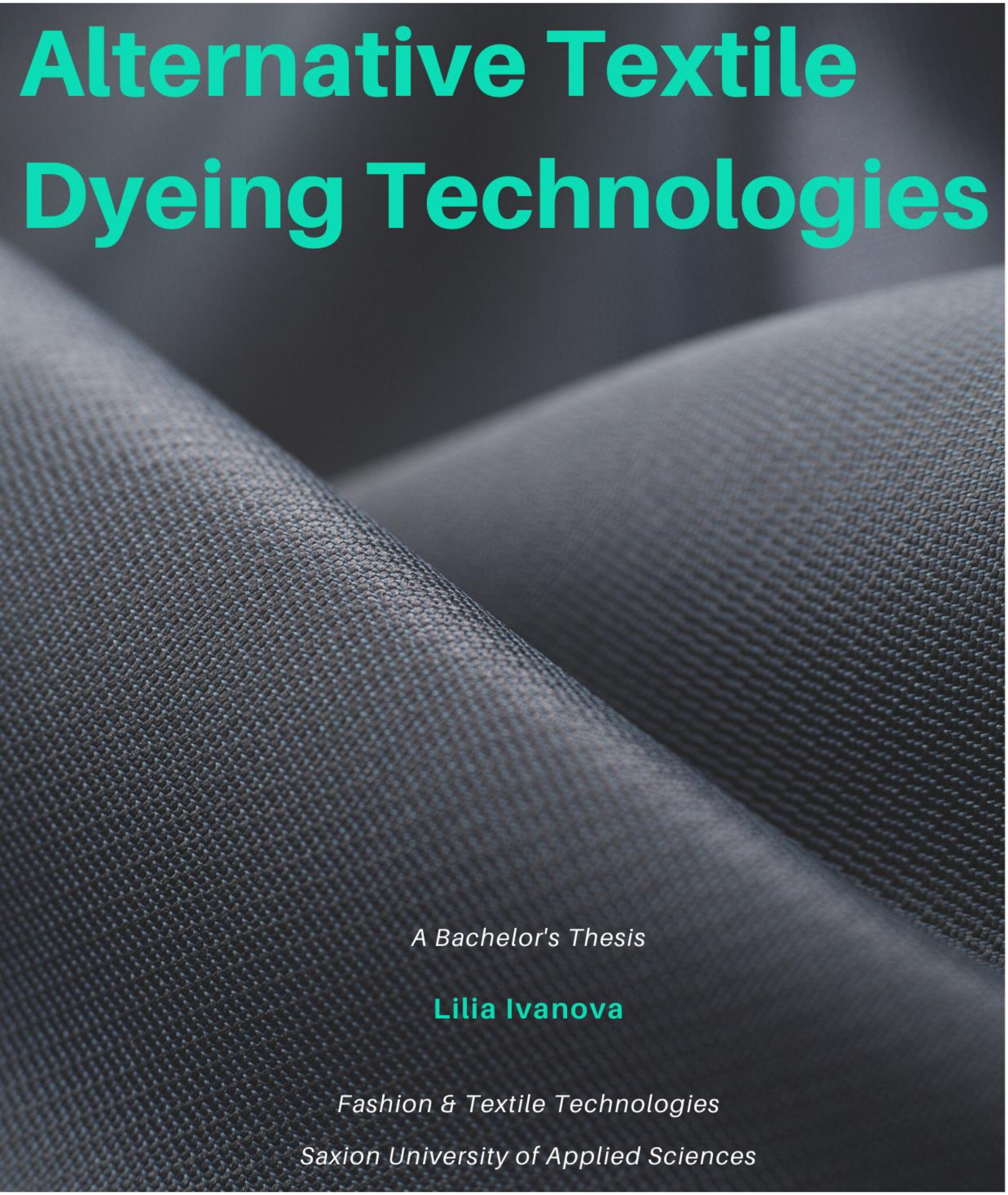
Circular Workwear: Alternative Textile Dyeing Technologies



June 2022

SIGNWEAR

A Bachelor's Thesis

Lilia Ivanova

Fashion & Textile Technologies

Saxion University of Applied Sciences

Circular Workwear: Alternative Textile Dyeing Processes

Which alternative textile dyeing technologies can improve the environmental impact of non-operational workwear?

A Bachelor's Thesis

Lilia Ivanova (464657)

Academy of Creative Technologies

Saxion University of Applied Sciences

Enschede, the Netherlands

Thesis coach: Usha Bhaskara

Second reader: Ioana Koh - Petcu

Saxion Research Group Sustainable & Functional Textiles

Anton Luiken, Theresia Grevinga

Ministry of Defence

Daisy van Groningen

16 June 2022

Table of Contents

List of Tables and Figures

List of Figures

List of Tables

List of Glossary

Algae ink	An ongoing development for non-toxic and biodegradable dyestuff/ coloring ink derived from natural resources of algae
Auxiliaries	Chemicals used in dyeing to increase efficiency
Auxochromes	Atoms attached to a chromophore which modify its ability to absorb light, altering the wavelength and intensity of absorption
Bleaching	A pre-treatment process aiming to remove any fabric impurities and achieve pure white tone
Bluescale	Approved scale to evaluate the colour change of a textile after performed lightfastness test
Bluesign®	Sustainability standard in textiles aiming to guarantee high level of security regarding chemical composition (safe and healthy materials)
CO_2-eq	The Carbon Dioxide Equivalent is a metric that compares the global warming potential of various greenhouse gases
Colourfastness	The property of resisting colour fading, loss, bleeding or staining after dyeing
Chromophores	A group of atoms responsible for the colour of a compound
Continuous/padding dyeing	A method of dyeing processing which involve passing the fabric between rollers and applying dyes
Dope dyeing	A method of dyeing processing, *a.k.a. solution dyeing, spin dyeing, mass colouration*, which involves adding pigment to the polymer that will be transformed into a filament. Used only for man-made yarns
Dyes	A natural/synthetic substance that can be used as a colourant, especially in a solution
Eutrophication (Aquatic)	An increase in phosphorus, nitrogen, and other plant nutrients in a water body results in excessive plant and algal growth. As a result, the ecological stability is threatened. (Sapkota, 2022)
Exhaust/batch dyeing	A method of dyeing processing
Greyscale	Approved scale to evaluate colour change and colour staining of textile after performed washing, rubbing, and sweat test
K/S value	a value for the colour strength of a dyed fabric derived from the Kabulka Munk Theory
Liquor ratio	The ratio of bath weight to fabric weight
Mordants	A substance used in dyeing processing to fix the colour
OEKO-TEX	A trademark representing labels issued by the International Association for Research and Testing in the Field of Textile and Leather Ecology

Pigments	Inorganic colouring compounds
pH value	“Potential of Hydrogen” A measuring unit which defines how acidic a product or solution is
REACH	European regulation: Registration, Evaluation, Authorisation and Restriction of Chemicals
Reactive disperse dyes	Dye group which contains a combination of hydrophilic and hydrophobic functional groups
Solvent	Substance (often liquid) that dissolves or disperse another substance
Spinneret	Device for extruding polymer solutions or polymer melts into fibers.
Technology Readiness Level (TRL)	A method used to estimate the maturity of a technology developed by NASA

List of Abbreviations

AATCC	American Association of Textile Chemists and Colorists
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CO2, CO_2 (emissions)	Carbon Dioxide (emissions)
CO2-eq	Carbon Dioxide equivalent
CO/PES blend	Cotton/Polyester blend
DMO	Defence Material Organization
DNA	Deoxyribonucleic Acid
FBA	Fluorescent Brightening Agents
LCA	Life cycle analysis
MVO	Nederland Corporate Social Responsibility Foundation *(in Dutch: Maatschappelijk Verantwoord Ondernemen)*
RLS	Restricted Substance List
$ScCO_2$	Supercritical carbon dioxide
SCF	Supercritical fluids
SDG	Sustainable Development Goals
SFT	Sustainable & Functional Textiles (research group)
OBA	Optical Brightening Agents
PET	polyethylene terephthalate, polyester
PET/CO	Polyester and cotton blend
TRL	Technology Readiness Level

Preface

The following graduation thesis henceforth was executed at the request of the Dutch Ministry of Defence and the research group of Sustainable and Functional Textiles at Saxion University of Applied Sciences. The thesis “Which alternative textile dyeing technologies can improve the environmental impact of non-operational workwear clothing?” contributes to the project Signwear. The project aims to investigate possibilities and challenges of designing circular workwear. The goal is to establish protocols for sustainable material selection, production development processing, traceability, and design. My interest in sustainability and the need for more sustainable production have motivated me to research about sustainable dyeing technologies that can lower the environmental impact of selected non-operational workwear. My research objective was formulated together with my company supervisors Anton Luiken and Theresia Grevinga. The final report is the outcome of the five months of research internship as part of the Bachelor’s program Fashion and Textile Technologies.

I would like to thank Daisy van Grooningen, Anton Luiken and Theresia Grevinga for the given opportunity to participate in this project. Also, special thanks for the conversations, guidance, and insight throughout my research process. I am profoundly grateful to Usha Bhaskara for the guidance during my thesis writing. Furthermore, my sincere thanks to all the companies and experts that gave me insights regarding different dyeing technologies and innovations. Lastly, my research would not be possible without the support of my family, friends, and partner.

I hope you enjoy reading my thesis.

Lilia Ivanova

Enschede, the Netherlands

16 June 2022

Summary

The aim of this graduation thesis entitled Circular Workwear: Alternative Dyeing Technologies is to investigate the possible future replacement of colouring technology to reduce the environmental impact of selected non-operational workwear clothing used by employees of the Dutch Ministry of Defence.

For this purpose, qualitative and quantitative research methods are used to answer the question: “Which alternative textile dyeing technologies can improve the environmental impact of non-operational workwear?”. Firstly, document analysis was executed to obtain colourfastness requirements for the selected workwear. Secondly, expert interviews were conducted to get a better understanding of novel dyeing technologies and their opportunities and challenges to implementation. Also, an industry perspective was sought to get insights from workwear, corporate fashion, and textile manufacturing supplier specialists. Furthermore, several alternatively dyed samples were collected and tested for colour resistance in the Saxion Textile Lab. These alternatives include natural dyeing, supercritical carbon dioxide ($ScCO_2$) dyeing, dope dyeing, digital spray dyeing, and powder pigment dyeing derived from textile waste. Also, MODINT Ecotool was used to estimate the environmental impact of the selected samples during their dyeing stage. Lastly, the alternative samples that met the colourfastness requirements were analysed in the Ecotool and compared to the traditional dyeing processing.

To conclude, dope dyeing proved its excellent colourfastness performance. None of the other tested alternatives met the ministry requirements. Further, dope dyeing is a prominent resource-efficient technique since it eliminates the environmental impact during the dyeing stage. In spite of this, dope dyeing can be used as a replacement only for the polyester content of the selected garments. In contrast, renewable dyes such as natural, bacterial, and waste textile resources were found to be irrelevant alternatives for garments mainly due to the limited colourfastness performance and non-commercial viability at the moment. Also, the environmental benefits of natural dyes were insignificant. Moreover, alternative methods, such as spray, $ScCO_2$, and plasma pre-treatment, require further technological improvement to replace conventional dyeing. For example, spray dyeing must guarantee higher colourfastness performance in wet rubbing and lightfastness. Also, it is necessary to investigate the scaling up of dyeing applications on all types of fibers. Plasma pre-treatment is a niche technology in the textile industry, and it still needs to prove its system and competitiveness in an operational manufacturing environment. However, it has a great potential to improve dyeability prior to conventional dyeing, thus lowering the operational and environmental costs. Lastly, $ScCO_2$ dyeing significantly reduces the environmental impact of dyeing. However, it still needs further investigation to solve the problematic dyeing of cotton and polyester blended textiles.

1 Introduction

1.1 General information

1.1.1 Research Group of Sustainable & Functional Textiles (SFT)

Sustainable & Functional Textiles is a research group established in Saxion University of Applied Sciences, located in Enschede, the Netherlands. In collaboration with researchers, companies, and students, SFT research group develops innovative concepts and products (Saxion, Sustainable & Functional Textiles, 2022). The research group is focused on two main research areas – sustainable textiles and functional textile. This project is part of the sustainable textiles research field focusing on circular textile industry.

1.1.2 Categorie Bedrijfskleding Rijk

In the Netherlands, the Defence Materials Organization (DMO) is part of the Dutch Ministry of Defence (Defence, Organisation, 2022). Since the Dutch government has started a plan to implement a circular economy by 2050, the department of Categorie Bedrijfskleding Rijk endorses the government policy and helps to realize the transition of the agenda (Rijksoverheid, 2018). The Category helps the ministry make wise decisions regarding its procurement of goods and services. It covers the entire product lifecycle, including needs formulation, contract management, divestiture, and evaluation. The company purchases workwear for government organizations, such as the Dutch Ministry of Defence, Facilities Management Haaglanden, Tax authorities, Rijkswaterstaat, Custodial Institutions Department, Customs (part of the tax authorities), Social Affairs and Employment Inspectorate, Human Environment and Transport Inspectorate, and Dutch Food and Consumer Product Safety Authority. All government organizations set requirements in the field of functionality, representativeness, and sustainability. Regarding functionality, the purchased clothing must meet requirements in safety, protection and wearing comfort. Moreover, clothing must meet representative requirements in terms of recognizability, appearance, and shape retention control. Regarding sustainability, the company must consider extension of the lifespan, corporate social responsibility (CSR) and service life.

The Ministry of Defence partnered with the local social enterprise company Biga Groep to collaborate on circular economy (Soufani et. al, 2020). The purpose of this collaboration is to give second chance to the clothing or use the materials for new products, meanwhile employing people with an occupational disability to sort out the items. About 35% of the sorted items are given a second life within the Ministry of Defence, and the remaining products are used to create new products that are no longer traceable (Organisatie, 2016). ***Figure 1*** illustrates the flow of the products within the ministry gathered by personal communication during company visit. Biga Groep sorts out all returned or discarded articles from military personnel when ending their service or changing their military position. Some of the returned articles are never worn or almost not worn. Therefore, it is possible to return to the department store and give them a second life. Some used articles, such as military helmets, can be refurbished and used again while other items cannot be used anymore. Thus, the company removes the logos, patches, and labels and sends them for auction in vintage military shops. However, some articles cannot be sold, and they are recycled or upcycled into new products or textile materials, depending on their construction, and printing and finishing.

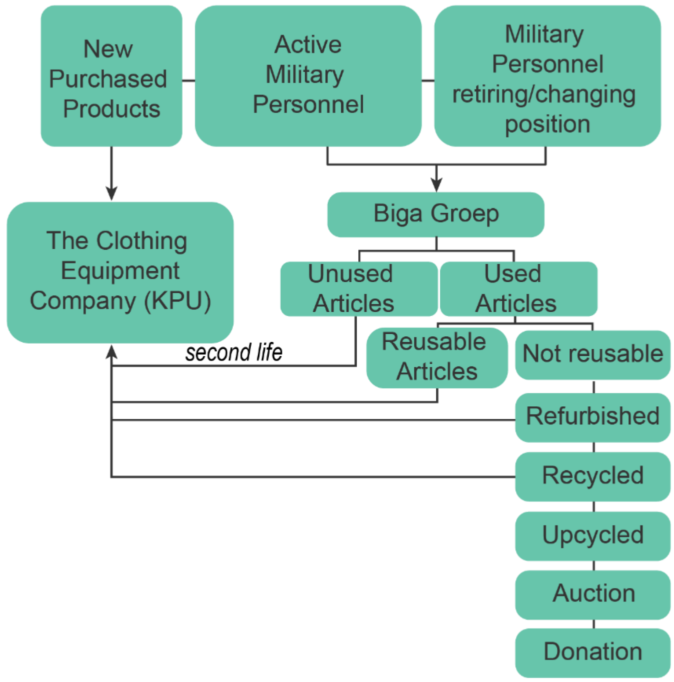


Figure 1 Product resource flow of the Dutch Ministry of Defence (Based on personal communication during company visit)

1.1.3 SIGNWEAR Project

SIGNWEAR is one of the projects within the Sustainable & Functional Textiles research group. The project aims to investigate the possibilities and challenges of developing circular workwear for the Dutch Ministry of Defence. The Categorie Bedrijfskleding Rijk and the SFT research group collaborate to create protocols and preconditions for designing circular workwear for the Ministry of Defence. The Dutch Ministry of Defence use two types of workwear – operational and non-operational. The non-operational defines the workwear that is not used on the field, whereas operational workwear is worn on the field during military missions. The circular economy aims to enhance the reusability of products to lower the pieces destroyed. According to MVO Nederland, there are specific principles to follow in terms of implementing circular economy (Rijksoverheid, 2018). Firstly, it is vital to consider the value retention of a product by continuously investigating the availability of product, components, and raw materials reuse. Secondly, another important principle is to design and manufacture for disassembly, as well raw materials to be easily separated in the end. Furthermore, it is crucial to eliminate emissions of harmful substances during the production processing and product use.

1.2 Problem Statement

As many European Union countries are working on future plan for circular economy, Netherlands introduced a timeline to implement a circular economy strategy. The Government of Netherlands has set a goal to transition to a circular economy by 2050 (Government NL, 2022). The Ministry of Defence is a major textile user, especially for workwear. Thus, the government organization is required to shift towards circular economy.

To begin with investigating the development of circular workwear, ex-Master student Roos Anne Herder researched on replacing virgin textiles by modern circular workwear textiles (Herder, 2021). Although, replacing virgin raw materials with circular materials is one step further to achieve circular economy, there is still more that needs to be done on achieving circular workwear. For this purpose, the life cycle of a garment must be thoroughly and closely analysed. Every stage of the textile manufacturing has a range of environmental and social impact. For example, textile dyeing processing faces many environmental challenges, such as water and energy consumption, air and effluent emissions, and use of global resources (Sinclair R. , 2014). Simply dyeing a polyester and cotton blended textile requires more than 100 liters of water per 1 kg, while adding a large amount of dyes, salts and alkali to the bath (Zhou et al., 2022). Also, the energy consumption is high due to processing time up to 10 hours. Furthermore, it is the textile finishing industry that generates the most wastewater when compared to other stages of textile manufacturing (Periyasamy & Venkatesan, 2018).

This thesis focuses on non-operational workwear and its production technologies during the textile dyeing processing. Moreover, the aim is to find possible alternatives to reuse raw materials, eliminate or minimize the environmental impact, while meeting the quality standards. The final goal is to list an overview with advisory methods of dyeing treatments that lower the environmental impact.

1.3 Literature Research

All stages of garment production have an environmental and human impact. However, when analysing a small fragment of a lifecycle of a garment, the problem becomes more visible and acute. To further investigate circularity, this section reveals available information about the current state of conventional dyeing processing and available textile technology innovations aiming to reduce the environmental impact. The data is collected through reliable sources, such as scientific and journal articles, books, statistical data, and other web sources.

Textile manufacturing is a complicated process, which involves different stages. Currently, the textile supply chain includes the collection and sorting of raw materials, the spinning of yarn, the weaving of fabrics, the application of pre-treatments, and finally the application of finishing treatments. The final textile finishing determines a fabric's appearance and aesthetic properties. It may also alter the aesthetics and functional properties of textiles according to the needs of consumers (Choudhury, 2017). Therefore, the finishing process is a vital textile manufacturing stage.

