifying:

- the climate implications of a specific water-free dyeing technology
- the potential for a broader adoption of this technology by dyeing houses and textile manufacturers.

Water-free dyeing means that water is required neither for dyeing, nor rinsing nor cleaning the dyeing vessels after each dyeing batch. The technology is based on supercritical CO_2 ($scCO_2$) used as dyeing medium instead of water within specially-designed equipment. The supercritical CO_2 is therefore an input material in the dying process and comes by means of carbon capture and storage processes of CO_2 previously emitted by other industrial processes, such as coal power plants. The emitted CO_2 is "compressed" in a liquid-like form, and repurposed in the dyeing process instead of being geo-sequestrated (for instance in deep geological formations or in the form of mineral carbonates). In ClimaDYE, economic and climate implications of $scCO_2$ dyeing are compared with alternative water-based dyeing technologies.

The focus of ClimaDYE on the dyeing phase should not be taken as a narrow scope of analysis. On the contrary, a system-thinking approach has been used, by taking into account:

- different stakeholders within the textile industry
- upstream, downstream and sidestream processes in addition to the sole dyeing process, whenever they affect the overall results of the analyses.

The three outputs of ClimaDYE are indicated with O1 (output 1), O2 (output 2) and O3 (output 3):

- O1: an economic and environmental evaluation of $scCO_2$ dyeing of PES compared to alternative water-based dyeing technologies (in particular jet dyeing and ZLD dyeing)

- O2: an estimation of environmental impact of $scCO_2$ dyeing of biofibers, to be confirmed by future physical tests on biofibers
- O3: a map of the business opportunities for PES and biofiber dyeing with $scCO_2$.

2. Data collection

The data for the analyses in ClimaDYE has been collected from different sources:

- Primary data from:
  - the company DyeCoo, which owns the $scCO_2$ dyeing technology
  - the company IKEA GreenTech, which owns part of the shares of DyeCoo and is evaluating $scCO_2$ dyeing for a set of IKEA's textile-based products,
  - an interview with professor V. Nierstrasz from the University of Borås, Sweden, expert on technologies for fabric dyeing and finishing (in collaboration with DyeCoo) and
  - an interview with professor C. Azar from Chalmers University of Technology, Sweden, expert on sustainable energy systems.
- Secondary data from peer-reviewed studies and reports on sustainable textile issued by established institutions and agencies.
- Qualitative primary data from the project workshop that took place in DyeCoo (Weesp, the Netherlands) on 2017-11-23. Four people participated in the workshop: Martijn van der Kraan, Narjes Shojai Kaveh, Johan Kronholm and Ilaria Barletta.

3. Project activities

The project activities (PA) of ClimaDYE, listed below, have different functions. Some of them constitute the research methods employed in order to analyze the data that has been collected, whereas some of them directly constitute project results. The list reports the project output(s) that each specific PA contributed to, indicated by the acronyms "O1","O2", and "O3":

1. Stakeholder analysis (O3 mainly, O1 and O2)
2. List of industry and customer requirements from $scCO_2$ dyeing technology (O3 mainly)
3. Mapping of the concept of sustainability and sustainable textile production by the project partners (O1 and O2)
4. Definition of the case study and outcome metrics to define project results (O1 and O2)
5. Modelling and calculation/estimation of climate and economic impacts from $scCO_2$ dyeing (O1 and O2)
6. Business opportunities and limitations for sustainable and climate-smart $scCO_2$ biofiber dyeing adoption in the textile industry (O3).

In the remaining part of the chapter, the core contents of each project activity will be reported, along with information on its contribution to the project outputs.

PA1: Stakeholder analysis

The first step of the project is to identify who has a stake on the adoption (or non-adoption) of scCO2 dyeing and in which way this stakeholder either influences or is affected by this technology when adopted on a wide, market scale. Knowing this information is pivotal for the contribution to O3 in particular, and to ultimately give recommendations to key decision makers: investors on production technologies, investors within the apparel and furniture industry and top managements leading those kind of companies. A stakeholder analysis is a method that allows to present this information, as it is "a process of systematically gathering and analyzing qualitative information to determine whose interests should be taken into account when developing and/or implementing a policy or program" [19].

Table 1: Stakeholder analysis for ClimaDYE.