1.3.1 Introduction To Dyes and Dyeing Processing

Dyeing processes are essential for the desired final appearance and representativeness. In publication from Mendelson (2017), colour offers a sense of authority in military workwear. Dyeing defines the colour application on fibre, yarn, textile, or garment (Bellini et al., 2002). According to M. Clark (2016), there are various factors affecting the final shade of a textile, such as texture and construction of a substrate, pre- and post-treatments applied before and after the dyeing step. Textile substrates are always pre-treated before dyeing, especially natural materials due to their natural impurities. Preparatory processes ensure the removal of all impurities, uniform better dye and chemical absorption in the following processes (Parisi et al., 2015). Further, P.R. Richards (2015) state that white shades are achieved by appropriate bleaching of the fibre. Also, it can be achieved by the application of fluorescent bleaching agents (FBA). According to McKeen (2016), optical brightening agents (OBA) and FBA are dyes that absorb light in the Ultraviolet spectrum. Thus, these agents produce a whitening effect. However, the author outlines that bleaching is done only on natural fibres, since synthetic materials can be produced without added colour.

Fabric coloration requires the use of dyestuff, such as dyes or pigments that are classified into synthetically made and naturally derived. It is vital to consider the best performing dye class before starting since good penetration ensures optimum fastness properties (Broadbent, 2001). Colourfastness defines the property of resisting colour fading, loss, bleeding or staining after dyeing (Cohen, 2015). In Ancient times, textiles were coloured by using natural organic (plants and animals) and inorganic (clay, earths, metal salts, stone) resources (Pereira & Alves, 2012).

In recent research from Samantha (2018), there is a significant increase in interest of natural colourants due to skin and eco-friendly characteristics. Both Kumbasar (2011) and Samantha (2018) mention that natural dyes are usually renewable and biodegradable, less toxic and polluting to the environment. Furthermore, both authors discuss that the application of natural dyes is advantageous because it reduces the consumption of fossil fuels based in synthetic dyes. Therefore, natural dyes reduce non-renewable resource consumption. In contrast, Cohen (2015) states that the common assumption that natural dyes can improve the environmental impact in dyeing is sometimes false. Samantha (2018) supports this statement by explaining that shifting from synthetic to natural dyes will cause a problem in replacing the land use to satisfy the demand of production. Also, R. Sinclair (2014) states that "natural" is not equal to "safe" since not all natural dyes are safe to use. Samantha (2018) complements this statement by stating that not all natural dyes are toxic-free, and that little research has been done on the toxicity of natural dyes. Furthermore, both Sajda.S. Affat. (2021) and S.S. Muthu (2018) state that some natural dyes require mordants to fixate the dye molecule on the textile substrate, which can be toxic and harmful. Most used mordants are Aluminium- (Al), Copper- (Cu), Iron- (Fe), and Chrome- (Cr) based salts. S.S. Muthu (2018) lists copper and chrome-based mordants as toxic to the environment. Research study from A. Ado (2015) mentions that there is a concern of the toxicity in Chrome-based salts among some practitioners. Additionally, R. Sinclair (2014) remarks that natural dyes are not suitable for large industrial scale due to availability limitation. Furthermore, a significant limitation of using natural colourants is the colourfastness poor performance after exposure to light, perspiration, and washing (Samanta, 2018). Furthermore, the author adds on that there is a limited in-depth research data on how to control the poor colourfastness properties. In the modern textile industry, synthetic dyes dominate due to their wide range of shades, excellent colourfastness performance, and cost-efficiency (Pereira & Alves, 2012). Synthetic dye molecule consists of chromophore atoms, which produce colour, and auxochrome electrons, which enhance the colour (Madhav et al., 2018). ***Table 9*** in Appendix 1 shows that the type of fibre determines the dye class. According to A. Khatri & M. White (2015), there are four key dye classes used for cellulose dyeing – reactive, direct, sulphur and vat dyes. Reactive dyes are the dominantly used in cellulose dyeing due to its bright shades and excellent colourfastness properties (A. Khatri, 2015), (Clark, 2016). Moreover, these dyes chemically react between the dye and cellulose fibre reactive groups, resulting in excellent colourfastness (Richards, 2015). Also, Kiron (2021) explains that reactive dyes require some additives to achieve proper colouration, such as salts, alkali, urea, and soaping agents. ***Table 10*** in Appendix 1 describes the importance of using these auxiliaries. Hence, in Appendix 1, it is evident that disperse dyes are a suitable dye class for polyester fibres. According to A. Ketema (2020), disperse dyes are water-insoluble dyes that are made to allow dyeing of manmade fibres, such as polyester (PET). A PET fibre is hydrophobic, partially crystalline and does not contain a functional group that permits dyes to bond to it (Richards, 2015). Gries et al. (2015) state that fabric dyeing takes place either through the dye affinity with the fabric or via a chemical reaction between the dye and fibre. The authors note that these dyeing mechanisms result in excellent colourfastness performance. In dyeing with disperse dyes, the dye molecules are dissolved in the fibre during solution process. However, textile fabrics often consist of multiple fibre types. Thus, dyers need to prepare separate formulas for each component to achieve uniform dye shade. In traditional dyeing, cotton and polyester blended textiles are dyed either in a two-bath process or in one-bath two-steps technique by using suitable dye classes, auxiliaries, and chemicals for each fibre component (Muralidharan, 2011). The author states that two-bath is a long and complicated process, whereas one-bath two steps result in poor dyeability and reproducibility.

In general, traditional dyeing involves several steps. According to Bellini (2002), the first step is to dissolve or disperse the dye in a water bath. Then, the dye solution is fed into the machine. During the next step, the dye is transferred from the liquor to the fibre. Both M. Clark (2016) and M. Günay (2013) state that most common dyeing methods are exhaust (batch) and continuous (padding). Under specific temperatures and time, the dye penetrates and fixates in the fibre structure. The process is achieved when the dye liquor and fibre are in complete equilibrium (Gries et al., 2015). The last step of the process involves washing off the material to eliminate the unfixed dyestuff on the fibre surface. Both Gries (2015) and Bellini (2002) state that good dyeing depends on specific parameters, such as the dye liquor composition, liquor temperature, process time, pH value, processing type and rate, and fastness evaluation. Gries et al., (2015) continue by adding that specific dyeing parameters, such as liquor ratio, water consumption, energy consumption, dye, and auxiliaries' consumption, need to be as low as possible. According to the author, these parameters can be accomplished by proper machinery selection.

1.3.2 Environmental Impact Caused by Dyeing Processes

There are various factors that needs to be considered during the finishing of a textile, including dyeing. The most concerning environmental impact is seen in water consumption, wastewater, chemicals, and energy (Muthu S. S., 2014). ***Figure 2*** summarizes some of the aspects that need to be carefully studied to achieve textile finishing with lower environmental footprint.

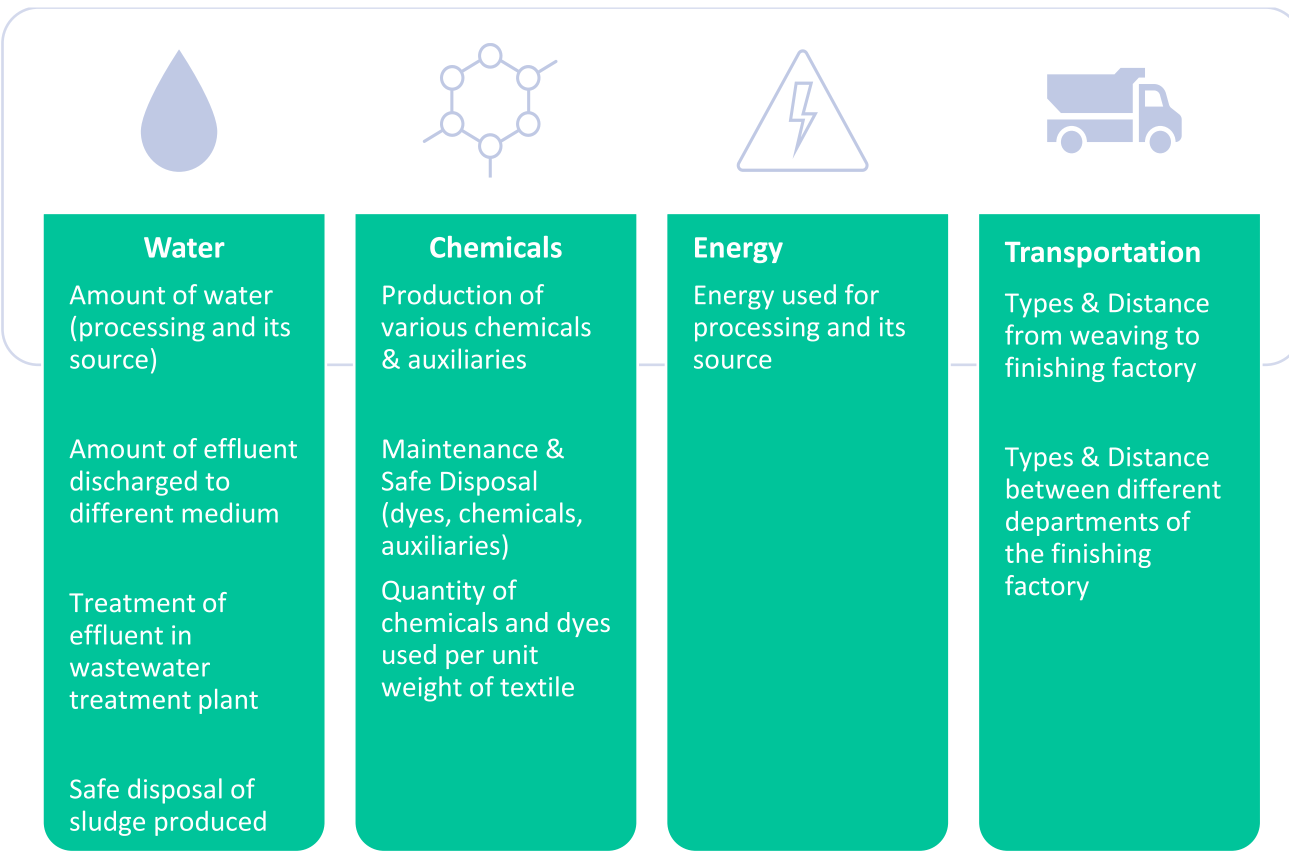


Figure 2 Environmental issues that needs to be considered before textile finishing (Muthu S.S., 2014)

Water pollution*.* A large amount of freshwater is consumed during wet dyeing processing. According to the World Bank (2012), textile dyeing and finishing treatments cause between 17% to 20% of industrial water pollution. According to Muthu (2021), water may be used in dyeing for dissolving dyes, processing medium, generating steam, and rinsing. For instance, M. A. Uqaili & K. Harijan (2012) claim that the water consumption norm is between 50 to 100 litres of water to treat 1 kg of textile materials. For example, ***Figure 3*** represents Nike's reduced freshwater consumption in textile dyeing and finishing from 2016 to 2020 (Nike, 2021). Moreover, Nike implemented four key strategies - innovative low-water materials and technologies, efficient water usage, reusing water, and scale-through industry collaboration (Purpose, 2022). By implementing Water Minimum Program, inefficient water suppliers started to optimize their processing by integrating water-efficient dyeing equipment or wastewater recycling systems (Aquatech, 2020).

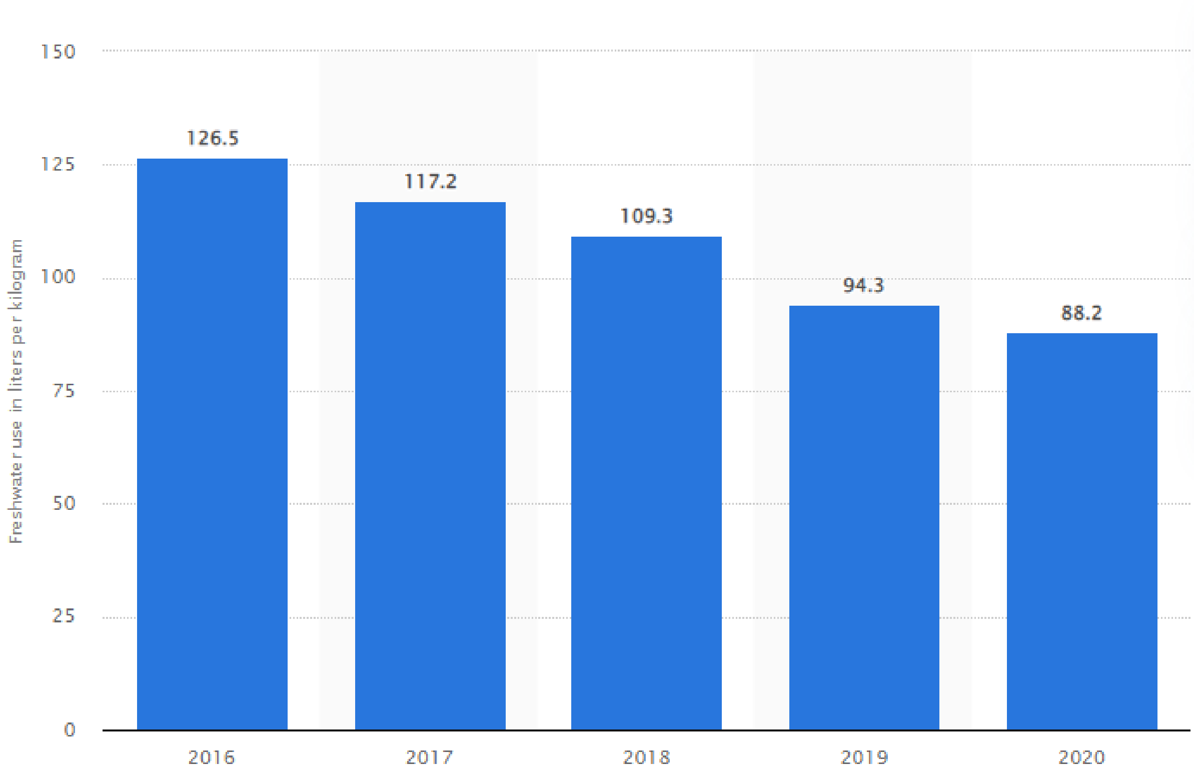


Figure 3 Volume of freshwater use in textile dyeing and finishing by Nike from FY 2016 to FY 2020(in litres per kilogram) (Nike, 2021)*

According to Pang and Abdullah (2013), a large amount of dyes is released in industrial wastewater. Also, L. Pereira & M. Alves (2012) discuss that dye fixation rate can provide an approximate value of dye amount released. For example, disperse dyes losses are less than 2 to 10%, whereas reactive dyes can reach 50% dye loss. This results in a coloured surface within the wastewater, ***Figure 4*** shows the significance of this problem.

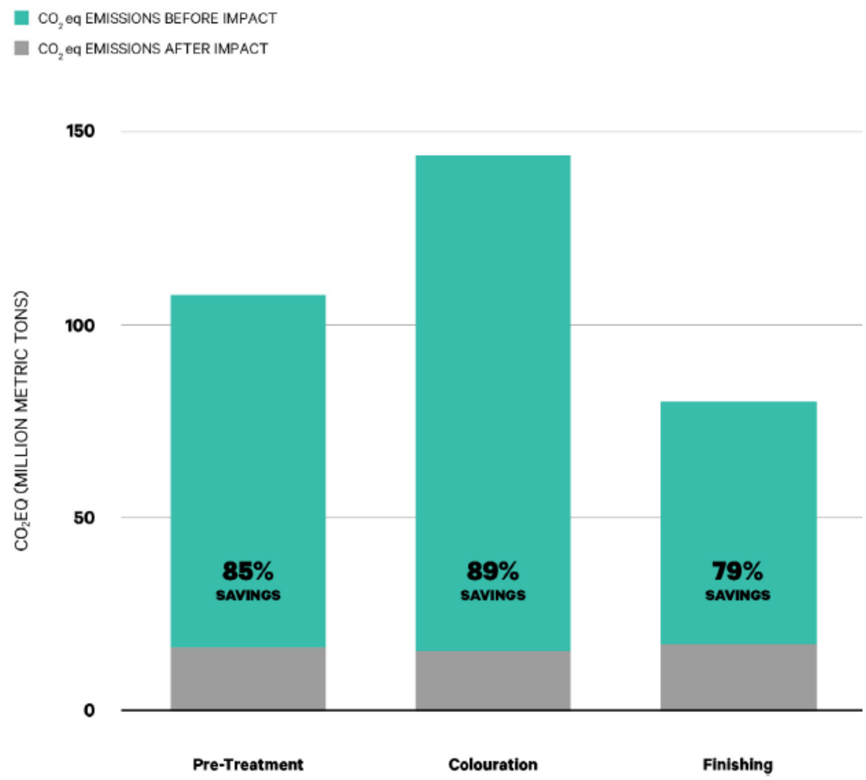
Figure 4 In December 2011, a red dye was poured into the stormwater system of the city of Luoyang, in China, causing a red coloured surface on the Jian River (Helen Regan, CNN, 2020)

Hence, specific chemical compounds, such as heavy metals, surfactants, fabric rinsing detergents, salts, Sodium Sulphate, Sulphuric Acid, and other dispersive agents, can be toxic to aquatic life (Pereira & Alves, 2012). Yaseen & Scholz (2019) further comment that the released chemical substances have a negative impact on the water ecosystem and nearby soil if wastewater treatment is not performed. As a result, people living nearby these plantations often suffer from carcinogenic effects due to the harmful substances. According to Madhav (2018), the textile finishing step is mainly done in underdeveloped or developing countries. Due to financial constraints, wastewater treatment technology is less likely to be invested in. Additionally, a recent epidemiology study shows that textile workers are exposed to toxic substances that cause chronic diseases (Tounsadi et al., 2020).

Energy consumption. The textile industry requires energy to operate successfully. Richards (2015), lists the energy consumption is related to generating steam for heating processing, running the machines, lighting, and heating the facilities. Research from Wang et al. (2017), examines the energy footprint of Chinese textile companies between 1991 and 2015. According to the researchers, China's textile industry will increase its energy footprint in response to then increased domestic and foreign market demand. In addition, the authors concluded that it is crucial to upgrade the textile industry with alternative technologies that consume less energy to improve industrial productivity and lower energy-related green gas emissions. Additionally, Richards (2015) supports this statement since most industrial energy is derived from fossil fuels. Also, the author underlines that the industry should incorporate energy-efficient technologies to reduce the consumption of non-renewable resources until alternative supplies such as solar panels, wind, and nuclear are cost-effectively available.

1.3.3 Environmentally Friendly Dyeing Approach & Technologies

Nowadays, there are many available approaches that can lower the environmental impact during dyeing stage. Research from Palacios-Mateo et al. (2021) outlines several recommendations to enhance sustainability at each stage of the polyester garment production chain. For example, it is possible to eliminate the use of fossil fuels as a raw material by implementing renewable dyes and chemicals. Also, water consumption and pollution can be reduced by incorporating dyeing with less water, water recycling, and wastewater treatment. According to research from the non-government organization Fashion for Good, a key solution to minimize environmental impact is to shift wet processing towards dry processing (FashionForGood, 2022). ***Figure 5*** illustrates the impact difference between the two approaches. Nowadays, there are several technologies that enable waterless dyeing.



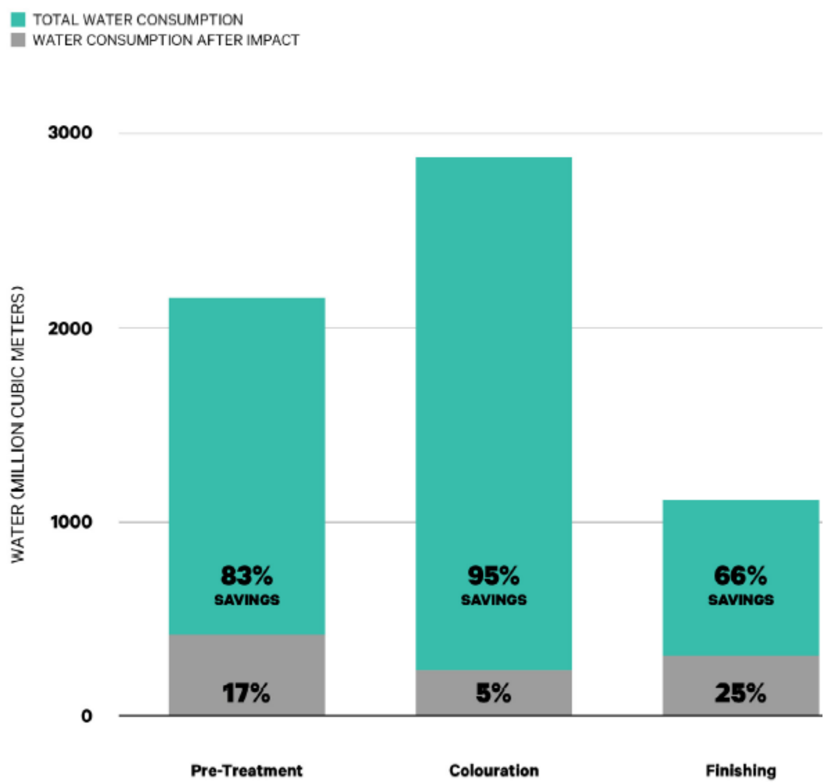


Figure 5 CO_2 emissions and Water Consumption Resource Saving after shifting from wet to dry processing (Fashion For Good, 2022)

Supercritical Carbon Dioxide ($ScCO_2$) Dyeing. Supercritical fluids refer to the state of the material when liquid and gas coexist by applying the critical values of temperature and pressure (Sihvonen, 1999). Both Muthu S.S. (2021) and A. P. Periyasamy et al. (2021) state that supercritical fluid is an excellent solvent due to its unique properties. $ScCO_2$ has high viscosity (gas-like) and density (liquid-like). The book authors Rather et al. (2021) describe $ScCO_2$ dyeing as innovative and emerging technology. Moreover, ***Figure 6*** illustrates the conditions at which a critical point of CO_2 is achieved. According to Patnaik and Patnaik (2019), supercritical fluids can dissolve dyes at high temperatures and pressure. Besides, the authors list possible substances that can result in a supercritical phase, such as carbon dioxide, ethane, propane, and ammonia. However, the authors mention that CO_2 is the most widely used due to its advantageous properties, such as convenient supercritical temperature, low cost, non-toxicity, non-flammability, recovery, reuse, and chemically inert nature and stability.

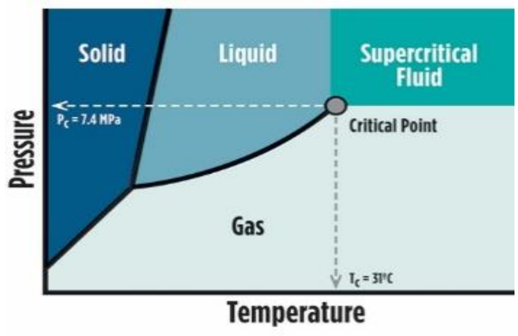


Figure 6 Phase diagram for Carbon Dioxide

Recent research from Goñi, M. et al. (2021), concludes that $ScCO_2$ can be used as a replacement medium for water during textile dyeing. A Research from Tušek et al.(2000) explains that $ScCO_2$ can dissolve hydrophobic substances like disperse dyes. Additionally, the researchers (2000) discuss the purpose of the $ScCO_2$ environment: (1) to heat the substrate and (2) to transfer the dyes onto it. According to Goñi et al. (2021), the process is faster, eco-friendlier, and more cost-efficient. Moreover, Abou Elmaaty & Abd El-Aziz (2017) concluded that the $ScCO_2$ dyeing technology is a more sustainable technology because it excludes water during the process, is energy efficient, and commercially feasible. The researcher Abou Elmaaty et al. (2017) compares traditional water-based dyeing and $ScCO_2$ dyeing in ***Figure 7***.

Conventional water textile dyeing	Alternative textile dyeing with $scCO_2$
Large usage of water	Elimination of water usage
High levels of salt and alkali	No additives
Hydrolysis of dye molecules	No hydrolysis of dye molecules
Costly water purification	No production of polluted water
Drying step of textile	No drying step (energy saving)
	Shorter process time due to high diffusion coefficients and low mass transfer resistance
	Easy separation of the dye from $scCO_2$ with dye recovery
	Carbon dioxide can be reused

Figure 7 Comparison overview: Conventional vs. $ScCO_2$ textile dyeing (Abou Elmaaty & Abd El-Aziz, 2017)

A. Amenaghawona et al. (2019), highlight a challenge to dye polar hydrophilic textures, such as natural fibres, because of the nonpolar nature of $ScCO_2$. In research by Bach et al. (2010), surface modification improves the natural fibre dye uptake by introducing hydrophobic functional groups.

These groups assist the interaction between the $ScCO_2$, the dispersed dyes and the natural fibres. Also, Elmaaty & Abd El-Aziz (2017) revealed that dyeing natural fibres in a $ScCO_2$ medium is still in research development stage and several options are investigated: (1) development of disperse dyes with reactive groups, (2) chemical modification, and (3) physical modification with auxiliaries. Nevertheless, further research on dyeing CO/PET blends is needed (A. Amenaghawona, 2019). Furthermore, the authors (2019) outline that $ScCO_2$ dyeing has been focused mainly on PET. However, dyeing of other synthetic materials, like polyamide, polyacrylic acid, and polypropylene, have been explored, too. Penthala et al. (2022) reported that dyeing polyamide with disperse dyes in a $ScCO_2$ environment produces poor fastness properties. No matter how well dispersed dyes are solubilized, physical bonds are needed to ensure the desired colour stability and strength. Thus, *reactive disperse dyes*[1] can form a strong bond with the reactive polyamide functional groups (-NH) and ensure a strong dye fixation (Penthala, 2022). Zheng et al. (2016) reported that the $ScCO_2$ dyed products performed excellent colourfastness to washing, rubbing, and light, when tested accordingly to the AATCC test methods (61, 8, 16.3). In addition, K. Babu (2022) affirms that 90% of used CO_2 can be recycled, and the dye leftover can be easily removed by elimination of air pressure.

Dope dyeing. Dope dyeing' or 'Mass coloration' or 'Solution dyeing' is another alternative method to lower the water consumption. For example, M. V. Wennberg (2019) suggests solution dyeing to phase out the wet process. Mahapatra (2018) explains that dope dyeing takes places during the manufacturing of synthetic fibres. Initially, dye is added to the spinning solution. When the spinning solution is extruded through the *spinneret*[2], the filaments are coloured. The author mentions that dope dyeing obtains permanent colourfastness since the colour becomes part of the filament/fibre. Patnaik and Patnaik (2019) state that dope dyeing requires fewer costs, and that effluent treatment is unnecessary. Mehdi et al. (2018) support this statement by listing its ecological benefits, such as saving time, energy, and chemicals, and it prevents dye loss to wastewater. Mass coloration is applied on all manmade fibres that can be extruded, such as polyester, nylon, viscose, etc. ***Figure 8*** illustrates the process of dope dyeing provided by a major yarn supplier.

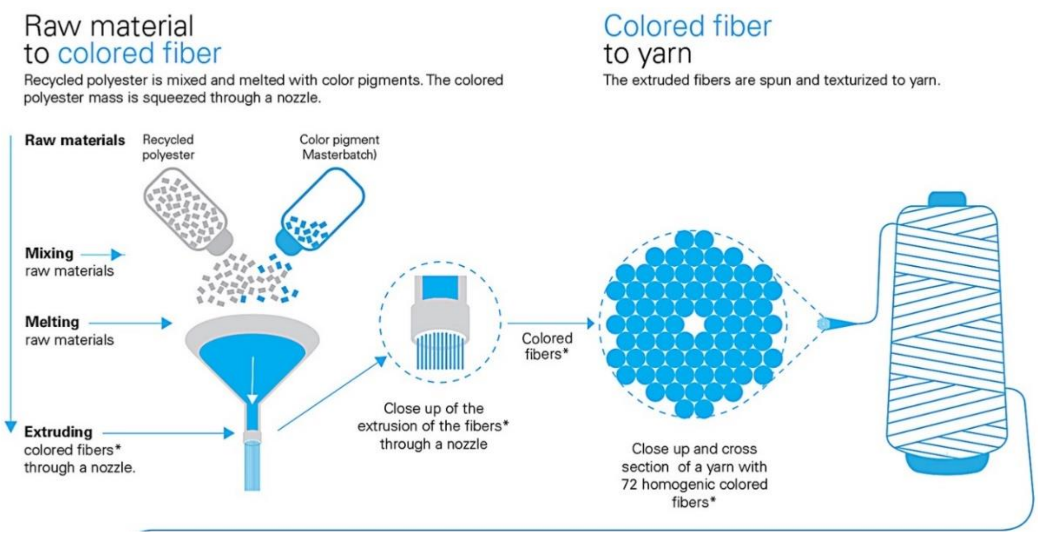


Figure 8 We aRe SpinDye® dope dyeing process

1 Reactive disperse dyes – dye group which contain a combination of hydrophilic and hydrophobic functional groups
2 Spinneret - device for extruding polymer solutions or polymer melts into fibers.

Environmental Product Declaration following ISO 14025 for polyester fabrics conducted an LCA comparison study between dope and piece dyeing (***Figure 26)*** (SMARTEX Solution, 2019). The study concluded that water and chemical consumption are eliminated during the dyeing process since the colour is added during the yarn spinning. Although the spinning process results in higher global warming potential, the total global warming potential (kg CO_2-eq[3]) of dope dyeing is still less than piece dyeing. However, S. Maiti et al. (2022) acknowledge that this technology is feasible for colours with large market volumes, such as dark blue, black, brown, and red. According to N. N. Mahapatra (2018), dope dyeing benefits in fade-proof colours. However, the author states some disadvantages, such as making early colour decisions, limited colour range, difficulties in storing various colour shades, and tedious equipment cleaning after each process.

Digital Spray Dye Technology. Another resource-efficient technique is digital spray dyeing. ***Figure 9*** illustrates the recently developed spray batch dyeing technology, which utilizes capillary forces and natural absorbency of materials to get deeper penetration (imogotech, 2022). The machine has a closed chamber in which the dye dispersion is done through spray valves. A key part of the technology is the spray cassettes consisting of spray nozzles. In contrast to the water-intensive processes, dyes and chemicals are applied as vapor in a highly precise and controlled manner (Apparel Resources , 2020). This technology significantly decreases the use of water, energy, chemicals, and generated wastewater due to a low-liquor ratio (Textile Value Chain, 2020). Limhamn (2019) reports that DyeMax uses precise spray nozzles and 0.5 litres of water per kilo of fabric. According to the tech company (2022), the system is a feasible replacement of pad and jet machines, but also it can be integrated into a pad continuous line system.

The Alchemies' technology combines spray and airflow to allow deeper dye penetration into polyester and cotton materials. A thermal and infra-red energy enable the activation of dye penetration and chemical fixation processes in this technology (Alchemie Technology, 2022). The company reported that the process reduces water and dyestuff usage and CO_2 emissions (Alchemie Technology, 2022). ***Figure 10*** represents an environmental impact comparison between Endeavour spray and jet dyeing technologies. Moreover, Alchemies' datasheet reports that the colourfastness performance is evaluated at 4/5 accordingly to rubbing (ISO 105-X12:2016) and washing (ISO 150-C06:2010) standards.

In a recent report, Fashion for Good contradicts the common assumption that digital spray printing and dyeing have the same results (FashionForGood, 2022). The printing sprays artwork onto textiles, whereas dye spraying results in solid colours. In contrast to spray printing, the spray dyeing nozzles are larger allowing traditional dyestuffs and chemicals to be used.

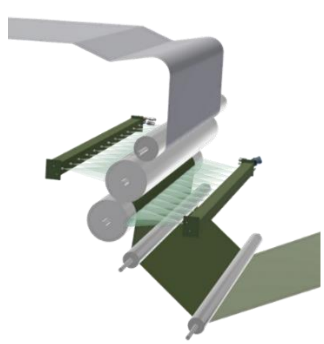


Figure 9 Digital Spray Dyeing DyeMax (imogotech, 2022)

3 CO2-eq – The Carbon Dioxide Equivalent is a metric that compares the global warming potential of various greenhouse gases

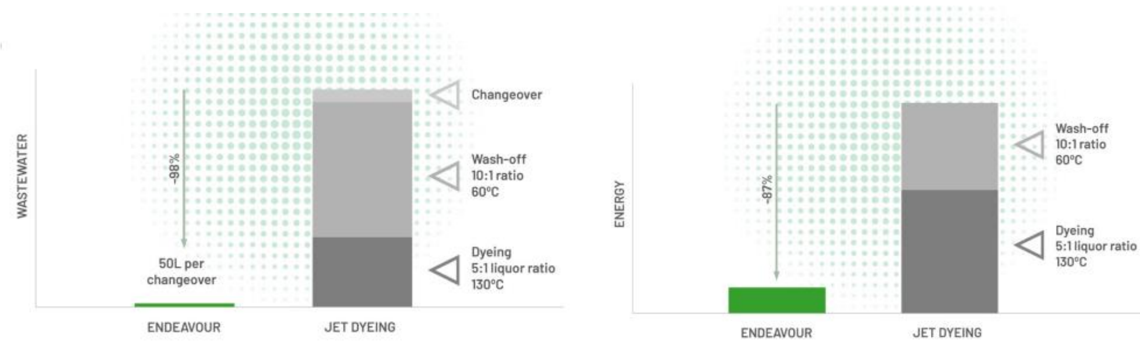


Figure 10 Environmental impact Endeavour spray dyeing vs jet dyeing technologies (Alchemie, 2022)

Renewable dyestuff and auxiliaries. The use of renewable dyes and auxiliary components is a possible approach to lower the environmental impact. However, M. Bide (2016) claims that synthetic dyes are the best to use since these colorants require less water and energy consumption and provide better wash fastness properties. Additionally, S. Saxena and A. S. M. Raja (2016) mention that many natural resources for dyestuff, such as plants and fruits, are seasonal and require large volumes of water to grow. Despite being a renewable source for dyestuff, natural dyes have some limitations. The authors discuss that these dyes involve tedious application processes, limited shade range, and low colourfastness performance. According to M. Bide (2016) natural dyes may be attractive, but they are not practically useful for large volumes.

In research from Venil et al. (2013), bacterial pigments are an environmentally friendly alternative to synthetic pigments due to biodegradability and a high environmental compatibility. However, the researchers emphasize the need to further investigate the fermentation medium development for each bacterial pigment on an industrial and commercial scale. Moreover, research from Gowri et al. (2019) discussed the importance of natural pigments derived from bacteria and their opportunities and challenges. However, the authors concluded that microbial pigment extraction is a tedious process which requires more research on proper pigment production, colour stability, and fastness. In 2016, a UK-based innovation company invented a patent for dyeing fabrics using microorganisms (UK Patentnr. WO2016162657A1, 2016). The method uses a DNA database of living organisms to reproduce the genes responsible for the desired colour. The pigment derives from building and growing DNA on bacteria. Then it is applied to the textile surface. Compared to conventional dyeing, microbial dyeing reduces water consumption by 49%, energy by 35%, and CO_2 emissions by 31% (Colorifix, 2022). Furthermore, bio design research "Living colour" from Dutch designers L. Luchtman & I. Siebenhaar (2021) explored the use of live bacteria and sound frequencies to study bacterial dyeing. The designers outline that microbe pigment fixation is possible on natural and synthetic materials. However, the researchers reflect on low wash fastness properties since the colour fades after several washes and exposure to light (TEDx Talks, 2019). Additionally, in research from Ren et al. (2017), a cleaner disperse dye, derived from the fermentation of Serratia marcescens bacteria, was used for dyeing a polyester fabric. The colourfastness properties were tested based on ISO 105 standards *(Figure 25, Appendix 1)*. The results showed excellent fastness properties in rubbing, sweat, and washing (grade 5), whereas the lightfastness was poor (grade 1).

Recycling colour. By applying the reduce, reuse, and recycle principle, it is possible to recycle colour from textiles. Recent research (2020) explored the opportunities of milling magenta 100% cotton waste material into fine coloured pigment for printing. The researchers found that cotton particles can be utilized for screen printing while preserving good fastness performance. Chemical company Officina+39 converts textile waste into a fine powder that can serve as a dye for cotton, wool, nylon, or any blended natural and artificial material (Barrie, 2018). The pigment is applied as a suspension rather than as a chemical solution. As a result, the process lowers both wastewater treatment costs and environmental impact. ***Figure 27*** illustrates an LCA comparison study between Recycrom and traditional dye development (Recycrom, 2022). The study concluded that aquatic eutrophication[4] scored with a negative impact, leading to a lower environmental impact of the whole system. To avoid dyeing recycled fibres, Niinimäki et al. (2017) investigated the colour stability and possible colour changes after the regeneration process. The researchers concluded that cellulose materials could be recycled as a textile and colorant. Hence, partial colour removal contributes to lower dyestuff consumption on remanufactured fibres.

Efficient Conventional Processing*.** Another possible approach is to utilize efficient conventional processing. Hence, Hasanbeigi and Price (2015) reviewed several emerging technologies for the energy and water reduction. The authors report that the ongoing trend of using efficient and safe textile auxiliaries is driven by expansion of restricted substances from policymakers. According to B. Carp (2020), chemical companies are developing safe products that can contribute to water, energy, and chemical savings. During Textile Today interview (2018), Eric Hopmann (DyStar Head of Global Sales & Marketing) revealed recently developed products enabling dyeing process optimization and resource efficiency, such as Cadira® and 8 Cadira®. Also, a global chemical provider's SWIFT Weave system implements a range of dyes, bleaching, and soaping agents that reduce the use of water, energy, chemical, and emissions of carbon dioxide (Archroma, 2022). In Appendix 1, *Table 12* briefly explains the efficiency of each chemical substance, whereas ***Figure 28 visualizes the environmental benefits.

Efficient traditional dyeing can be accomplished by introducing adequate pre-treatment, such as plasma surface modification. The term plasma refers to an ionized gas that displays a balance of positive and negative charges under extreme pressure and temperature (Muthu S. S., 2018). Plasma forms when a neutral gas is heated or exposed to an electromagnetic field, resulting in active species, such as ions, electrons, neutrons, excited molecules, free radicals, and photons (A. Haji, 2020). ***Figure 11*** illustrates the formation of plasma (Haji, 2021).