Stakeholder	Influence of the stakeholder on/from the adoption of $scCO_2$ dyeing on a wide scale	Additional information
$scCO_2$ dyeing technology providers Example: DyeCoo	New market opportunities, increased profits, lower entry barriers for new players	DyeCoo was the first player in this market and paved the way for other players to come alongside with CO_2 dyeing machines
Dye Suppliers Example: Huntsman, Dystar, Colourtex	New market and product development opportunities in terms of specific dyes that react and perform well with $scCO_2$.	Dye Suppliers can profit from $scCO_2$ dyeing and use it as opportunity to innovate, as they would provide special dyes. In the long term, also companies that sell finishing agents would develop and profit from new products for CO_2 dyeing
Providers of Carbon Capture and Sequestration Technologies and related customer companies Example: Shaanxi Yanchang Petroleum (Group) Co Ltd.	More $scCO_2$ dyeing machines means more $scCO_2$ that can be sold to dyeing houses and used in industrial processes rather than being geo-sequestrated.	It is difficult to establish an overall environmental benefit in using more and more $scCO_2$ for dyeing processes rather in than other competing industrial processes, as the latter might have more or less impactful environmental performances (and resulting final products) than dyeing has.
Providers of alternative dyeing technologies to $SCCO_2$. Example: Wuxi Sunsky Machinery Co., Ltd	A reduction of the market share of them might occur if $scCO_2$ dyeing is more and more adopted or regulations about water usage by industry become tighter.	There could be the unlikely but still possible case where some companies selling for instance low-liquor ratio jet machines might sell more though, as a result of a diffidence towards the “hype” about $scCO_2$.
Fashion brands Example: H&M, Zara, Mango	They will adopt $scCO_2$ dyeing as long as they are able to claim a reduction of carbon and water footprint of their products and payback the initial investment in a time they find reasonable.	Brands selling CO_2 dyed fabric now are: Nike, Adidas, Mizuno, GAP, Peak Performance, Decathlon. There might be the chance that mass-market fashion brands (e.g., H&M, Zara) can soon join.

Stakeholder	Influence of the stakeholder on/from the adoption of $scCO_2$ dyeing on a wide scale	Additional information
Furniture companies Example: IKEA **Carpentry and automotive textiles companies.**	These stakeholders will adopt $scCO_2$ dyeing as long as their requirements are satisfied from an investment standpoint and operational standpoint. Moreover, companies may invest in $scCO_2$ dyeing if it will make them win a growing number of environmentally-conscious customers.	These companies can get bigger market shares should they be able to claim a reduction of carbon and water footprint of their products through an EPD, when such EDP is valued by their customers.
Auditors and environmental NGOs Example: Greenpeace, Organizations that issue Environmental Product Declarations (EDP)	If environmental benefits are proven to sustainable over time, these stakeholders will champion $scCO_2$ dyeing.	There is no involvement of these stakeholders right now but they could be so in the future.
End customers Example: Consumers buying clothes and accessories, furniture, etc.	Clothes with reduced carbon and water footprint are appealing to environmentally-conscious customers, to the point that they would be willing to pay a premium price that the technology will impose at the beginning of his adoption.	The technology is still expensive for small and medium enterprises (SMEs.) However, when $scCO_2$ will land in the mass production market of textiles, it is expected to become much cheaper.

PA2: Industry requirements

The purpose of this project activity is to identify what the success factors and the requirements from the customers of dyeing factories are. These customers are apparel companies, but also furniture and automotive textile companies, as displayed in Table 1. But prior to identifying the requirements, it is important to understand what in business is known as “critical success factor” (CSF) for the customers aforementioned. CSFs are “limited number (usually between 3 to 8) of characteristics, conditions, or variables that have a direct and serious impact on the effectiveness, efficiency, and viability of an organization, program, or project. Activities associated with CSFs must be performed at the highest possible level of excellence to achieve the intended overall objectives” [20].

For the case of the customers of dyeing houses that use the $scCO_2$, the CSFs are:

- Cost: due to increase competition and reduced margins, they have to be kept low and competitive
- Responsiveness, which in this industry implies an agile supply chain, which is flexible, quick in terms of lead time and demand driven, far from the traditional supply chain concept characterized by high levels of inventory and are forecast driven [21]
- Lead time: (reduction of it) in order to achieve responsiveness
- Stability of operations: the equipment has to be up and running all the time (no disruptions) in order to satisfy customers’ demand and amortize the high cost of the equipment
- Sustainability: not only financial but also environmental and social, due to pressing regulation and customer awareness of environmental and factory operators’ welfare issues.

Industry requirements are:

- Bringing the payback time of the equipment below 4-5 years
- Identifying suitable range of products for which $scCO_2$ dyeing can be successfully used and for which the customers would be willing to pay a premium price
- Remote maintenance guidance from equipment producers (e.g., DyeCoo), as the uptime of the equipment has to be maximized.

Knowing what the CSFs and industry requirements are is pivotal for the understanding of the business opportunities for but also the limitations to a wider adoption of $scCO_2$ dyeing in the textile industry (O3).

PA3: Mapping of sustainability understanding

In projects related to sustainable production and sustainable development, it is sometimes difficult to grasp a common and shared understanding of sustainability among the different participants. It is important to achieve such a shared understanding between the project partners, as each of them brings his/her own perspective on the concept of sustainability, mostly dictated by the owned domain knowledge. Conceptual maps, sometimes referred to as concept maps, are a well-established tool in academia for organizing and representing knowledge. In a concept mapping task, participants are asked to write key concepts or phrases on a blank page and connect them with lines where they identify relationships among them. Several studies over the last two decades have used concept maps to assess knowledge about sustainable development, in particular [22, 23].