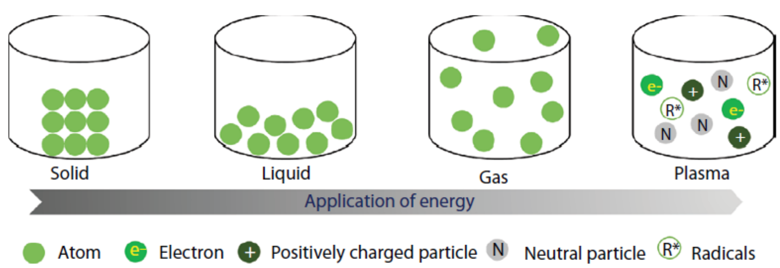


Figure 11 Plasma formation: Schematic diagram

The researcher reports that these reactive species can disconnect chemical bonds. According to Muthu (2018), plasma is primarily applied onto textile substrates for surface modification and property enhancement, such as dye rate and colour improvement. Besides, Zille (2020) emphasizes the use of plasma technology to enhance dye molecules' diffusion, leading to enhancement of colour intensity and colourfastness properties. Also, plasma application boosts the efficiency of dye exhaustion and uniformity. Thus, resulting in lower water and dyestuff consumption. According to M. Yusuf et al. (2022), plasma-treated textiles easily incorporate functional groups. Therefore, plasma enhances the dye uptake of hydrophobic fibres, such as polyester. For instance, a recent study from Jamaliniya et al.(2019) explored cold plasma treatment on polyester fabric. After bleaching and dyeing with jet and thermosol methods, the researchers concluded the whiteness degree is higher in plasma-treated compared to untreated

[4] *(Aquatic) eutrophication - An increase in phosphorus, nitrogen, and other plant nutrients in a water body results in excessive plant and algal growth. As a result, the ecological stability is threatened. (Sapkota, 2022)*

polyester fabric. Furthermore, the K/S[5] value or the colour absorption is higher when the polyester fabric is treated with plasma and dyed with the thermosol method. ***Figure 12*** depicts the results from the researchers.

Table 1. Whiteness of the untreated and plasma treated polyester fabrics.

No.	Sample	Whiteness degree before bleaching	Whiteness degree after bleaching
1	Untreated polyester fabric	74.1	88
2	30 s plasma treated	73.6	90.14
3	1 min plasma treated	73.2	91
4	3 min plasma treated	73.05	94
5	5 min plasma treated	72.45	94.3

Table 2. *K/S* value of untreated and plasma treated samples after dyeing.

No.	Sample	*K/S* value (jet method)	*K/S* value (thermosol method)
1	Untreated polyester fabric	3.42	11.84
2	30s plasma treated	3.6	12.1
3	1 min plasma treated	3.65	13.2
4	3 min plasma treated	3.7	14.2
5	5 min plasma treated	3.8	14.2

Figure 12 Results of using low temperature plasma for surface modification of polyester fabric (Jamaliniya, 2019)

Further, Jelil (2015) affirms that plasma pre-treatment benefits the dyeing and printing processes. For example, the researcher reports that the dyeing rate of cotton significantly increases after low-pressure oxygen plasma treatment. Correspondingly, the dye exhaustion is quicker and higher. Thus, the processing shortens the production time and chemicals usage. Furthermore, Kan (2019) reviewed the application of plasma treatment for pre-treatment on cellulosic, protein, and synthetic fibres. The author concludes that plasma can effectively treat surface impurities from fibres. Also, the researcher reveals that plasma treatment introduces an essential surface property of wettability, a property that influences dyeing. Besides, Clark (2016) discloses that fibre wettability is a crucial factor determining dyeability. According to Muhammad Naveed (2018) and Andrea Zille (2020), plasma technology can decrease the environmental impact of production since plasma treatment is clean, waterless, and operates at low temperatures. As A. P. Periyasamy and J. Militky(2020) state, the main benefit of using plasma technology is that it can alter the surface characteristics without affecting the bulk properties. However, a significant drawback is a difficulty of scaling up to a continuous process(Jelil, 2015). Hence, Zille (2020) depicts the main barriers to applying plasma, such as gaps in research and limited commercial and industrial systems. However, a collaboration with the textile technology expert Xefcoto and Deakin's Institute for Frontier Materials aims to develop new atmospheric plasma technology to improve conventional dyeing (Palich, 2021). The research objective is to make the traditional textile dyeing process more sustainable and energy-efficient.

1.4 Research Questions: Main Question and Sub-questions

Which alternative dyeing technologies can improve the environmental impact of non-operational workwear?

1. What are the colourfastness standards and requirements of the selected workwear garments?
2. What is the environmental impact caused by the dyeing on the selected workwear?
3. What state-of-art alternative dyeing methods can reduce the environmental impact of conventional dyeing?
4. Which alternative dyeing methods meet the colour fastness requirements of the provided workwear garments?

1.5 Reading Guide

Chapter one introduces the reader to the project, the principle of textile dyeing, its environmental impact, and possible approaches to improve it. Furthermore, the research objective and questions are clearly stated and elaborated in the section. Chapter two describes the undertaken research

5 K/S – a value for the colour strength of a dyed fabric derived from the Kabulka Munk Theory approach to answer the main and sub-questions. Then, Chapter three outlines the data collection results, whereas Chapter four involves discussion and conclusions based on the collected qualitative and quantitative data. The report ends with recommendations, limitations, and reflection on the study. Lastly, the Appendix section includes all figures and tables, interview transcriptions, quality research, and environmental impact assessments.

2 Methodologies

This section elaborates on the approach taken to determine colouration alternative, aiming to reduce the environmental impact and improve circularity on the selected workwear. Firstly, technical requirements and product analysis were carried out to acquire basic product information and its colourfastness standards. In addition, expert interviews were conducted to gain insights into current and future techniques for reducing the environmental impact of the coloration process. Besides, quality research and ecological footprint evaluation are performed on alternative dyeing technologies.

2.1 Technical Requirements and Product Analysis (Content Analysis)

Document analysis collected the colourfastness standards and technical requirements of the selected garments. Moreover, by reading through the documents, relevant information was collected to construct the ***Table 1*** *Product Introduction on selected garments*. Three documents contained the product purpose, lifetime, size specs, material content, construction, technical requirements, and testing standards. Moreover, the garment purpose, material content, colourfastness standards and requirements are crucial for the study. The garment purpose defines the importance of the colourfastness requirements, whereas the standards determine the quality research methodology. Also, the material content characterized the alternative dye classes and technology feasibility. Hence, the material production information was vital to measure the current environmental impact caused by the colouration stage in section 3.4. The colourfastness requirements were used as a comparative value in the quality research findings in section 3.3. The document analysis was the most suitable approach to gather the requirements from the Dutch Ministry of Défense since standards and requirements differentiate from company to company. The qualitative method categorized the different technical requirements and discussed the colourfastness standards.

2.2 Expert Interviews

The method chosen to explore further the environmental issues concerning textile colouration and possible sustainable alternatives is expert interviews. The approach allowed obtaining in-depth insights and experiences from stakeholders and experts from the textile industry. Therefore, a semi-structured interview was executed with open-ended questions, allowing the interviewer to ask for further clarifications throughout the conversation. The expert interviews were categorized into two groups. The expert interviewees were selected based on their knowledge and expertise in novel textile dyeing innovations. Also, into companies that aim to improve their environmental and social impact based on the seventeenth Sustainable Development Goals (SDG). The contact information of workwear suppliers was obtained by following an ex-master student thesis research. Whereas the textile supplier was contacted throughout the personal network of the researcher. Some of the alternative technology experts were discovered through supervisor's network. Others were obtained through company websites and social media platforms, such as LinkedIn. In total, 14 experts participated in the study, which took approximately 30 to 60 minutes. Interviews were conducted primarily via Microsoft Teams. However, some of the interviewees responded through email. Lastly, there was one exception of face-to-face conversation with a corporate fashion company. Before each interview, participants were asked for their consent to record the conversation for reliability and validity purposes. Later, the interviews were transcribed in Appendix 3.

2.3 Quality Research

Quality research was conducted at the Saxion chemical lab to analyse the colourfastness performance of available alternative dyeing technologies. Initially, three garments were collected from Biga Groep's assortment and tested. Furthermore, some of the interviewees sent samples of their latest developments, and other fabric swatches were purchased or collected from the

Saxion Fabric Library. A list of researched materials can be found in Appendix 4. Colourfastness properties were tested against washing, rubbing, perspiration/sweat, and light exposure, accordingly to the standards from *the List of requirements* obtained by the document analysis from 103744/06 and 105114/01 (*See section 3.1, Table 1*). The durability of colour is crucial feature in workwear and corporate fashion workwear. Thus, it is essential for colour to not fade away or transfer on other materials during washing. The washing test is performed accordingly to the ISO - 105-C06:2010 standard. Colour durability is tested against rubbing in accordance with ISO 105-X12:2016 standard. It is a significantly important colour property, especially for trousers worn daily by the military police. Colour can change due to alkaline or acidic environment exposure caused by human body sweat. Thus, the fabric samples are tested for colourfastness based on ISO 105-E04:2013 standard. Finally, light exposure can influence the colour appearance. Thus, it is essential to test the materials for lightfastness according to ISO 105-B02 standard. Appendix 4: *Quality Testing Methods* describes each procedure explanation, apparatus and materials, test specimens, and procedure.

2.4 Environmental Impact Assessment

MODINT Eco tool 3.0[6] assessed the environmental impact of the dyeing technologies that met the colourfastness requirements. This research method aimed to compare the environmental impact of the currently used conventional versus alternative dyeing processes. The approach allowed the researcher to obtain quantitative data, assisting in determining possible future replacements. The expert Anton Luiken provided access and explanation of the tool. All input data can be seen in Appendix 5, in which the values and processes were included in the study. The document analysis depicted the material content and product lifespan. Also, the tool allows to choose between different processing methods of each production chain step. ***Figure 13*** represents the studied product life cycle's steps. However, the extra materials assembly, packaging, transportation, and end-of-life steps were not included. Literature and official lifecycle databases of the material and production processes determine the final environmental scorecard. The output data (scorecard) outlined the impact of climate change, energy content, and use of water and chemicals. The land use was excluded since it does not say anything about the colouration process. Later, the current dyeing environmental impact was compared to the alternative dyeing techniques that meet the colourfastness requirements. Moreover, the Ecotool was suitable for the study because it provided an environmental impact scorecard on all available production chain steps of the workwear garments.

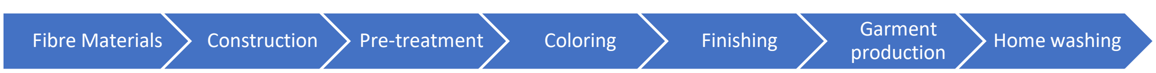


Figure 13 Studied production chain process

[6] MODINT Eco tool 3.0 – an Excel-based tool which allows environmental impact calculation of textile products within the entire life cycle (Modint EcoTool, 2022).

3 Results

This chapter presents the outcome of the collected data. Firstly, the collected garments were analysed by reviewing technical documents. In the results section, it is presented the purpose and colourfastness requirements of the selected workwear garments. Secondly, interviewee insights were reported. The result chapter ends with a LCA comparison between the current and alternative dyeing methods that meet the colourfastness requirements during the quality research.

3.1 Technical Requirements and Product Analysis Results

The document analysis collected the product information and each item's colourfastness requirement and standard. ***Table 1*** below introduces the product overview information. The white and light green man's long-sleeved shirts are part of the Royal Netherlands Army uniform, whereas the OPS Kmar trousers are part of the Royal Netherlands Marechaussee uniform. The first article refers to a white man's shirt or Product A. The second article refers to a light green man's shirt or Product B. Lastly, the third item refers to (OPS) Kmar trousers or Product C.

Table 1

Product Introduction on selected garments

	Product A	Product B	Product C
			
Document Garment	NSN: 8405-17-113-4508	NSN: 8405-17-133-3794	NSN 8405-17-125-3210
Textile/specs	103744/06	103744/06	105114/01
Material content	60% combed cotton / 40% polyester	60% combed cotton / 40% polyester	50% cotton/ 48% Polyester / 2% Elastane
Weave	plain	plain	twill
Colour	White	Light green	Dark Blue
Dyestuff	OBA	*Reactive & disperse*	*Reactive & disperse*
Chemicals used	*Unknown*	*Unknown*	*Unknown*
Application technology	*Combined bleaching step (presumed)*	*CO/PES continuous dyeing (presumed)*	*CO/PES continuous dyeing (presumed)*

3.1.1 Product A and Product B – White and Light Green Long-sleeve Shirt (KL)

Document 103744/06 depicts the technical requirements and specs of the white and light green long-sleeve shirt used by the Royal Netherlands Army or Koninklijke Landmacht (KL). Products A and B are part of the daily uniform, or the occasion uniform used during official occasions and services. The shirts are worn under normal Western European climate conditions during winter and summer. According to the document, the shirts should be durable for wearing for at least two years. In general, the uniforms are worn one to two days per week. However, the lifespan is dependent on whether the product care is done accordingly to regulations. The material composition consists of 60% combed cotton and 40% polyester. These fibers are ring-spun, twined, and part of an intimate blend. The fabric binding construction is a plain weave.

3.1.2 Product C – OPS Kmar Trousers (Royal Netherlands Marechaussee)

Document 105114/01 describes the technical requirements and specs of the Kmar trousers, part of the uniform for the Royal Netherlands Marechaussee. The clothing is used during general police service, border guard service, and security tasks. It is worn under normal Western European climate conditions. The trousers' lifespan is expected to be more than two years with intensive use. The material composition consists of 50% cotton,48% polyester, and 2% elastane. The binding structure is 2/2 Z Twill.

3.1.3 Dyestuff, Chemicals, and Application technologies

The documents did not reveal the used dyestuff, chemicals, and application methods. Therefore, suppliers were reached out for further information. Unfortunately, the suppliers did not share the requested information. Therefore, it is assumed that the colour of Product A is achieved by adding OBA agents to the bleaching formula. Also, assumptions are made regarding the dyeing of Products B and C. According to the literature research, the most common dyeing method is continuous CO/PET dyeing with reactive and dispersed dyestuff. Due to the large variety of textile auxiliaries, it is impossible to assume the exact chemical used during the dyeing process. However, in a public procurement document of the Dutch Ministry of Défense, a list of restricted substances (RSL) is highlighted. Furthermore, the tenderer requires to provide proof of a quality management system complying with ISO 9001:2015 and proof of environmental management system complying with ISO 14001:2015.

The *List of Requirements* located in *Appendix 2* reveals the colourfastness standards and requirements of the selected garments. Based on personal communication with Daisy van Groningen from the ministry, all quality requirements are essential. For instance, colourfastness properties are equally meaningful to pilling, abrasion, and tensile strength. In the field of workwear, the key features are durability and safety. The high-quality level is essential in offering a long-life garment. However, product care plays a crucial role in the colourfastness properties of the product's end-life. Therefore, it is impossible to compromise colour standards and quality requirements. In workwear, quality is more important than sustainability.

3.2 Expert Interviews Results

This section outlines the results of the expert interviews from different stakeholders' points of view, including textile processing experts, fabric, workwear, and corporate fashion suppliers. ***Table 2*** represents the overview of expert interviews conducted per topic.

Table 2

Expert Interviews Overview per topic

Category	Alternative tech	Textile Supplier	Workwear supplier	Corporate fashion supplier
Participants	• **$ScCO_2$ dyeing** – *Expert 1, Expert 2* • **Spray dyeing** – *Expert 3* • **Plasma** - *Expert 4* • **Microbial pigmentation** – *Expert 5, Expert 6, Expert 7* • **Recycrom** – *Expert 8*	KLOPMAN *Expert 9 & 10*	FRISTADS *Expert 11* HAVEP *Expert 12*	ETP *Expert 13 & 14*

3.2.1 Supercritical Carbon Dioxide Dyeing

This section outlines the results of the conducted interviews regarding $ScCO_2$ dyeing technology.

Expert 1

In 2007, the participant got introduced to supercritical CO_2 technology. The interviewee was very enthusiastic about it because he saw great opportunities in developing industrial-scale machinery. Thus, he participated in co-founding the Dutch company DyeCoo. Today, DyeCoo machines operate mainly in Asia.

The interviewee briefly explained the principle, benefits, and limitations of using $ScCO_2$ dyeing technology. When high pressure is applied, the CO_2 gas transforms into liquid. The application of more pressure to the liquid reaches the supercritical point, in which the properties are gas-liquid alike. The interviewee listed the environmental benefits by comparing water and $ScCO_2$ dyeing (***Table 3***).

Table 3

The advantages of ScCO2 dyeing compared to conventional polyester dyeing

$ScCO_2$ dyeing	Conventional polyester dyeing
• No large volumes of water • No high temperature water • No additional chemicals and auxiliaries • 99.9% dyestuff fixation • Unfixed dyestuff can be reused • 99% of the CO_2 can be reused • Same or better colourfastness • Some dyestuffs penetrate deeper • Productions costs are lower	• Large volumes of water are required • Rising water temperature up to 120°C to swell up the polyester fibre • Additional chemicals to disperse the dyestuff in the water bath • Huge volume of wastewater is generated • Disperse dyes cannot be recollected and reused • Disperse dyes and auxiliaries are difficult to recycle in the wastewater

The participant shared some of the challenges of utilizing this novel technology. According to the participant, supercritical technology cannot be applied to natural fibers. For instance, cotton is dyed with reactive dyestuff because a reaction is necessary between the fiber and the dye. Also, water is one of the exaggerators to create the reaction. Unfortunately, $ScCO_2$ cannot ensure this reaction, and as a result, cotton is undyed. The interviewee shared that it is possible to achieve dyeing of natural fibers on a lab scale, but it is not ready yet. Also, it is possible to add the necessary quantity of water to swell up the cotton fiber, but it is not relevant to use in a waterless solution dyeing process. Another solution is to add ethanol, but this will be negative for the machinery since it is explosive and not health-friendly to use.

The interviewee's insight shows that dyeing of blended textiles is possible, but it will result in different appearances, such as the mélange effect. Also, fabric weave construction can play an important role. To better illustrate, imagine the warp yarns are made from polyester, whereas the weft yarns are from cotton. In addition, this will result in the weft yarns facing the back of the fabric. As a result, the cotton content will face the inside of the garment, which creates softness and comfort to the wearer's skin. Also, when using $ScCO_2$ technology, the polyester will be dyed efficiently, whereas the cotton will not be dyed. The inside of the garment will have a lighter shade compared to the outside, just like jeans. Another challenge of implementing $ScCO_2$ dyeing is the high investment costs of the machinery. The interviewee elaborated that machinery cost is higher than traditional ones, but the production costs are lower. Furthermore, the expert discussed that utilizing supercritical technology will be more beneficial due to the current high energy and gas prices. Also, the participant commented on the benefits of supercritical technology in the mechanical recycling of fabrics.

Expert 2

Expert 2 affirmed that DyeCoo is the only technology provider that supplies $ScCO_2$ dyeing machines. These dyeing machines operate throughout Vietnam, Thailand, South Korea, the Netherlands, and Taiwan, and purchase is pending in Turkey and India.

The interviewee depicted that $ScCO_2$ dyeing is possible on 100% PET materials such as yarn, knit, and woven fabric. The most significant disadvantage of this waterless dyeing technology is the impossible processing of cotton and other natural fibers. The absence of dye chemistry makes it incompatible with a $ScCO_2$ environment. For instance, $ScCO_2$ dyeing of PET/CO fabric will dye only the PET material content, whereas the cotton will be unstained. The interviewee enthusiastically shared that the above mentioned provides the chance to create a mélange effect on both fabric and yarn level. Also, it is possible to sufficiently dye if the fabric is constructed so that the cotton part is not on the face fabric. A significant advantage of $ScCO_2$ dyeing is that it requires pure chromophores without any auxiliary chemicals. Therefore, it was clearly stated that the colourfastness properties are the same or better than water dyeing. Several global brands and retailers that use $ScCO_2$ dyeing were shared, such as NIKE, Adidas, Decathlon, Inditex, BonPrix, Brooks Running, and Walmart. Thus, it was ensured that $ScCO_2$ dyeing meets high-quality colourfastness standards. Fortunately, the participant shared an LCA study and datasheet of Couranger PE CO_2 dye range of Colourtex India which is the largest CO_2 dye supplier in the market (Separate Appendix 3).

Based on the introduced information on the current samples, several insights were shared. For instance, the current material content challenges $ScCO_2$ dyeing. Therefore, double dyeing needs to be considered if the reactive dyes for cotton are available. Also, the client needs to consider the environmental impact caused by cotton dyeing. According to the interviewee's expectations, this will be commercially possible after a few years. It is challenging to obtain a shade match between the two fibers so that in the end the fabric is uniformly dyed. To achieve a matching shade, the market must provide a sufficiently large amount of cotton dye range that matches the CO_2 polyester dye range.

3.2.2 Digital Spray Dyeing

This section sums up the results of the conducted interview with an expert in the field of textile processing and digital spray dyeing technology.

Expert 3

Expert 3 discussed the aim and principle of recently developed digital spray dyeing technology machines from Imogo Tech. The technology allows spraying the exact amount of dye required on the fabric surface. It is a digitalized technology since the operator adds the fabric weight and dyestuff pick up for the spraying process. This alternative technology allows pre-treatment, dyeing, and finishing. The interviewee shared the advantages and disadvantages of using spray dyeing technology DyeMax (***Table 4***).

As an expert on textile pre-treatment, dyeing, and finishing processing, the participant shared some insights on other alternative technologies. The expert acknowledged that $ScCO_2$ dyeing is a great waterless alternative, especially for large production volumes. Unless the machine is completely loaded, it is not economically viable. Moreover, the technology dyes only PET materials, which is a big drawback for the workwear textile industry. Also, the high investment is not comparable with the spray dyeing machine developing company. Furthermore, the $ScCO_2$ requires pure disperse dyestuff, a particular type of dyes. On the other hand, DyeMax can work with diverse pigments, algae ink[7], all types of dyestuff, and finishing chemicals. Expert 3 insight suggests that these challenges are the slowing down factor of new and sustainable technologies emerging on the market as major players. Therefore, her focus is on technologies that can be quickly implemented, while other sustainable technologies are still in development.

Table 4

Advantages and Disadvantages of spray dyeing technology DyeMax

Advantages	Disadvantages
• Great alternative for cellulose dyeing • Less wastewater is generated • Less water and dye consumption • No levelling agents • Salt-free process • Use of Caustic soda is less compared to jet dyeing • Fixation rate is higher leading to better colour fastness properties compared to exhaust dyeing • The low dyebath volume limits the chance of chemical reaction between the reactive dyes and water • Colour matching between lab dips and production is efficient due to MiniMax	• Batch dyeing process • Low volume of production at the moment • Polyester spray dyeing is still on lab-scale • The company needs investment to further optimize the process • The machinery needs improvement, especially for the loading of knitted fabrics

The expert shared her insights from experience with algae dyes. The company Imogo tech has collaborated with Mounid's algae ink in a research project. Firstly, they are a great replacement for synthetic dyes since they are naturally derived resources. Also, they work perfectly with spray dyeing technology. Expert 3 believes that the colorfastness performance needs to be improved to meet the technical requirements.

Another possible alternative coloration technology is dry processing, such as digital sublimation printing on the textile surface. However, the final appearance result is different than conventional dyeing technologies, which challenges designers to be convinced to opt for it. Also, $ScCO_2$ dyeing of polyester and undyed cotton creates a similar obstacle to convincing designers to shift towards this technology. From the interviewee's perspective, this is possible to achieve when starting a new product instead of improving an existing one.

The expert shared some insights on dope dyeing technology. This is the best resource-efficient process for large volumes of polyester fabrics. However, it is troublesome to make an early decision on color from stock. Moreover, it is best to use it in black or dark blue colors. While the light green color is not suitable for large volume production.

Lastly, the expert optimistically shared the benefits of plasma pre-treatment application since it improves the dye fixation. According to the specialist, the textile industry needs to stop thinking about the machinery cost investment. Instead, it should start thinking about the cost savings and payback time after incorporating such technology.

3.2.3 Plasma Technology

This section encapsulates the results of the conducted interview with an expert in the field of plasma technology.

Expert 4

[7] Algae ink – an ongoing development for non-toxic and biodegradable dyestuff/ coloring ink derived from natural resources of algae

Expert 4 discussed the basic principle of plasma technology, its opportunities and challenges when applied on textiles. During the discussion, it was noted that plasma is not applicable as a direct dyeing alternative technology. It was out of the interviewee's knowledge if plasma can be used to directly dye textile substrates.

The researcher reported that it is a suitable technique to modify the surface of the textile, so it can be beneficial for pre-treatment processes. Additionally, the expert enthusiastically shared that this technology can consequently increase the fastness properties of traditional dyeing and printing. In general, the interviewee describes plasma as an environment filled with many reactive species. For instance, when high temperature is increasing on certain matter, it will melt and then it will become in a gas state. The expert revealed that during the gas state the molecules are separate from each other but still intact. However, the more temperature is increased, the more molecules will separate from each other, and eventually the electrons will get out of the molecules. As a result, there will be many types of reactive species. Lightening and the sun are examples of this phenomenon. Additionally, scientists can initiate plasma by applying electrical fields. When plasma is applied on textile, the reactive species attack the surface and create chemical bonds and many reactive groups. Consequently, the plasma activates the surface of a fiber, but it cannot get into core of the fiber. In the end, the material's surface appears to be better because the plasma can get in-between and touch all fibers. The expert discussed the differences between the two main plasma systems – (vacuum) low-pressure and atmospheric (***Table 5***).

Table 5

Comparison of Vacuum vs. Atmospheric plasma systems

Vacuum (Low-pressure) systems	Atmospheric systems
• Batch process • Long preparation time processing (extensive pumping on the large vessel to remove the gas) • Difficulty to apply on natural fibres • High investment	• Continuous process • Avoids long preparation time processing • The process should be carefully controlled to avoid formation of lightening which can damage the fabric like burning hole. • High investment

According to the interviewee, the environmental benefit of using plasma is that it requires mainly electricity, which can be powered by renewable sources, such as wind or solar panels. The vacuum plasma does not require gases, but there is a small amount of Nitrogen released. In general, the gas used is very low. Hence, chemical consumption is lower since it requires the pure chemicals for finishes.

3.2.4 Dyeing with microorganisms (bacteria pigmentation)

This section summarizes the results of the conducted interviews with experts in the field of growing color-producing microorganisms and microbial pigmentation.

Expert 5

Expert 5 discussed the basic principle of using biotechnology, specifically growing microorganisms, and extracting color pigments for dyeing textiles. Regardless of the type of microorganism, it is essential to provide the necessary conditions to grow, such as food, air, optimum temperature, and aqueous solution. In some processes, the microorganisms are allowed to multiply up to a certain point or kept in a state that promotes reproduction. Lavrič explains that when the microorganism is grown in a medium, it is easy to remove the medium and extract the necessary pigment by using special isolation techniques, such as chromatography.

The participant enthusiastically discussed the Colorifix' process based on the available data. The expert indicates that the mentioned database contains information on the accessible sequenced genes of different microorganisms. Further, the researcher elaborated on the option to apply genetic engineering. For instance, through plasmid technology, certain DNA information can be packaged and placed in a carrier. Then, the participant explained that this package of information is transferred inside the microorganism. Next, an induction agent that triggers the microbe to start growing. The participant shared his expert bio-technological concerns and possible opportunities (***Table 6***).

Table 6

Bio--technological opportunities and concerns

OPPORTUNITIES	CONCERNS
• Natural properties can be preserved if the molecule, as in its functional form, is directly applied to the textile substrate. • The use of gene engineering can keep the balance of the process so that it is functional while it is made.	• It is essential to study carefully the sequence and number of steps that are involved to result in effectively produced pigments from microorganisms. • It is crucial to achieve nontoxic process to avoid killing the microorganism. • It is important to produce pigment that tolerates the essence of the microorganism. • It is possible to lose natural properties if the molecule gets accumulated inside the microorganism. • The process is based on trial-error method, which requires a lot of time and effort to develop a formula for one or similar species. • Difficulty to optimize the process for different species.

Note. Natural properties of the living organism may be preserved depending on the produced molecule throughout the process.

Expert 6

The interviewee shared insights on dyeing with living organisms based on her experience. The expert revealed that it is possible to dye all types of fibers by applying color-producing microorganisms. However, the process depends on pigments and their affinity with natural and synthetic fibers. The interviewee responded positively to implementing uniform dyeing with microorganisms on industrial scale. Furthermore, the participant disclosed Colorifix as an example to achieve uniformly dyed textiles on different fabric lengths. According to the interviewee's experience, microbial pigment fixation varies depending on the nature of pigment and fiber used. The researcher shared insight information that she experienced pigment fixation without the use of any chemicals or auxiliaries. However, she depicted that some pigments are fixed more efficiently by using chemical binders. Lloyd shared that binding fixation and colourfastness performance is still being studied. Additionally, the interviewee acknowledged that she did not perform color fastness testing. Thus, quality testing results were not possible to be shared from interviewee's side.

The interviewee was positive that this is a viable future replacement for the project, but it is currently in a Research & Development stage. Also, she felt optimistic regarding the opportunities of dyeing in light green and dark blue color. Unfortunately, the researcher did not seem confident that these shades are currently available on neither industrial nor small scale production. Thus, the interviewee participant expressed her expectations on synthetic engineering and its opportunities to eliminate these challenges in dyeing with microorganisms.

Expert 7

Expert 7 revealed that microbial pigmentation is possible on both natural and synthetic fibers. However, it was highlighted that natural fibers work better than synthetics, especially when aiming for rich coloration. Furthermore, the interviewee participant responded positively that dyeing uniformly textiles on an industrial scale is feasible. However, there are some challenges, such as the volume of chemical binders, budget, and high-level equipment costs. Besides, Post Carbon Lab is a small-scale company. The participant shared experience insights on the fixation principle. For instance, the nature of the textile substrates and pigments determines the level of chemicals, temperature, and pH adjustment.

According to the expert's experience, the colorfastness results differ depending on the nature of the textile, fiber, and pigment. Furthermore, the participant acknowledged that the current results are not as satisfying as the synthetic dyes. Therefore, these results were not shared. Based on the introduced information regarding the current samples, the interviewee optimistically revealed that it is possible to produce light green and dark blue. However, it was brought to light that the color is not as durable as synthetic dyes. Lastly, the interviewee argued that everything narrows down to the user's perception of whether re-dye or over-dye is an option. The interviewee's context of the problem is that convenience is still perceived as the central factor rather than a collective effort to tackle the climate crisis.

3.2.5 Using pigment powder derived from textile pre-consumer waste

This section sums up the results of the conducted interview with an expert in the field of transforming textile waste scraps into pigmented powder for textile coloration.

Expert 8

Officina 39+ is a chemical company that provides a selected range of chemicals and dyestuff for the textile industry. Officina 39+ patented a sustainable alternative technology that develops pigment powder from textile scraps. The interviewee shared insights on the recently developed sustainable product Recycrom, which is made from pre-consumer textile scraps collected from Italian and Bangladeshi companies. Recycrom is not a direct, reactive, vat dye class, but it is a total recycled product.

The process starts with collecting and sorting the textile scraps into different colours and shades. The interviewee highlighted that the powder pigment development process is not a colour extraction, but it is a physical process that transforms textile scraps into powder. Also, the interviewee explained that 1 kg of textile produces 1 kg of textile powder. Nevertheless, the participant shared some of Recycrom advantages and disadvantages (**Table 7**).

Table 7

Advantages & Disadvantage of recycling colour

Advantages	Disadvantages
• Recycled textile into pigment (circular economy) • Significant decrease of eco-footprint compared to conventional dye production	• Complex to efficiently obtain powder pigment from fabric consisting of >10% polyester content • Application on polyester is complex • Indicative colour card *(It changes over time since the collected raw material changes every time)*

• Possible to apply on cotton, Tencel, viscose, wool, linen, rayon, and polyamide.	• Similar or better colourfastness properties than pigment dyeing • Challenging to control the lightfastness properties (*Depends on raw material*)

3.2.6 Textile Supplier

This section summarizes the results of the conducted interview with textile manufacturing supplier KLOPMAN.

Expert 9 & Expert 10

KLOPMAN's employees discussed the current environmental challenges of textile production. Currently, the company is working on integrating sustainable practices to lower the environmental impact from textile production to the customer care lifecycle of a textile. However, the participants revealed that the production process still needs to reduce its CO_2 emissions, water usage, and energy usage. Expert 9 revealed the current hurdles and sustainable practices to improve the environmental footprint:

CO_2 footprint	Challenging to lower due to commercial & price hurdles
Oil usage	Challenging to lower due to commercial & price hurdles
Energy consumption	It is a more complex process to switch Asian plantations from coal and oil to renewable energy sources (compared to Europe)
Water consumption	Wastewater treatment, water recycling
Dye & Chemical usage	In workwear, the finishing and dyeing must withstand approximately 3 years of industrial washing, which involves higher temperatures, more mechanical action, and damage to the fabric. So, it is challenging to opt for alternative dyes that can meet the strict standards of the industry, while reducing the toxicity and environmental impact.

The interviewees shared some insights on plasma technology application based on previous project. The interviewee felt sceptical about the high investment to scale up and see the benefits. The project result did not justify the investment. Furthermore, plasma is seen as a niche sector because there are limited developments in big-scale production. Besides, this technology can be a future replacement if the environmental benefits are significantly greater, it ensures a cost reduction or at least a similar cost price, and durability. Currently, it is still more expensive, which is a considerable disadvantage because KLOPMAN cannot be competitive on the price level. Additionally, Expert 10 acknowledged that it is challenging to be a trendsetter because it is a risk to be above the market price level because it can eliminate you as a competitor. Expert 9 added that these technological innovations are attractive to the market, but it is difficult to find customers willing to pay for them. Thus, expert 9 constantly presents novel technologies and educates the market to raise awareness. expert 9 revealed that shifting customer's mentality takes a longer time than the company's willingness to shift towards sustainable practices.

The interviewees shared insights about $ScCO_2$ and dope dyeing. The participant stated that supercritical carbon dioxide dyeing has a great potential as a future replacement. However, the main challenge of implementing this technology is that KLOPMAN has a few 100% polyester fabrics and mostly blended textiles. If there is no solution to dye the plant fibre or a cotton/polyester content, KLOPMAN cannot consider $ScCO_2$ dyeing. Hence, expert 9 shared positive insights on dope dyeing since it offers high colourfastness performance while reducing environmental impact. However, like $ScCO_2$ dyeing, it is troublesome to find a solution for the cotton content since dope dyeing is applied to extruded man-made fibres. Also, expert 9 that it is questionable to implement dope dyeing due to the limited dye range, while KLOPMAN has 3500 active colour combinations. Every company has its unique representative corporate identity colour. Thus, it is difficult to generate such a colour range by dope dyeing. However, the participant felt optimistic about colours, such as black and navy blue.

The interviewees did not know about the microbial pigmentation and Colorifix dyeing method. However, the participants were excited about the feasibility and if it meets the requirements and durability standards. Lastly, the participants shared some insights on natural dyestuff. Expert 10 stated that the current challenge is to produce in big quantities, whereas expert 9 expressed that part of the problems is related to the limited colour range.

3.2.7 Workwear Supplier

This section reports the results of the conducted interview with workwear suppliers FRISTADS and HAVAEP.

Expert 11

Expert 11 discussed the dyeing technologies used in FRISTADS's green collection. The workwear company utilizes only one alternative sustainable technology - dope dyeing on polyester fibres, whereas the cotton part is undyed. The result is a melange effect while lowering water, energy, and chemical consumption. The utmost advantage of using dope dyeing is the significantly lower water and chemical consumption within the process. The expert explained that dope dyeing occurs during the spinning of the fibre, where colour pallets are added to the solution before extruding the filament through the spinneret. However, the most significant disadvantage is the limited amount of colour range. The interviewee discussed that every company desires its representative colour shade, which is not possible with dope dyeing.

The expert enthusiastically shared that the colourfastness properties performed better than conventional dyeing because the colour is inside the polyester yarn. The colour is durable, which is an important feature for workwear clothing. According to the workwear specialist, durability is the key to sustainability to ensure a longer lifetime. The interviewee elaborated that there are other sustainable colouration methods, but their colourfastness is not sufficient for this product range. Therefore, this is problematic because the dye resource could be presented as sustainable due to biodegradability, but the prolonging of the garment's life is reduced. Besides dope dyeing, the company utilizes conventional dyeing technology while complying with all OEKO TEX and REACH certifications. According to the interviewee, this is the best from the worst method to colour the garments that meet the customer's requirements. Since dope dyeing of polyester and undyed cotton results melange effect, the interviewee acknowledged that it is a major problem to convince the customer in implementing it due to the different design appearance. Based on his experience, workwear suppliers are ready to shift towards sustainable practices, but the customer is not yet eager to do so. The interviewee stated that strict technical requirements need to be reduced if a customer desires a sustainable dyeing process.

Expert 12

HAVAEP is a B2B workwear and protective wear supplier. The company's customers are diverse. Thus, the fabrics and colour range differ due to the variety of representative colours in each customer. According to the expert, protective wear that includes high visibility colours such as neon yellow and orange is challenging to produce in a sustainable way. The most significant environmental issues related to dyeing processing are the carbon dioxide footprint, water, and chemical consumption.

The interviewee explained that the textile colouration stage is still an area to explore the possibilities in achieving a more sustainable outcome. HAVEP's current state-of-art sustainable dyeing is utilizing Bluesign certifications and following the manufacturing restriction list (MRSL) and restricted substances list (RSL) regulations. The company's strategy is based on the sustainable development goals to ensure that its production is socially and environmentally responsible.

The interviewee shared insights on challenges to implementing alternative dyeing technologies. The most important feature of workwear is durability, including colour resistance. Therefore, it is a challenge to implementing sustainable dyeing technologies that can keep high-quality standards. Especially in workwear and protective wear, the quality level needs to guarantee that the colour does not fade away after at least a year lifetime. The workwear standard requires that a garment can be washed at a minimum of 60°C, preferably 75°C, at least 50 times.

The participant shared some insights on alternative dyeing technologies based on her experience. Expert 12 stated that most textiles used in workwear are blends of cotton and polyester due to their unique properties and performance. Although dope and $ScCO_2$ dyeing are applied only on synthetic polyester fibres, the interviewee expressed interest in the solutions provided by mixing undyed cotton and waterless dyed polyester resulting in a mélange effect on textiles. The ongoing and upcoming Dutch legislation regarding circular economy will increase the demand for sustainable production. According to the expert's experience, the current market is not ready for developing sustainable and circular workwear. However, the interviewee shared insight that in the coming years customers will be in such a position that they will not have the choice whether to make sustainable and circular workwear. Therefore, they will be obligated to look for the closest alternative. The 25 years of experience in fashion taught her that sometimes it is not about what the customer wants, but more about what you bring to the market. Expert 12 was aware of digital spray dyeing from the Fashion For good. However, uncertainty was expressed in terms of the colourfastness properties, especially if the garment is intensively used during workdays. For instance, she described that the users are often working with dirt, oil, and grease, and bending their knees. So, a series of doubts were expressed about whether this type of coloration technology can provide the quality level for end-user workers. Moreover, dyeing with naturally derived sources was described as irrelevant dyeing technology for workwear. Also, replacing synthetic dyes with powder pigments is similarly compared to natural dyes. These colouration methods would not meet the high colourfastness standards.