An example of map realized in ClimaDYE is shown in Figure 3. At the center of the sheet, the concept “Sustainable Textile Production” has been drawn.

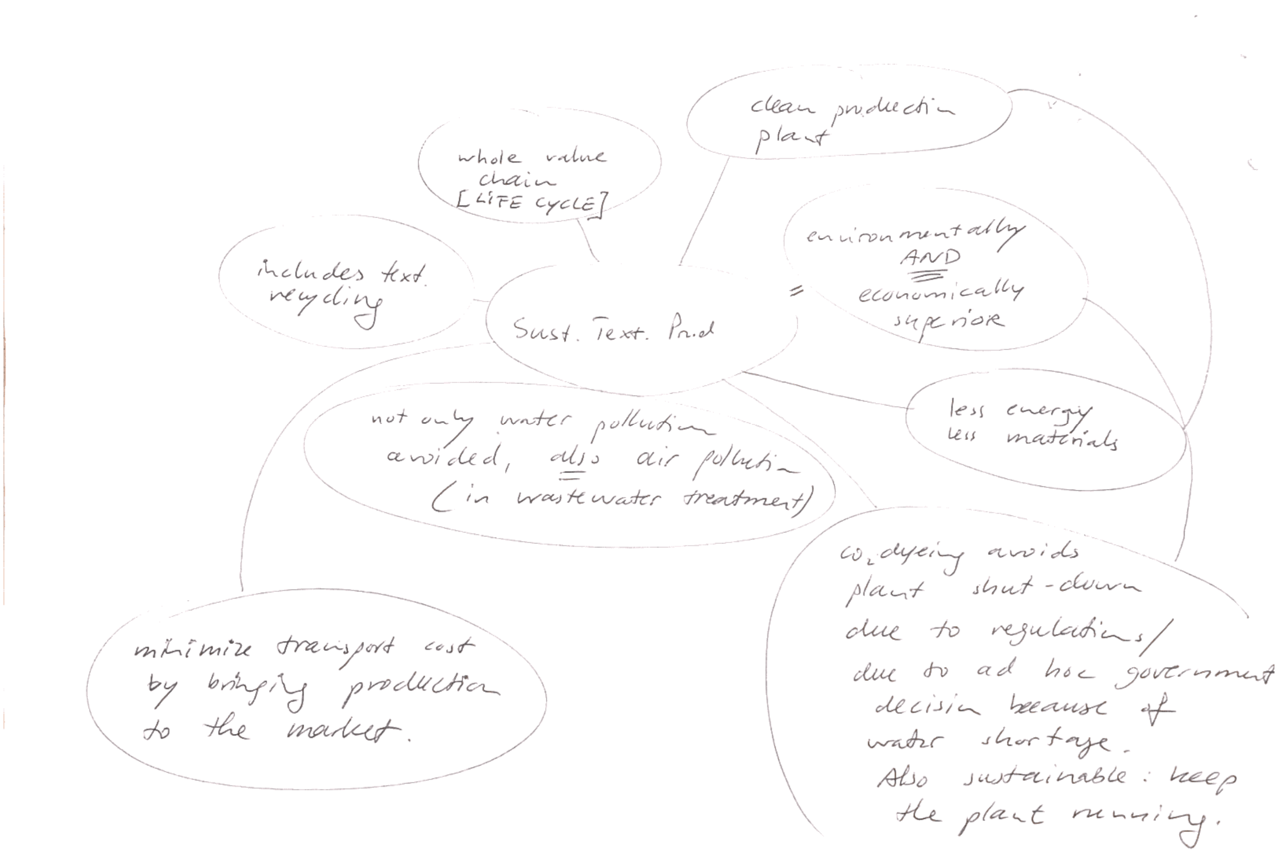

Figure 3: A concept map drawn during the workshop in DyeCoo, Weesp, NL, on 2017-11-23.

The conclusion coming from the synthesis of the concepts maps drawn during the project workshop are:

- Consideration of the whole product life cycle (may it be a piece of furniture or cloth). Concepts related to it were for instance, product recyclability
- Reduction of water usage and pollution
- Reduction of CO_2 emissions
- Reduction of chemicals for dyeing and finishing
- Eco-labelling
- Proximity to the final customer
- Financial and business sustainability (e.g., no disruption of factory operations)
- Customer awareness and accountability in reducing their own footprint by means of conscious and informed purchasing

PA4: Case study

The results from the concept maps exercise suggested indicators to quantitatively measure and factors to qualitatively describe the project results. When it comes to quantitative indicators, they are: industrial and equipment costs, measured in USD or USD/kg of dyed fabric, carbon dioxide emissions measured by kg of CO_2 emissions/kg of dyed fabric, Global Warming Potential (GWP) measured in kg of CO_2 equivalent/kg of dyed fabric, water footprint measured by liters of water used/kg of dyed fabric, liters of water treated/kg of dyed fabric. From a qualitative standpoint, elements like environmental product declarations (EDP) and customer awareness have been considered instead.