3.2.8 Corporate Fashion Workwear Supplier

This section reports the results from the interview conducted with a corporate fashion company Emergo Textile Projects (ETP).

Expert 13 & Expert 14

The participants expressed the current sustainable dyeing initiatives of ETP's production process. The company has adapted the MRSL and RSL as a tool to ensure that there is nontoxic chemical release during the production. However, expert 14 mentioned that they can inspect only the end-product accordingly to the RSL. On the other hand, the end-product cannot ensure what is used during the dyeing processing because some chemicals can be washed away. Thus, expert 13 implements a code of conduct that needs to be followed by all their suppliers. Unfortunately, the participants acknowledged that this is a challenge to regulate on daily basis. Nevertheless, their work of experience notably showed that suppliers from India and China have advanced in terms of water management system to close the loop.

The company is facing challenges in implementing alternative dyeing technologies. According to both participants, corporate wear is focused on long-lasting products. So, durability is a key feature regarding color resistance. Thus, most sustainable, and organic dyeing techniques are not feasible for their collections.

The interviewee shared insights of a possible approach based on their focus to minimize the environmental impact. For example, the current state of mechanical recycling is that clothing is collected, sorted in colors, recycled and then there is no need for redyeing. However, the company is still exploring this area and yet it has not implemented it for their customers. Another possible approach to lower water consumption is to focus on the end-user product care. For instance, CO_2 washing have much lower impact than home washing. Currently, the company is focusing on how to implement better product care options rather than improving their dyeing processes.

The interviewees shared some insights on dyeing with naturally derived sources. Currently, natural dyeing is not an alternative that corporate wear can opt for since it does not guarantee the necessary colorfastness standards. Regarding dyeing with microorganisms, the participants expressed positive interest in deriving pigments from bacteria because it is a better ecological resource saving technique compared to natural dyeing. However, they expressed negative concern on the available range of colors that can be produced by microorganisms. It is difficult to achieve the right color brightness or darkness that a customer requires for corporate representativeness.

Both participants expressed interest in the environmental impact savings caused by shifting from wet to dry dye processing. Thus, dope dyeing and $ScCO_2$ dyeing has a potential in replacing the dyeing of polyester content in their collections. Nevertheless, the mélange effect caused by mixing undyed cotton with dyed polyester will be suitable for customers like Consolidated. However, it is difficult to sell it to government organizations, such as the military police because the mélange effect will provide a casual look, which immediately creates less authoritative feeling. Thus, the expert 14 expressed interest in the possibility to combine dope dyeing for polyester and digital spray dyeing for cellulose material content to achieve uniformly dyed textile. Hence, expert 13shared insights that generally cellulose dyeing in dark shades have lower rubbing fastness, especially for black, red, and navy colors. Thus, it is best to proceed by mentioning that these specific garments should not be worn or washed together with light colors. Then, the staining can be prevented.

The corporate wear experts shared insights on replacing synthetic dyes with textile waste powder pigments. In general, this technology is suitable for fashion companies, especially for casual collections. Although, it is a nice story to make use of the textile pre-consumer waste and transform it into pigment powder, it is not suitable for corporate wear since pigment dyeing does not provide the necessary durability standards. Furthermore, the hurdle to achieve the accurate PANTONE color for the same item in a period of five to six years is not feasible.

Lastly, the participants shared insights on utilizing efficient and safe chemicals in the conventional dyeing process. Both responded positively on minimizing the production time because it will certainly reduce the electricity consumption. However, the interviewees doubted if this will positively reduce the overall environmental impact on water, chemical use, and CO_2 emissions.

3.3 Quality Research Results

This section summarizes the outcome of the conducted quality research regarding colourfastness to washing, rubbing, sweat and light exposure. The quality research results are listed in ***Table 8.*** Unfortunately, sustainable alternative to the current white fabric was not received and researched. See detailed information about each alternative in *Table 17*, Appendix 4.

Table 8

Quality Research Results (Alternatives) Overview

Materials	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**NB**	**Testing evaluation**
Dyeing	Spray	Spray	Spray	Spray	Spray	Spray	Dope	$ScCO_2$	Recycrom	Recycrom	Natural	
Supplier	Imogo tech	Imogo tech	Imogo tech	Imogo tech	Imogo tech	Imogo tech	e.dye fristads	Saxion	Officina+39	Officina+39	Ecological textiles	
Washing 60° ISO - 105-C06:2010	4-5	5	4	4-5	4-5	4-5	5	5	3-4	4	1	Colour change
Rubbing ISO 105-X12:2016	4-5 wet, 5 dry	3-4 wet, 4-5 dry	4-5 wet, 4-5 dry	3-4 wet, 4-5 dry	N/A	4 wet, 4 dry	4-5 wet, 4-5 dry	4 wet, 4-5 dry	N/A	4-5 wet, 5 dry	N/A	Colour change
	4-5 wet, 5 dry	1-2 wet, 4 dry	3-4 wet, 4-5 dry	1-2 wet, 3-4 dry	N/A	1-2 wet, 4 dry	4 wet, 4-5 dry	4 wet, 4-5 dry	N/A	2-3 wet, 5 dry	N/A	Staining Unbleached cotton
Perspiration ISO 105-E04:2013	4-5	4-5	4	5	N/A	5	5	5	N/A	4	N/A	Alkaline
	5	4-5	4-5	5	N/A	5	5	5	N/A	4	N/A	Acidic
Lightfastness ISO 105-B02	4	-	4	4	5	4	8	3	1	1	1	
Shirt requirements	**No**	**No**	**No**	**No**	N/A	**No**	**No**	**No**	N/A	**No**	**No**	
Trousers requirements	**No**	**No**	**No**	**No**	N/A	**No**	**Yes**	**No**	N/A	**No**	**No**	

Note. *Red letters show if results are not meeting the requirements.*

A1-A6 (spray dyed samples from imogo tech), A7 (dope dyed sample from FRISTADS), A8 ($ScCO_2$ dyed sample from Saxion Library), A9-A10 (Recycrom dyed samples from Officina+29), NB (naturally dyed sample from Ecological textiles)

3.3.1 Washing Fastness Results

In Table 18, washing fastness results are listed for all tested materials. ***Figure 14*** depicts the colour change in all tested materials. Primarily, wash fastness was tested on naturally dyed versus reactive dyed wool samples. It is vital to mention that the fabric supplier had a limited colour range of naturally dyed textiles. Moreover, sample NB did not meet the list of requirements. ***Figure 15*** illustrates the colour change comparison between natural and synthetic dyes. Overall, the NB sample's colour faded away entirely after the second performed washing test. Hence, colourfastness to sweat and rubbing was not executed due to limited textile material and unsatisfied results from washing. The washing test at 60°C proved that samples A1, A2, A3, A4, A5, A6, A7, and A8 meet the standards. However, third test was executed to test the washing fastness on conditions of industrial laundry, in which only A1, A2, A3 and A7 scored highly on both change colour and staining on other fibres. Powder pigmented samples A9 and A10 met the standards at 30°C, but the colour durability gradually decreased during 60°C and 90°C. On the other hand, A7 and A8 are the most outstanding performing samples in terms of colour change. However, A8 did not perform good on staining on other fibres (during industrial washing test 3), whereas sample A7 kept results of 4-5 to 5.

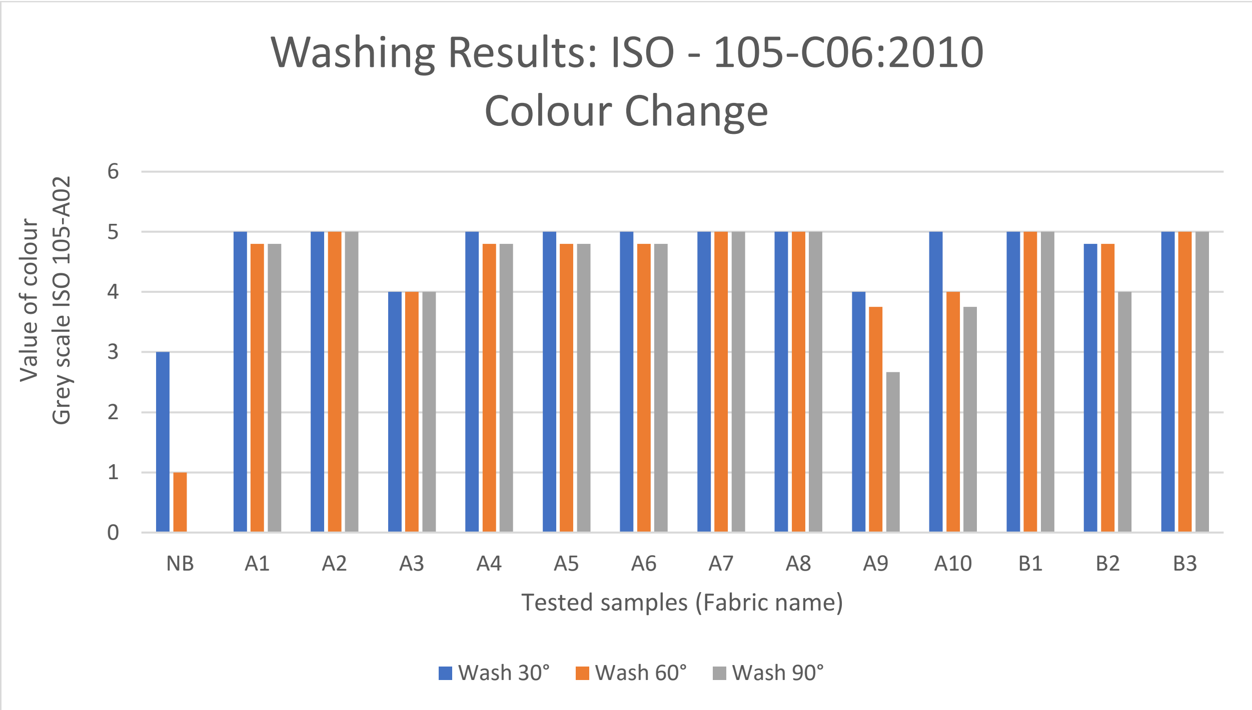


Figure 14 Washing Results: Colour Change

Note. Green line represents the standards requirements. B1, B2, and B3 are benchmark tested materials from the original products

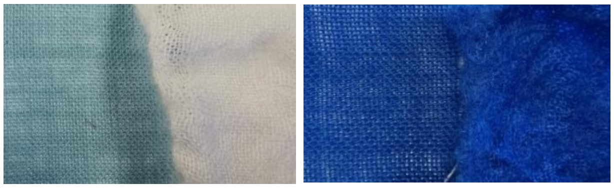


Figure 15 Colour Change: before and after washing test (Naturally dyed vs. Reactive dyed sample)

3.3.2 Rubbing Colourfastness Results

Table 19 & 20 represent the colour resistance against rubbing. ***Figure 16*** illustrates the colour staining level on unbleached cotton by rubbing the warp wet, warp dry, weft wet, and weft dry rubs. Whereas ***Figure 17*** shows the colour change on the fabric after rubbing. The quality research evaluated that benchmark sample B3 did not meet the wet rubbing colourfastness standards due to the depreciation at the of its lifetime. Samples A1 and A7 scored the best rubbing fastness results. However, only A1 met the rubbing standards of the shirt, whereas A7 and A8 is suitable for the trousers. On the other hand, A2, A3, A4, A6, and A10 did not meet the requirements. Unfortunately, it was not possible to execute a rubbing test on samples NB, A5, and A9 due to a fabric shortage.

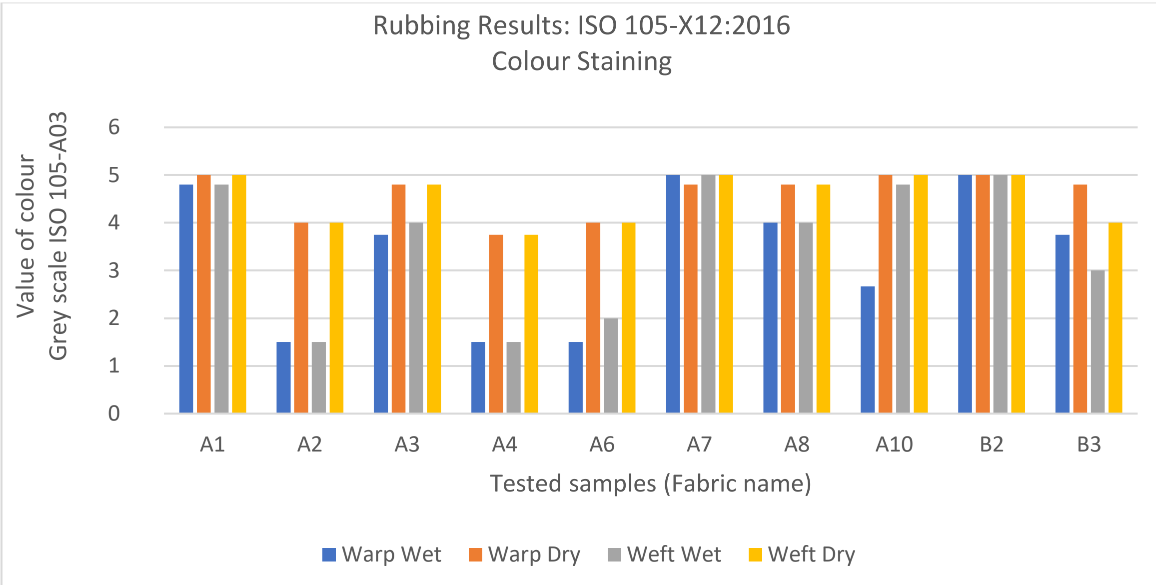


Figure 16 Rubbing Results: Colour staining on unbleached cotton

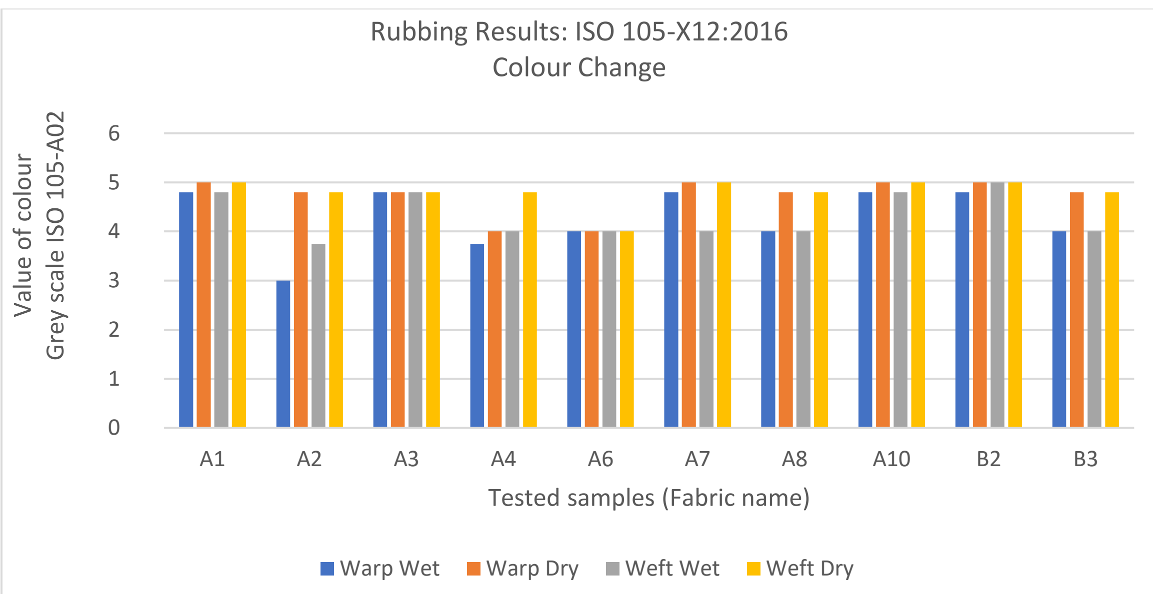


Figure 17 Rubbing results: Colour Change

Note. B2 and B3 are benchmark tested materials from the original products

3.3.3 Perspiration Colourfastness Results

Table 21 illustrates the results of colour resistance against human perspiration. Samples A1, A6, A7, and A8 met the requirements for Product A & B, whereas samples A1, A3, A4, A6, A7, A8, and A10 met the requirements for Product C. ***Figure 18*** illustrates the colour change results after sweat test. ***Figure 33*** *Dye transfer on multifibre* focus on the staining results.

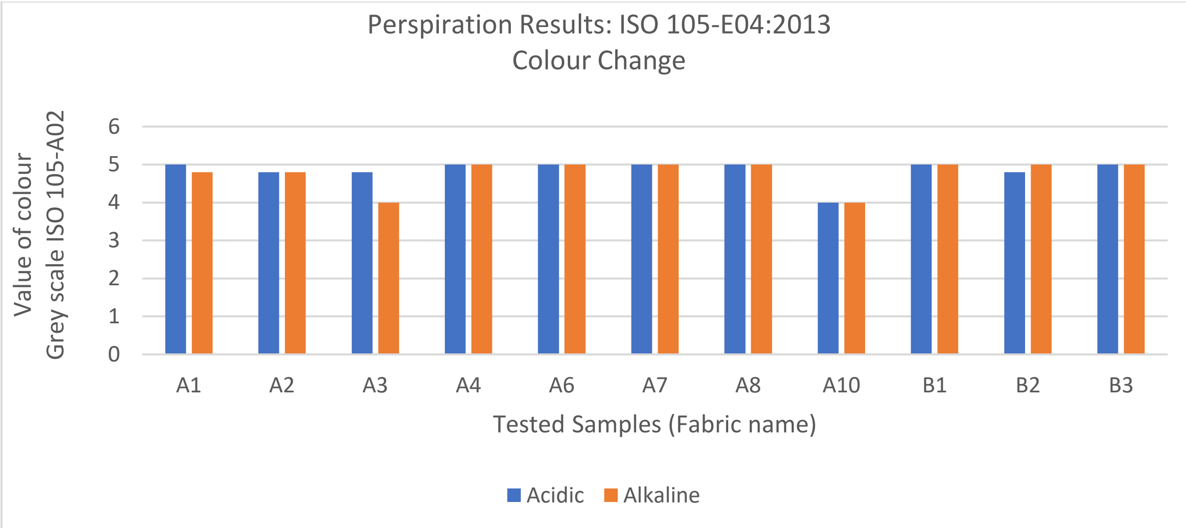


Figure 18 Colour change after Acidic and Alkaline Sweat test

Note. B1, B2, and B3 are benchmark tested materials from the original products

3.3.4 Lightfastness Results

Table 22 and Figure 34 depict the lightfastness results obtained by evaluation using the blue scale grading system (1-8). The higher the number, the better the colorfastness performance against light exposure. ***Figure 19*** illustrates how each tested alternative sample performed compared to the original benchmark samples (B1, B2, B3). Overall, sample A7 (spin dyed) has excellent colourfastness properties justified with a grade of 8. It did not change its colour for the tested period. It did not change its colour for the tested period. Thus, it will take more time before change is visible. On the other hand, the rest of the samples showed unsatisfactory results. The lightfastness requirements for the selected garments are - grade ≥ 5 (Product C) and grade ≥ 5-6 (Product A&B). Thus, only A7 and A5 meet the standard. Samples NB, A9, and A10 completely failed the test as their colour faded away after the light fastness test (grade 1).