It is important to understand the basics of how $scCO_2$ dyeing works before describing the characteristics of the dyeing machine chosen as case study.
First, supercritical fluids are highly compressed gases that have properties of both a liquid and gas. They have higher diffusion coefficients and lower viscosities than liquids, as well as the absence of surface tension, allowing better penetration into materials. As a result, $scCO_2$ offers advantages for the dyeing process for different reasons: $scCO_2$ acts as both a solvent and a solute and completely replaces water. Commercial $scCO_2$ dyeing was launched by the Dutch company DyeCoo and has been operating since 2008. The customers of DyeCoo are mainly located in Thailand and Taiwan, where big-scale apparel production takes place. The customer base is now expanding in other countries of the Asia Pacific area. The operating principles of this technology are simple: the dye powder and fabric are loaded into the vessel. CO_2 is then pumped into the vessel until the desired temperature and pressure are reached. Dyeing in $scCO_2$ is done in a temperature ranging from 80 °C to 120 °C and with a pressure in dyeing vessels from 200 to 250 bar. Then the CO_2 is circulated (pumped) through the dye and fabric for 2-3 hours. During this period, the dye is continuously dissolved into the CO_2 and absorbed by the fabric, until no dye powder is left and because all of it permeated the fabric. The specific dyeing conditions depends on the desired color for the textile and are regulated by setting the right temperature and

pressure values. From an equipment perspective, the advantage of $scCO_2$ dyeing is that the extraction of spinning oils, the dyeing and the removal of excess dye can delivered by only one piece of equipment, compared to water dyeing. Naturally, drying is not required, because at the end of the process CO_2 is released as a gas in the atmosphere. However, for an equipment of 1600 kg of capacity, at least 90% of the $scCO_2$ is recycled in a closed loop system, after precipitation of the extracted matter in a separator [24]. The rest is dispersed in the atmosphere at a gaseous state. This means that at the 10^{th} batch, all the CO_2 employed for the process gets released in the atmosphere.

A piece of $scCO_2$ dyeing equipment includes four units: pressure and heating unit, dyeing unit, recycle unit and control unit. Normally, for big-scale production, 3 dyeing vessels are part of each equipment. The overall capacity of them is 2000 l and 1600 kg of fabric (Figure 4). This is the equipment that has been considered in the case study of the project.

Figure 4: $SCCO_2$ dyeing machine produced by DyeCoo and installed in Yeh Group's facility in Tong Siang, Thailand. A machine is made up of three vessels and has a capacity of 2000 l, producing 1600 kg per batch.

DyeCoo has in its facility a piece of equipment of 200 l for R&D purposes, displayed in Figure 5 (next page). The only difference between the actual equipment sold to the market and the equipment for R&D is just scale and not performance. During the project workshop in DyeCoo, the operations of the dyeing processes have been observed by means of an ad-hoc demonstration.

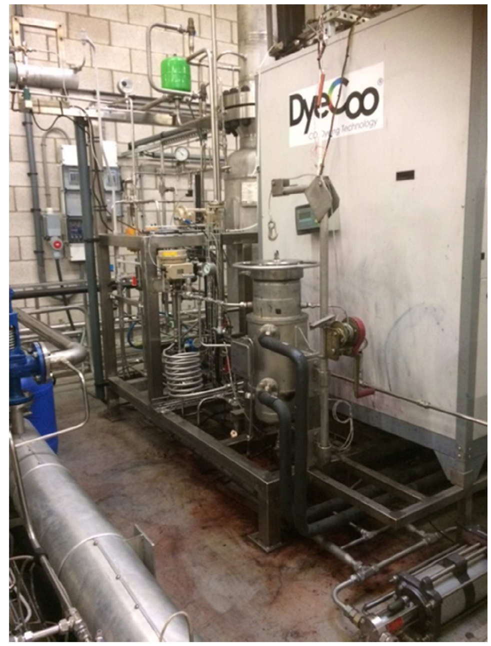

Figure 5: The 200-l dyeing vessel for R&D tests (left) and pressure and heating unit, recycle unit and control unit (right) in DyeCoo.

The benchmark used for the technology evaluation compares $scCO_2$ dyeing with two alternative water-based dyeing technologies, provided data availability: jet dyeing with low-liquor ratio and water-based dyeing with systems for zero-liquid discharge (ZLD) and zero discharge of hazardous chemicals (ZDHC). The former is by far the most widely used technology for PES. The liquor ratio is the ratio of mass of dye bath to mass of fabric. A low liquor ratio (ranging from 1:3 to 1:20) aims to consume less water and chemicals. There are three main types of jet dye machines: overflow dyeing machines, soft-flow dyeing machine and airflow dyeing machines [25]. Traditional dyeing machines can be equipped with systems for water recovery used in dyeing and bleaching operations, so that no discharge of effluents and related hazardous chemicals to the environment occurs. However, there may be solid waste that needs to be stored in landfills because the ZLD systems can't treat it properly [26]. When no data is available about specific figures of these two technologies, a comparison has been done with "traditional" water-based dyeing.

PA5: Climate and economic impacts from $scCO_2$ dyeing

This is the most important PA of ClimaDYE. The analyses have been displayed into four sections, according to the project output (O1, O2) and the type of fabric (PES and biofibers). They are:

- O1: Economic evaluation – PES case
- O1: Climate evaluation – PES case
- O2: Economic estimation – biofibers case

- O2: Climate estimation – biofibers case

O1: Economic evaluation – PES case

From a short-term perspective, only operational costs have been considered, whereas investment costs have been considered in a long term perspective instead, as they may change in the future as the technology development progresses and the market outlook changes.

The operational costs are costs related to the resources and the industrial processes necessary to come up with a unit (kg) of dyed and dried fabric, in this case PES. In the analyses done in ClimaDYE, the operational costs are machine operating costs specifically. These cost include: energy, people, dye, water intake and water treatment and it does not include machine/building depreciation. The effect of reduced dye time lays actually on the depreciation as it is expressed per kg of final product.
In order to put the figures about costs in the right perspective, it is important to point out that so far dyeing houses which adopted DyeCoo's machines are located in Thailand and Taiwan, and that the costs will be reported in USD.
First, here is no such as thing as a "typical value" of operational costs. The operational costs are variable because they strongly depend on the location of the dyeing factory, how the factory is being managed and the customer companies. These factors determine the cost of the energy (thermal energy, fuel used for electricity generation) used by the dyeing factory, the manpower's salary, the types of dyes, the order sizes and the transport costs for supplying the scCO_2 to the factory. Nevertheless it was possible to present percentage variations of costs and illustrate specific examples helpful to compare scCO_2 dyeing with other competitor technologies.

It was found that scCO_2 dyeing reduces operational costs normally to 20% in comparison to water-based dyeing [9, 27]. There are different reasons that explain lower operational costs achievable through scCO_2 dyeing. The main one is reduced operation times and consequent reduction of energy consumption. The time of the whole set of operations occurring to turn a batch of non-dyed fabric to a dyed fabric is for scCO_2 dyeing 2-3[2] hours, compared to 3-4 hours taken by alternative technologies [28]. The actual dyeing time for DyeCoo's machines takes 20 minutes, against the 60-70 minutes taken by a rapid jet, low-liquor ratio dyeing machine, for instance [29].
Since no water is used in scCO_2 dyeing (and follow-up cleaning of the machine), no costs for water intake and water treatment (high for ZLD systems) occur. Further, no drying step is required in scCO_2 dyeing since CO_2 is released in gaseous state. By switching scCO_2 with water as dyeing medium, a peer-reviewed study based in China [30] calculated a saving of 0.32$ per kg of fabric. In fact, cost for specific CO_2 intake appeared to be only 13% of the cost that would be otherwise spent for specific water intake (water and steam use). This sounds sensible, if considering that

[2] 2 hours of preparation for light-color dyes and 3 hours of preparation dark-color dyes,

the range of water usage for traditional dyeing goes from 100 l/kg fabric to 150 l/kg fabric [24], usually exceeding 100 l/kg fabric [28].
From internal analyses done by DyeCoo and shared during the project workshop, machine operational costs for scCO_2 dyeing range from 0.76 $ to 1.37 $ per kg of dyed PES fabric, which are lower than the costs in traditional, water-based dyeing. A reason for lower costs for dyes is the absence of chemicals, for instance dispersing agents, levelling agents, and carrier agent, that are otherwise necessary in the case of water-based dyeing. Moreover, around 10% of dye is lost in traditional dyeing because it stays in the water. For CO_2 dyeing, 1% of dye is lost because it remains in the CO_2 (data collected over the focus group in the workshop).

From a mid and long-term perspective, the costs that have been examined are those due to processes or events that happen beyond the boundaries of the dyeing factory.
First, the advantage of not being reliant on water allows freedom of location of the factories, which as a result can be located close to the customer. This possibility can bring about savings in transport costs, as big as the proximity of the factory to the customer is.
Another cost saving comes from the opportunity cost of avoiding a sudden closure of the factory ordered by the authorities when environmental regulations are not respected, even though this example refers to the case of companies that do not tend to follow regulations as legally demanded. In China, factories have been shut down for several months after the authorities discovered wastewater discharged from hidden pipes and untreated pollutants discharged in lakes and rivers.
Last but not least, today, a machine of 2000 l made up of three vessels requires 9 people for loading/unloading operations, supervision, etc. It is arguable that scCO_2 dyeing machines are suitable to be more and more automated over time, which would further reduce the cost of ownership of the equipment.
All these advantages, when converted in cost savings over the life time of the equipment (20-30 years) and discounted by time and risk factors, can make the payback time of the equipment shorter than the actual one (4-5 years).