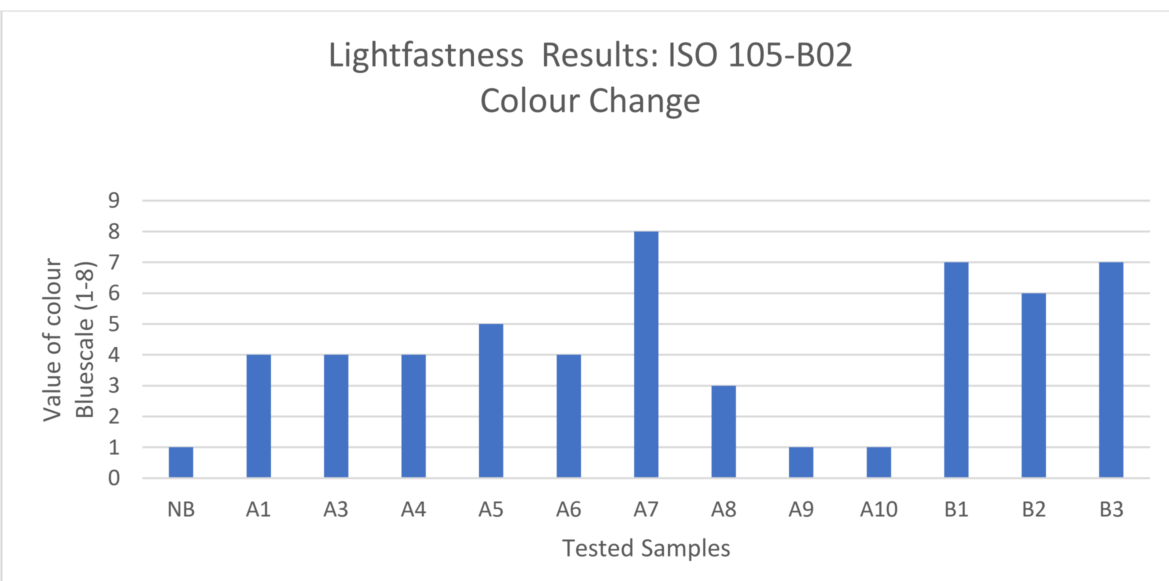


Figure 19 Lightfastness Results

3.4 Environmental Impact Assessment

The following section outlines the results from the life cycle analysis executed via the Modint Eco tool. Extended input data is in Appendix 5.

Primarily, the shirt and trousers' environmental impact was analysed. A detailed environmental comparison is seen in Appendix 5. In the trousers' environmental assessment, the colour is responsible for 21% of the total climate change impact and primary energy content. Meanwhile, the shirt's scorecard highlighted at 18% of the total kg CO_2-eq and energy produced. Fibre production processing is the biggest water user in shirts and trousers. Coloration takes the next largest share of water. A major portion of the total chemical consumption (29%) is from dyeing. ***Figure 20*** illustrates the environmental footprint caused during the colouration production chain step. It is evident that the most significant impact is driven by the water consumption. Secondly, the next highest scoring result is caused by energy usage. Additionally, dyeing has impact on climate change, but it is not as significant as the water and energy use.

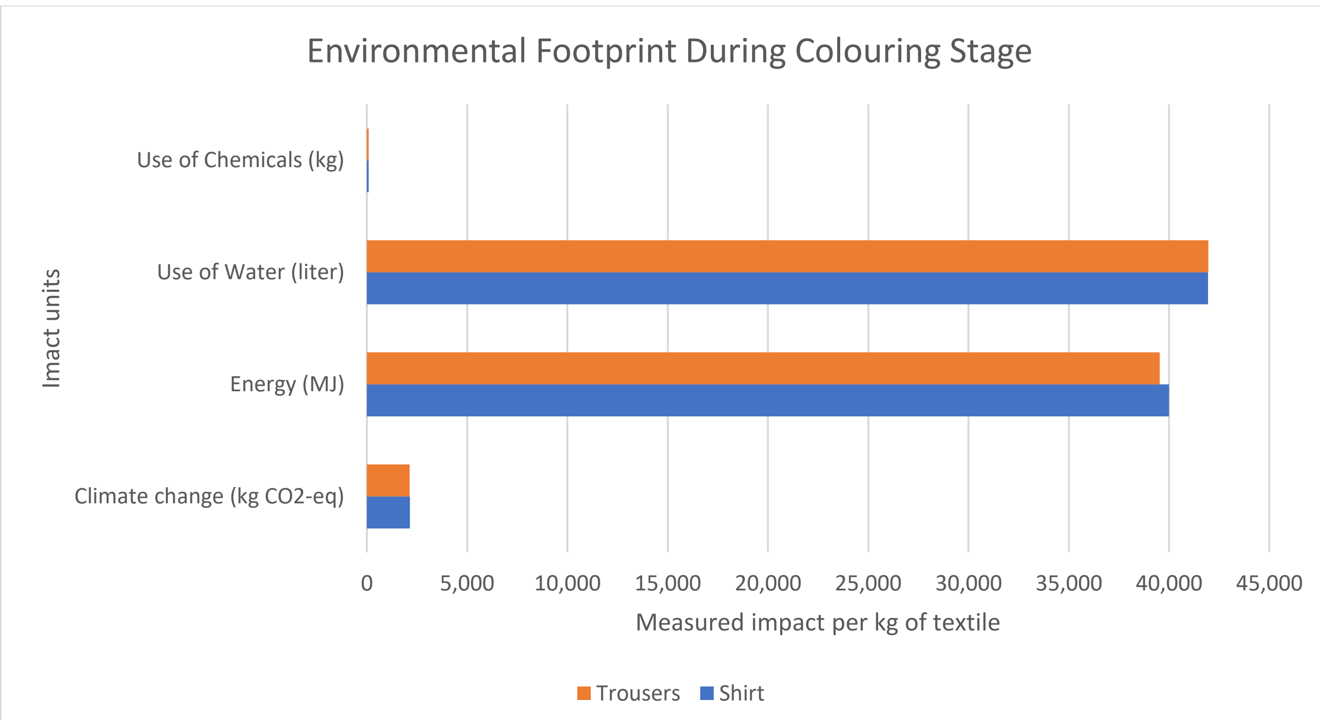


Figure 20 Dyeing environmental impact comparison (Shirt vs. Trousers), obtained from Modint Ecotool 3.0 scorecard results)

3.4.1 Alternatives for Kmar Trousers

Appendix 5 describes the input data for each alternative. The lifespan, fibre production, pre-treatment, finishing, assembly, and SUCAM home cleaning are kept same as the benchmark trousers. There are differences in the construction (dope dyeing) and colouration technologies (undyed, spray dyed). The quality research proofed that sample A7 meets the colourfastness requirements. However, A7 is producing a melange effect. Thus, a combination of dope dyeing and spray dyeing is examined, too. In ***Figure 21***, conventional, dope, and a mix of spray and dope dyeing are compared in total climate change, energy, water, and chemical consumption. Dope dyed PET and undyed cotton phase out the dyeing stage, which results in complete elimination of environmental impact. However, the extended environmental analysis shows that dope dyeing increases the chemical and energy consumption during the extrusion of the polyester

(*Appendix 5*). A combined technology application is used as an alternative for uniformly dyed textile. The water and energy usage are significantly decreased compared to benchmark.

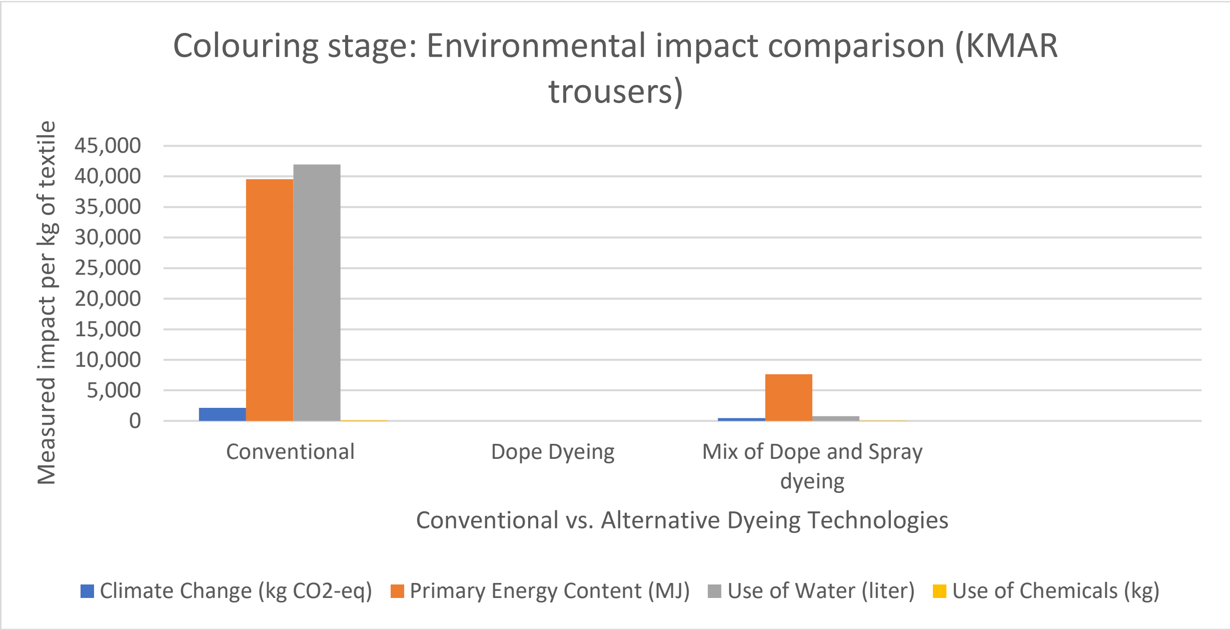


Figure 21 Environmental impact comparison Kmar conventional vs. alternative dyeing technologies (obtained from Modint Ecotool 3.0 scorecard results)

3.4.2 Alternatives for Light Green Shirt

The quality research proofed that sample A1 met the shirt's colourfastness requirements in terms of washing, rubbing, and perspiration. However, the lightfastness result (*grade 4*) scored below the necessary requirement (*grade 5-6*). Thus, none of the tested alternatives are suitable for replacing the colouration method of the shirt. However, environmental impact comparison between conventional and spray dyeing is given below (***Figure 22)***. Overall, the use of water, chemicals and energy is significantly decreased when applying this technology.

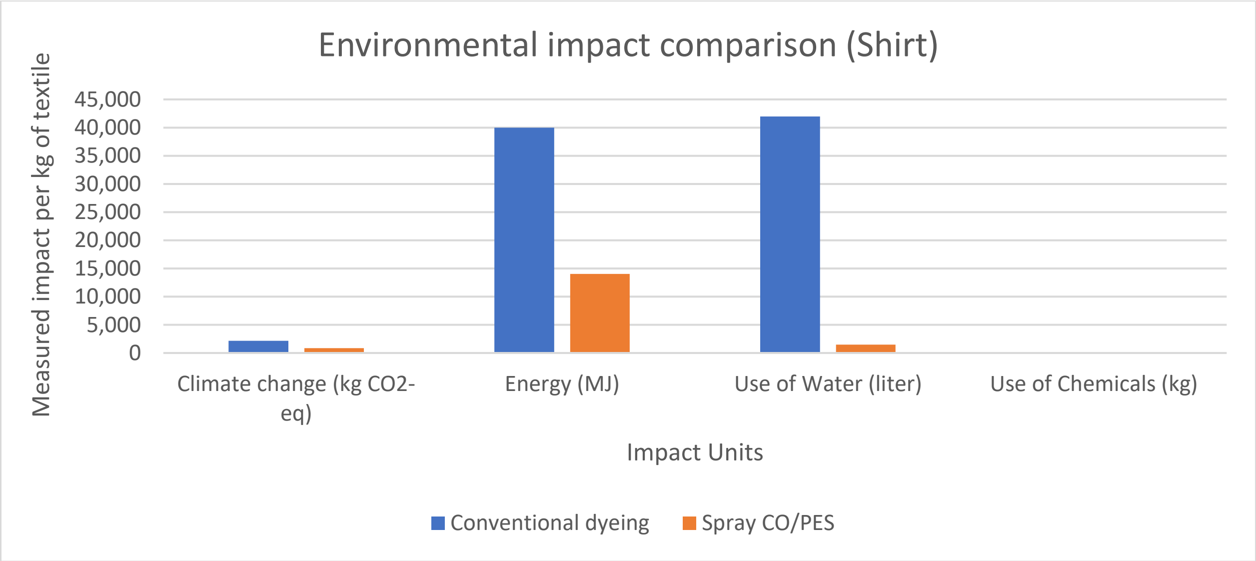


Figure 22 Environmental impact comparison benchmark shirt vs. alternative dyeing technologies (obtained from Modint Ecotool 3.0 scorecard results)

4 Conclusion and Discussion

The Dutch Ministry of Defense must consider transitioning towards more sustainable and responsible workwear production, especially after the introduction of the circular economy strategy by the Dutch government. This thesis aims to provide a future coloration technology replacement that may reduce or eliminate the environmental impact of selected non-operational workwear items, while meeting the colorfastness requirements.

The document analysis obtained the colorfastness standards and requirements for the selected garments. This information was essential for the quality research and analysis of alternative samples. However, the used technologies, chemicals, and dyestuff were not mentioned. Also, suppliers did not provide the necessary information. Consequently, assumptions were based on the available literature. In addition, MODINT Ecotool has databases for each step of the production chain, allowing it to estimate the environmental impact. In line with previous literature studies, major environmental footprint during dyeing can be attributed to water, chemicals, and energy consumption. The LCA findings found that coloration is responsible for 21% of the total CO_2-eq kg emissions, contributing to climate change. Lastly, the dyeing stage holds the largest share of chemical usage. The present expert interviews confirmed that dyeing's main environmental issues are related to water, chemical and CO_2 footprint. This is an important finding in the understanding of the problem and looking for alternatives that can improve the environmental footprint.

One out of four companies incorporated sustainable dyeing techniques to lower their environmental impact by dope dyeing. Most of the interviewed companies are still exploring this production chain step. The textile manufacturing company utilizes wastewater treatment and recycling. Whereas, the corporate fashion company is focused more on the product care footprint, such as replacing home laundry with CO_2 washing. The companies are using the RLS and Manufacturing Restricted List of Substances as a tool to avoid toxic chemical release. It is interesting to note that this is a fundamental requirement by the EU legislation system to ensure that the textile processing do not involve the banned hazardous chemicals or above the accepted concentrations. Thus, it is not a choice but a requirement from the government. Therefore, expert interviews were vital to get better understanding of novel technologies that can reduce or eliminate the environmental footprint during coloring. ***Figure 23*** illustrates the researched approaches that can contribute to more sustainable and responsible textile dyeing.

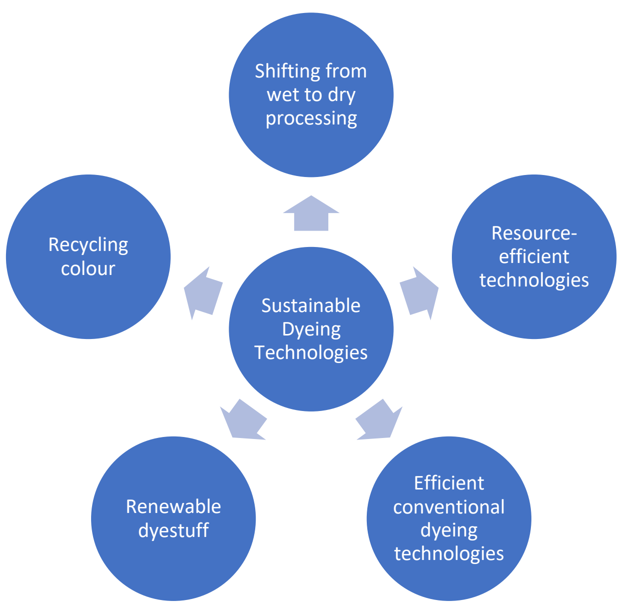


Figure 23 Overview of novel alternative and sustainable dyeing technologies

The interview and Ecotool findings support the theory that shifting from wet to dry processing decreases the total footprint. According to an expert 1 interview, the $ScCO_2$ dyeing has proven its system in its operational system. Based on the NASA's Technology Readiness Level (TRL), the technology is in a mature stage of level 9 (NASA, 2010). Furthermore, the findings confirmed the environmental benefits of $ScCO_2$ dyeing compared to conventional polyester processing. In addition to eliminating freshwater consumption and chemicals, dyes are also used more effectively. Also, the leftover CO_2 and pigments can be reused, which contributes to the circular economy. The washing test results showed that $ScCO_2$ dyed sample scores excellently on color change and durable. However, the lightfastness properties were below the given requirements. Although the textile supplier participants were enthusiastic about the technology, they expressed concern about the limited fiber applications. A popular choice of workwear fabric are CO/PET blends. There is a lack of chemical reaction between the $ScCO_2$ environment and natural fibers. However, expert 1 and 2 argued that fabric construction plays a crucial function in dyeing CO/PET blends, resulting mélange effect or jeans-like lighter shade inside the fabric. The altered appearance raises the question of whether it is possible to persuade the ministry to opt for it. Furthermore, corporate wear experts 13 & 14 revealed that the mélange effect is perceived as a casual look, which will lower the sense of authority and representativeness. Therefore, a possible way to achieve uniformly dyed blended textile is by double dyeing. However, conventional cotton dyeing requires a large volume of water, dyestuff, chemicals, and energy. Also, it will be a challenging since the current market cannot provide a sufficient amount of cotton colorant range matching $ScCO_2$'s pure chromophore disperse dyes. Thus, the system needs some technological improvement before applying it within the selected product range production since the CO/PET dyeing still in its embryonic stage (TRL 2 – *Concept of application formulated*). Furthermore, it will take time until a sufficient amount of cotton dye range is produced.

The study indicated that dope dyeing is one of the best resource-saving polyester dyeing processes. The technology itself is not new and it has proven its system in an operational system (TRL 9). However, it is not widely used due to price hurdles and color range limitations. The quality research found this technology meets the workwear colorfastness requirements. Nevertheless, the interviews support the theory that dope dyeing is limited in color range. There is a possibility that there is no color shade matching the corporate identity of the targeted ministry departments, which is a drawback for the alternative. FRISTADS' collection incorporated dope dyed polyester blended with undyed cotton, resulting in a mélange effect for workwear trousers. Again, the final appearance will influence the level of representativeness, as mentioned in the previous paragraph. However, the upcoming Dutch legislation will push workwear' customers with a limited choice of colouration. Then, they will be required to opt for the closest alternative to the original.