The **climate impacts** were calculated in terms of kg of CO_2 emissions and global warming potential (GWP), measured in kg of CO_2 emissions equivalents. GWP is an indicator that measures the potential and the extent of the warming effect of GHGs to world's climate. GHGs in fact, result in warming the Earth by absorbing energy, rather than let it escape to space. The methods for calculating the GWP for different time horizons are established by the Intergovernmental Panel on Climate Change (IPCC).

O1: Climate evaluation – PES case

Many of the aforementioned savings translate into savings in kg CO_2 emissions and therefore in GWP values. However, impacts from the transports of the compressed CO_2 from the CCS plants to the dyeing factories must be accounted.

When it comes to the processes in the dyeing factories, the reason for savings in CO_2 emissions and consequent GWP is the reduction of energy consumed from the dyeing process, which ranges from 20% to 60% if compared to other water-based technologies [28, 31]. The kWh's used for dyeing alone are determined by electricity and steam. DyeCoo shared that electricity use is slightly higher for the case of $scCO_2$ dyeing, but it is offset by a greater energy saving coming from avoidance of steam. DyeCoo shared also that a possible range of reduction of CO_2 emissions from $scCO_2$ dyeing may range from 25% to 40% in comparison to water-based dyeing. The precise energy saving depends on the technology chosen for the comparison.

Interestingly, other sources, although non-peer reviewed [32, 33] reported 50% of energy savings achievable also with jet dyeing. Dyeing with ZLD did not appear to outperform neither $scCO_2$ dyeing nor jet dyeing. ZLD dyeing has been designed to reduce water pollution and decrease water use, but the technology is constrained by high cost and intensive energy consumption that is still hard to reduce [34]. Moreover, dyestuff still needs chemical additives.

It was understood from the workshop at DyeCoo that the main reasons for less energy consumptions than water-based dyeing were lesser dyeing times, the avoidance of steam usage during the dyeing process and the avoidance of a following drying phase. In DyeCoo's machines, $scCO_2$ is used as dyeing medium and normally 90%-95% is recycled in a closed-loop system and the rest ends up as CO_2 gas exhausts. It is important to remark that such a closed-loop system does not imply reduced CO_2 exhausts in comparison to the CO_2 used as input material. In fact, this simply means that at the 10^{th} production batch (1600 kg of fabric rolled around a perforated beam), all the $scCO_2$ employed for the dyeing process gets released in the atmosphere. No other GHG (like water vapor) is part of the exhausts. Ultimately, since less climate impacts in $scCO_2$ dyeing are linked to reduced energy consumption only, the type of fuel burnt in the factory to supply energy to the factory determines the extent of the value of GWP reduction. Dyeing and finishing activities in many cases depend on fossil fuels [35]. DyeCoo reported that some dye houses have coal-fired steam boilers, some oil-fired and some gas-fired and that the electricity is mostly generated on-site from the same sources. Yeh Group is located in Thailand and uses fabrics dyed by DyeCoo's machines. They have publicly reported that $scCO_2$ dyeing allowed a reduction of 50% of energy [36]. In this example, assuming that the factory burns hard coal to produce energy, the GWP of the dyeing operations would be 20.82 kg of CO_2 eq./kg fabric, which would be reduced of 6 percentage points if adopting hydro power instead (19.48 kg of CO_2 eq./kg fabric).

This value comes from the following data:

- The energy requirement for processing of 1 kg of textile material for conventional dyeing, finishing and drying ranges from 8 MJ/kg to 18 MJ/kg [37]. A reference value of 13 MJ/kg has been chosen, which, with $scCO_2$ dyeing would be reduced to 6.5 MJ/kg (18.06 kWh/kg).

- Values of GWP 100 per unit of fuel generated have been drawn from the software for Life Cycle Assessment "Open LCA". A value of 1.153 kg of CO_2 eq. (GWP) refers to a unit of energy (in kWh) from the production of high voltage electricity in Thailand from hard coal. The value of GWP per unit of energy would be instead of in case of hydroelectricity (powered in a general "rest of the world" location) 1.079 kg of CO_2 eq.

Biofibers case: status of scCO_2 dyeing today

As laboratory tests on cotton and other biofibers (e.g., coming from forestry resources) were not in the scope of ClimaDYE, qualitative estimations have been drawn during the project workshop at DyeCoo. These estimations are based on the extensive experience of business and R&D developers at DyeCoo, which is the pioneer in scCO_2 dyeing and has attempted to successfully dye cotton through scCO_2, but so far without getting the hoped results from a product quality standpoint. The application of the same operating principles of scCO_2 dyeing for PES faces problem not in the dyeing per se but in the finishing step, where the cotton has to be made hydrophilic (moisture management) and dyes appeared not to stick to the cotton fabric.

O2: Economic estimation – biofibers case

From the perspective of operational costs, at this stage it is possible to determine that the dyeing time will remain unchanged, in comparison to the one already taken for PES (20 minutes).
It is not known whether the finishing time will remain the same, though, because a solution to overcome the problem aforementioned has to be found yet.
What is certain is instead that the time for dye preparation will take longer than the pre-treatment stage currently in place for PES dyeing. It was estimated to be 2 hours of preparation for light-color dyes and 3 hours of preparation dark-color dyes. This will result in increased cost of the input materials because of increased complexity (and previous research effort) in the preparation of the dyes. It was estimated a range of prices between 10 €/ kg to 30 €/ kg of dye, against average prices of 5 €/ kg to 25 €/ kg of the dyes currently employed for PES. Dye amounts on fiber is 0.5% for light colors and 2.5% for black colors.

O2: Climate estimation – biofibers case

Energy savings and reduced GWP from scCO_2 dyeing compared to competing technologies will be maintained because of same dyeing time and same energy consumed in comparison to the PES case. The differences lay in pre and post dyeing treatments. Although it will require some additional energy to synthetize dyes suitable for cotton (in comparison to just using pure dyes as in the PES case), it was estimated that this additional energy would be much less than the energy used in traditional cotton drying and bleaching. It is unknown whether finishing treatments will require further energy.

From a systemic point of view, it is arguable that if $scCO_2$ dyeing will be widely adopted because of proven increased environmental performance and reduced investment costs over time, then dyeing biofibers and PES will be done in the same vessels.
Another interesting argument, which might also contradict the previous one, is that if the market recognizes the benefits of $scCO_2$ dyeing, more plants to realize $scCO_2$ dyeing will be built. This would in turns incentivize sells of carbon captured by CSS plants from fossil fuels power plants, which would help reduce GWP from energy generated by fossil fuels. This would not result in a reduction of GWP on a global scale though, if the increased amount of captured carbon would rather be used by industries whose products are less impactful in their GWP than by the textile industry (volumes being equal).

PA6: Business opportunities and limitations

This PA displays the data that contributes to O3: a list of business opportunities for and limitations to a widespread adoption of $scCO_2$ market in the textile industry. Most of the data come from previous PAs, and most of them in turn have been shared during the interviews occurring during the project workshop. This PA constitutes a sort of "legacy" of the project, by inspiring further research on climate implications on $scCO_2$ dyeing of biofibers, as limitations exist and there's economic and environmental return in overcoming them.

Opportunities:

Increased product margins from reduced operational costs, along with improved environmental sustainability performances (reduced water and carbon footprint of textile products) in comparison to water-based dyeing. This should appeal to companies in the apparel mass-market which more than any other companies would welcome further reductions of costs and increased environmental performance due to their huge production volumes.

Compliance with environmental regulatory agencies & continuity of operations: the fact that $scCO_2$ does not use any water implicitly makes managers of dyeing houses avoid sudden closures of factories ordered by the authorities when environmental regulations are not respected. In China, factories have been shut down for several months after the authorities discovered wastewater discharged from hidden pipes and untreated pollutants discharged in lakes and rivers [38]. Avoiding this risk prevents also factory workers from suffering from temporary unemployment. Naturally, this opportunity appeals to companies that did not always tend to follow regulations as legally demanded or struggle to do so for lack of proper infrastructure and technology support.

Freedom of location: as the dyeing houses do not need to rely on water. This would promote local and national growth of geographical areas which suffer from droughts and lack of water, such as African countries. Part of which are going through fast industrial developments. Moreover, freedom of location allows companies to improve their responsiveness by being logistically close to the main customers.

Participation in climate mitigation strategies: The International Energy Agency has estimated that globally 3400 carbon capture and sequestration (CCS) plants will be needed by 2050 in order to meet the target of 2 degrees above pre-industrial levels [39]. $scCO_2$ is being provided by CCS plants for different production services, dyeing among those. It is difficult to establish whether more CCS plants will incentivize more $scCO_2$ plants to be built (or more machines to be installed) or vice versa, though.

Demonstration of commitment of apparel and furniture companies to tackle a set of **sustainable development goals** (SDG, issued by the UN in 2015) by means on technological advancements. These goals are like "Responsible Production and Consumption", and "Life below water", specifically.

Limitations:

Higher investment costs do not seem to be so far justified by higher opportunities and potential future benefits by investors in the textile industry (e.g., top management of apparel and furniture companies, venture capitalists)

Poor dyeability of cotton leaves market opportunities untapped: Cotton is the most abundantly produced natural fiber in the world. Over 82 million tons of textile fibers were consumed in 2013: chemical fibers accounted for 68.6%, followed by cotton (30%), and all other natural fibers less than 2% [40]. As extensively reported by [37, 41], cotton suffers from poor solubility of polar dyes in $scCO_2$ and poor affinity of non-polar disperse dyes towards these fibers . "Different approaches such as fiber modification, dye modification and adding of a co-solvent or a modifier to improve the solubility have been attempted to solve this problem" [41] but have not been successful.

4. Conclusions and recommendations

The three major findings of ClimaDYE are have been outlined here. They constitute a synthesis of the analyses illustrated in the previous chapter.

Output 1

Output 1 is a synthesis of the results in PA5 for the most part. PA1, PA2, PA3, and PA4 supported in turn the analyses done in PA5.

scCO_2 dyeing reduces operational costs normally to 20% in comparison to water-based dyeing. There are different reasons that explain lower operational costs achievable through scCO_2 dyeing. A component of the operational costs is the cost of the dyes. scCO_2 utilizes pure dyes and their cost ranges from 0.76$ to 1.37$ per kg of dyed PES fabric, lower than the costs of dyes for traditional, water-based dyeing. A reason for lower costs per kg of dyed fabric is less dyeing time (almost halved in comparison with water-based dyeing technologies). A reason for lower costs per kg of dye is the absence of chemicals, for instance dispersing agents, levelling agents, and carrier agent.

The main reason for savings in CO_2 emissions and consequent GWP by scCO_2 dyeing is the reduction of energy consumed from the dyeing process, which ranges from 20% to 50% if compared to other water-based technologies. A couple of sources reported also a 50% of energy consumption reduction with jet dyeing. Dyeing with ZLD did not appear to outperform neither scCO_2 dyeing nor jet dyeing. Yeh Group is located in Thailand and uses fabrics dyed by DyeCoo's machines. They have publicly reported that scCO_2 dyeing allowed a reduction of 50% of energy [36]. In this example, assuming that the factory burns hard coal to produce energy, the GWP of the dyeing operations would be 20.82 kg of CO_2 eq./kg fabric, which would be reduced by 6 percentage points if adopting hydro power instead (19.48 kg of CO_2 eq./kg fabric).

Output 2

Output 2 is a synthesis of the results in PA5 for the most. PA1, PA2, PA3, and PA4 supported in turn the analyses done in PA5.

No cost increase has been forecasted in comparison to the existing costs for PES dyeing. A range of prices between 10 €/ kg to 30 €/ kg of dye It was estimated, compared to average prices of 5 €/ kg to 25 €/ kg of the dyes currently employed for PES.
Energy savings and reduced GWP from scCO_2 dyeing compared to competing technologies will be maintained because of same dyeing time and same energy consumed in comparison to the PES case. It is unknown whether finishing treatments will require further energy.
From a systemic point of view, an interesting argument is that if the market recognizes the benefits of scCO_2 dyeing, more plants to realize scCO_2 dyeing will be built. This would in turns incentivize sells of carbon captured by CSS plants from fossil fuels power plants, which would help reduce GWP from energy generated by fossil fuels. This would not result in a reduction of GWP on a global scale though, if the increased amount of captured carbon would rather be used by industries whose products are less impactful in their GWP than those in the textile industry (demands and volumes being equal).

Output 3

Output 3 comes from PA1 and PA6 for the most part and it is outlined as follows:
The main opportunities for dyeing houses are:

- Increased likelihood of compliance with environmental regulatory agencies and continuity of operations
- Freedom of location, which opens up new geographical markets and reduces transports of dyed fabrics to customer companies

The main opportunities for apparel and furniture companies are:

- Active participation in climate mitigation strategies by buying less impactful fabrics (less GWP value on the ecological footprint of the product)
- Demonstrable commitment towards some of the Sustainable Development Goals like “Responsible Production and Consumption” and “Life below water”.
- Increased market share for products appealing to environmentally-conscious customers
- Improved company reputation.

Limitations are:

- Higher investment costs that, for the case of SMEs do not seem to be so far justified by potential future benefits by investors in the textile industry (e.g., top management of apparel and furniture companies, venture capitalists)
- Poor dyeability of biofibres in scCO_2 due to poor solubility of polar dyes in scCO_2, which hinders dyeing of cotton with scCO_2.

In the light of the project results, we ultimately recommend:

- Disseminating knowledge about the economic and environmental benefits of $scCO_2$ dyeing by workshops, talks, and campaigns
- Spreading further awareness on the enormous impact that dyeing has on aquatic toxicity, as it would encourage customers to pay a premium price for a water-free dyed piece of cloth and help $scCO_2$ dyeing reduce fixed costs over time
- Having the proven economic and environmental benefits properly accounted for in investment evaluation models
- Funding research to achieve $scCO_2$ dyeing on cotton, either through adjustments on the dyeing technology or, more promisingly, through the synthesis of reactive dyes that successfully absorb pure pigments via $scCO_2$. Interesting applications like anti-fungal and anti-bacterial treatments on cotton could be made via $scCO_2$ dyeing, opening up new markets such as the healthcare care sector for $scCO_2$ dyeing houses.

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