The findings affirmed that digital spray dyeing is a possible resource-efficient replacement, especially for coloration of natural fibers. Textile processing specialist confirmed that by explaining the benefits of their recent development. Currently, the system is complete and approved (TRL 8) and it is ready to be sold to textile manufacturers. To date, it is questionable whether the batch process will transition into large scale production sooner. Also, the spray batch process is applied only on cellulose fibers, while PET dyeing is still in the lab development stage (TRL 4). Nevertheless, a cold spray batch has environmental benefits compared to large-scale jet dyeing. In a jet, you have a nearly similar need for chemicals, energy, and water even if you run half the production, but in the DyeMax, you produce on demand. In contrast to black and navy-blue shades, the quality research proved that spray dyeing meets the standards for washing, rubbing and perspiration when applied on 100% cotton content with a light colorant shade. Generally, dark colors on cellulose materials do not perform excellently on wet rubbing. A possible explanation for this is the high absorbency rate and the low fixation rate during production. Another explanation is that dark shades absorb more light than lighter shades, resulting in poorer wet rubbing on unbleached cotton. A possible counter measurement is to ensure excellent pre-treatment, optimized dyeing and rinsing process as mentioned in the literature.

The interviews support the theory that plasma technology improves the dyeability of textiles. In general, plasma is not a new technology, and it has been approved system in a operational finishing system (TRL 8). Plasma pre-treatment can ensure efficient conventional dyeing, lowering the environmental impact and increasing the colourfastness properties. However, interview results found that plasma's high-cost investment and limited large scale operational systems are perceived as a major drawback. Although the invention is not recently developed, textile industry struggle to incorporate it due to commercial and price hurdles. Thus, it needs more time to be approved as a competitive manufacturing system (TRL 9). Nevertheless, the industry should stop thinking about investment costs. Instead, production costs, payback time, environmental and colourfastness benefits should be considered. The plasma expert 4 states that the system uses primarily electricity that can be generated from renewable resources and consumes fewer chemicals. However, the industry perspective depicted that it is more challenging to switch Asian facility energy resources compared to Europe.

The present interviews argued the hypothesis that renewable dyes are a possible replacement for workwear garments. All interviewed companies promote responsible consumption and sustainable production (SDG 12) through high-quality garments. The higher the quality, the higher the colourfastness and lifespan of a garment. Colour quality plays a critical role in the recognizability, uniformity, and representativeness of workwear. However, washing and wearing decrease it. Thus, the interview findings affirmed that colour durability is crucial for meeting the industry requirements and ensuring sustainability. Therefore, the findings confirmed that natural dyes are not suitable for workwear due to poor colourfastness performance. Interviewees confirmed that all-natural and organic dyeing techniques are not feasible for their collections since the colour is not durable for a long period of time Also, the quality research of natural versus reactive dyed wool fabric proved that natural dyeing is not suitable for the selected products. Firstly, the colour range is limited and challenging to replace the original. Secondly, the colour faded away completely after the second washing test at 60°C. These wash fastness results shows that natural dyes shorten the garment lifetime due to lowered colour quality. Besides, the literature review further explored the unsustainable practices of this method. It involves large land use, chemical fixation mordants, and tedious processing. Furthermore, KLOPMAN representatives stated that natural dyeing is not a possible alternative due to the challenge of large volume production and limited colour range. On the other hand, ETP's interviewees were interested in the microbiological coloration process since it does not require large land use as in natural dyeing. However, they were sceptical about the available colour range. Both bacterial pigmentation specialists confirmed that it is possible to apply to both synthetic and natural fibres. Also, it is viable to uniformly dye textile substrates on an industrial scale. However, Post Carbon Lab's representative highlighted that industrial scale should be carefully determined due to the volume of chemicals, binders, and high-level equipment cost. Moreover, the colourfastness results are not as satisfying as the synthetic dyes. According to the microbiology expert, the natural properties of the bacteria can be preserved only if the functional form of the molecule is directly applied to the textile. Both expert 6 and 7 noted that microbial fixation and colourfastness depend on the nature of the pigment, textile, and fibres. Furthermore, dyeing with microorganisms is still in the research and development stage. According to expert 6, colour shades are not available, but this challenge can be eliminated by implementing synthetic engineering in the future. Also, expert 5 suggested the use of gene engineering to keep the balance of the process so that bacteria's natural properties are preserved. However, it will take a lot of time to optimize the process, especially for different bacterial species. Industrial dyeing with microorganisms has been demonstrated in an operational working environment (TRL 7). Nevertheless, it still needs technological development to achieve completion and proof to be a feasible and competitive manufacturing replacement. According to expert 3, the algae have great potential as renewable dyes, but currently, they are not a possible alternative due to poor colourfastness properties. In line with previous studies, synthetic dyes are still the best option to choose regardless of the fossil fuels usage during their production.

Another possible way to phase out fossil fuels during dye production is to recycle textiles into powder pigment. Also, this approach can contribute to the circular economy. However, the interviews results found that Recycrom is not feasible for the ministry since it is challenging to dye textiles containing more than 30% of polyester. When blends are dyed with Recycrom, the outcome is a marble effect, which is again a questionable appearance look for the selected workwear. Also, the indicative color card changes over time due to different raw materials. In terms of corporate and workwear, it is crucial to deliver the same corporate identity color. Furthermore, the quality research found that these dyes do not meet the colorfastness requirements. A possible explanation for this is the fact that pigment powder has similar colorfastness properties to pigment dyeing. The interview findings revealed that pigment dyeing is not feasible dyeing option when it comes to workwear.

4.1 Limitations

Although expert interviews were a great source to obtain in-depth information, the process was time-consuming for the study. Online video meetings saved a lot of time in traveling. Nevertheless, there were connectivity issues, such as poor Internet connection. Also, sometimes microphone issues evolved. The face-to-face interview offered a higher level of engagement than video and email conversations. For example, some participants responded through email, resulting in short, concise answers. Unfortunately, the email interview prolongs the possibility of asking follow-up questions and clarifications.

A big limitation of this study is the shortage and lack of alternative testing materials for quality research. Therefore, the fabric shortage limited the quality research to only single testing. The lab tests are reliable based on ISO standards, but the reliability could have been enhanced with duplicate testing. Furthermore, microorganism dyeing and plasma novel technologies were not available for quality research due to limited market availability. Also, no reference samples matching the same original's or/and alternative's colour shade and fabric structure were found.

4.2 Conclusions

Primarily, it is essential to find solutions that can minimize the environmental footprint on the most concerning impact areas – (1) water consumption, (2) water effluent release, (3) energy consumption, (4) CO_2 footprint, (5) chemical usage. The most impactful areas are water and energy consumption. Secondly, the available alternative dyeing methods should meet the colour fastness standards found during the document analysis. By answering the sub-questions, a conclusion on the "*Which alternative dyeing technologies can improve the environmental impact of non-operational workwear?"* is given below.

Royal Netherlands Marechaussee - Kmar trousers

Environmental impact can be lowered by eliminating the dyeing phase through adding the pigment in the spinning solution. Dope dyeing offers excellent colourfastness properties which meet the list of colourfastness requirements of the selected trousers. Cotton can be left colourless to eliminate the amount of freshwater, chemicals, dyestuff, and generated wastewater. As a result, the environmental footprint of the trousers will be significantly reduced. However, the final appearance will lower the feeling of representativeness and authority due to melange effect produced. The ministry should consider whether the appeal meets their design standards. It is possible that the melange effect does not meet the design standards due to lowered sense of authority and representativeness. Therefore, the ministry can opt for a resource-efficient cotton dyeing, such as spray dyeing. However, the quality research found that the technology does not offer sufficient colourfastness against wet rubbing and lightfastness. Thus, it is required technological improvement to fulfil the ministry's list of requirements. Furthermore, it will be completely feasible when a large-scale production is reachable on the market. Unless the ministry is willing to request a production on demand.

Koninklijke Landmacht – Long sleeve shirts

None of the alternatives meet the colourfastness requirements of the selected shirt. Therefore, none of the suggested alternatives is feasible as a replacement at the moment.

In general, sample A1 (spray dyeing) met the colourfastness against washing, rubbing, and perspiration, but it was not sufficient in terms of lightfastness. It is a great alternative to decrease the total environmental impact. Also, it is a convenient technology since it be used for pre-treatment, dyeing, and finishing. Thus, it is possible for the pre-treatment and dyeing of the light green and white shirt. However, Imogo's polyester spray dyeing is still in a lab-scale development. Based on the NASA's Technology Readiness Level (TRL), the polyester spray dyeing still have some stages to prove the system is completed and qualified to meet the requested industry expectations and standards (NASA, 2010). Moreover, as mentioned earlier, spray dyeing needs technological improvement to be able to replace the conventional dyeing technology. Until the requirements are not met, the ministry cannot opt for it.

4.3 Recommendations

This report can be used as a starting point to consider various dyeing methods to replace conventional processing (See ***Figure 24***). As a result, the colouring production stage will have lower environmental impact. Due to the novelty of some dyeing technologies, it is still early to implement these alternatives immediately. Moreover, these alternative suggestions can increase the sustainability when circular materials are used.

The ministry can opt for dope dyed PET yarns made from recycled plastic bottles to limit the fossil fuel consumption. However, additional consideration of the melange effect on the representativeness and authoritative feel of the garments is necessary. Nevertheless, the mechanical properties should be tested to guarantee excellent quality.

The ministry can consider shifting from wet to dry processing by replacing water with supercritical carbon dioxide environment. However, additional research is necessary for the challenges and opportunities of CO/PET dyeing. On the other hand, the ministry can further consider the design appearance standards. It is possible to dye the blended fabric and produce a lighter inside shade similarly to jeans.

The government organization can consider implementing resource-efficient dyeing technology in the future. However, further research on the digital spray dyeing should be conducted. For example, Imogo tech's batch spray technology needs some improvement on wet rubbing and lightfastness performance. Also, PET dyeing is still in a lab scale. Thus, it is possible to look for other companies, in which CO/PET spray dyeing is developed, such as Alchemie Endeavour smart waterless solution.

More quality and LCA research should be done on plasma pre-treatment and resource-efficient conventional dyeing processing for the garments. Also, it is recommended to look for chemical companies and their development of safe, efficient, and enhanced dyestuff, auxiliaries, optical brighteners, and soaping agents. Furthermore, the ministry should consider suppliers who incorporate close-loop water management systems and resource-efficient dyeing technologies.

Figure 24 Recommended Colouration Guide

5 Reflection

At the beginning of this thesis, the goal was to provide sustainable alternatives for the wet processing of selected workwear. However, this production chain step covers a broad range of preparatory, colouring, and finishing treatments. Later, I narrowed down my research focus to colouration. The ex-master student Roos Anne Herder found out that the Ministry of Defence is already a front runner in implementing circular strategies for their textiles compared to workwear stakeholders. Thus, I wanted to contribute to the project by following up her research by listing advisory dyeing techniques that can lower the environmental footprint of the same garments. Colours are essential in the designing of corporate, workwear, and fashion collections.

Firstly, I was researching about the dyeing principle, environmental challenges and possible approaches that can be undertaken. I never thought this is a complex process challenging the workwear industry. By interviewing industry experts, I found out that workwear dyeing is still an exploration area for the majority. However, I saw a great opportunity to write this thesis aiming to help the ministry to be one step further on responsible consumption and production (SDG12). Currently, attention is given at the raw materials selection and product end-of life phase. However, these sustainable materials are still treated with the same harmful practises. Since the Ministry of Defence is a government organization, it should lead as an example to the workwear industry for their textile production. There are various approaches that can be applied as discussed in the thesis. Although there are many great sustainable initiatives, not all of them are suitable for the essence of workwear.

Primarily, it was difficult to select and find the most suitable sample for the interviews. Fortunately, I had backup from my company supervisor Anton Luiken who help me contact many experts in the field of $ScCO_2$ dyeing and plasma systems. Also, during my first internship I started building industry network which helped me to find corporate fashion and textile supplier perspective.

Unfortunately, the collection of all discussed alternatives was compromised due to unforeseen circumstances. Some companies did not send samples as requested. Since lockdown restrictions are lifted, many companies are busy with preparation for international fairs and exhibitions. Furthermore, some of the technologies were just launched, so some companies did not share extended insight data and available samples. Moreover, some companies did not respond to my request at all. On the other hand, plasma pre-treated and dyed fabric was challenging to find on the market. Thus, I recommended follow-up research for this matter.

In conclusion, I am grateful that I had the opportunity to analyse the complex problem of dyeing. Regardless of the mentioned difficulties throughout the research, I managed to list advisory dyeing technologies that can be incorporated in the non-operational workwear in the future (*competence 4*). Besides, I acquired new theoretical knowledge regarding colouration processing, emerging technologies and their opportunities and challenges (*competence 2*). I enjoyed my time in the lab where I tested the materials accordingly to the relevant standards (*competence 3*). At the end of thesis, I feel confident that I can offer my obtained knowledge regarding resource-efficient colouration methods when working in a company. I strongly believe that clothing should be designed in a responsible and sustainable way by implementing circular designs, sustainable materials and processing, such as pre-treatment, dyeing and finishing.

References

A. Haji, M. N. (2020). Cleaner dyeing of textiles using plasma treatment and natural dyes: A review. *Journal of Cleaner Production, 265*, 121866. doi:https://doi.org/10.1016/j.jclepro.2020.121866

A. Khatri, M. W. (2015). Sustainable dyeing technologies. In R. Blackburn, *Sustainable Apparel: Production, Processing and Recycling* (pp. 135-160). Woodhead Publishing Series in Textiles. doi:https://doi.org/10.1016/B978-1-78242-339-3.00005-4

Abou Elmaaty, T., & Abd El-Aziz, E. (2017). Supercritical carbon dioxide as a green media in textile dyeing: A review. *Textile Research Journal, 88*(10), 1184–1212. doi:10.1177/0040517517697639

Ado A., Y. H. (2015). Dyeing of textiles with eco-friendly natural dyes: A Review. *International Journal of Environmental Monitoring and Protection, 1*(5), 76-81. Retrieved from http://www.openscienceonline.com/journal/ijemp

Affat, S. S. (2021, 05 18). *Classifications, Advantages, Disadvantages, Toxicity Effects of Natural and Synthetic Dyes: A review*. Retrieved from University of Thi-Qar Journal of Science: https://www.jsci.utq.edu.iq/index.php/main/article/view/790

Alchemie Technology. (2022). *Endeavour Waterless textile Dyeing*. Retrieved from Alchemie technology: https://www.alchemietechnology.com/endeavour/

Alchemie Technology. (2022). *Our Technology*. Retrieved June 06, 2022, from Alchemie Technology: https://www.alchemietechnology.com/our-technologies/

Amenaghawon, A. N., Anyalewechia, C., Kusumab, H., & Mahfud, M. (2019). Applications of supercritical carbon dioxide in textile industry. In A. M. Asiri, & S. Kanchi, *Green Sustainable Process for Chemical and Environmental Engineering and Science* (pp. 330-343). Elsevier.

Apparel Resources . (2020, November 21). *Imogo develops Dye-Max spray dyeing technology*. Retrieved from Apparel Resources: https://apparelresources.com/technology-news/manufacturing-tech/imogo-develops-dye-max-spray-dyeing-technology/

Aquatech. (2020, February 13). *Nike races ahead to reduce water use*. Retrieved from Aquatech: https://www.aquatechtrade.com/news/industrial-water/nike-races-ahead-reduce-water-use/

Archroma. (2022, 03 21). *SWIFT WEAVE*. Retrieved from Archroma: https://www.archroma.com/systems/swift-weave

Bach, E. C. (2010). Past, present and future of supercritical fluid dyeing technology – an overview. *Review of Progress in Coloration and Related Topics, 32*(1), 88–102. doi:https://doi.org/10.1111/j.1478-4408.2002.tb00253.x

Barrie, L. (2018, 11 01). *Dyestuffs made from textile waste set to be scaled up*. Retrieved from Just Style: https://www.just-style.com/news/dyestuffs-made-from-textile-waste-set-to-be-scaled-up/

Bellini, P., Bonetti, F., Franzetti, E., Rosace, g., & Vago, S. (2002). *Finishing Reference Book for Textile Technology.* Milano: ACIMIT Foundation.

Bide, M. (2016). Using Synthetic Dyes Sustainably. In S. Muthu, *Roadmap to Sustainable Textiles and Clothing: Environmental and Social Aspects of Textiles and Clothing Supply Chain (Textile Science and Clothing Technology)* (p. 81). Hong Kong: Springer.

Broadbent, A. (2001). *Basic Principles of Textile Coloration.* Society of Dyers and Colourists.

Carp, B. (2020, 09 01). *Textile Chemicals: Sustainability and Transparency*. Retrieved from AATCC: https://aatcc.org/textile-chemicals-sustainability-and-transparency/

Chavan, R. (2011). Environmentally friendly dyes. In M. Clark, *Handbook of Textile and Industrial Dyeing: Principles, Processes and Types of Dyes* (pp. 515-561). Bahir Dar University, Ethiopia: Woodhead Publishing Series in Textiles. doi:https://doi.org/10.1533/9780857093974.2.515

Chequer, F. M. (2013). Textile Dyes: Dyeing Process and Environmental Impact. In M. Günay, *Eco-Friendly Textile Dyeing and Finishing* (p. Chapter 6). Intechopen. doi:10.5772/53659

Choudhury, A. K. (2017). Introduction to finishing. In A. K. Choudhury, *Principles of Textile Finishing* (pp. 1-19). Woodhead Publishing Series in Textiles. doi:https://doi.org/10.1016/B978-0-08-100646-7.00001-1

Circular Dutch economy by 2050. (2022). Retrieved from Government of Netherlands: https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050

Clark, M. (2016). *Handbook of Textile and Industrial Dyeing: Principles, Processes and Types of Dyes (Woodhead Publishing Series in Textiles).* Woodhead Publishing Series in Textiles.

CO2 Dyeing. (2019). Retrieved February 15, 2022, from Dyecoo: http://www.dyecoo.com/co2-dyeing/

Cohen, A., & Johnson, I. (2015). *J.J. Pizzuto's Fabric Science.* New York: Fairchild Books.

Defence, M. o. (2022). *Organisation*. Retrieved from Ministry of Defence: https://english.defensie.nl/organisation

ETP. (2022). *ETP Portfolio*. Retrieved from ETP: https://etp.nl/portfolio/abn-amro/

FashionForGood. (2022). *Textile Processing Guide: Pre-treatment, Colouration & Finishing.* Amsterdam: Fashion for Good.

Gan, L. X. (2020). Coloured powder from coloured textile waste for fabric printing application. *Cellulose, 28*(3), 1179-1189. doi:10.1007/s10570-020-03573-0

Goñi, M., Gañán, N., & Martini, R. (2021). Supercritical CO2-assisted dyeing and functionalization of polymeric materials: A review of recent advances (2015–2020). *Journal of CO2 Utilization, 54*, 101760. doi:10.1016/j.jcou.2021.101760

Gries, T., Veit, D., & Wulfhorst, B. (2015). *Textile Technology: An Introduction* (2nd Edition ed.). Munich: Hanser Publications.

Haji, A. H. (2021). The Effect of Plasma Treatment on Dyeing of Synthetic Fibers. *Innovative and Emerging Technologies for Textile Dyeing and Finishing*, 213–233. doi:10.1002/9781119710288.ch8

Hasanbeigi, A. &. (2015). A technical review of emerging technologies for energy and water efficiency and pollution reduction in the textile industry. *Journal of Cleaner Production, 95*, 30–44. doi:https://doi.org/10.1016/j.jclepro.2015.02.079

Helen Regan, CNN. (2020, September 29). *Asian rivers are turning black. And our colorful closets are to blame*. Retrieved from CNN: https://edition.cnn.com/style/article/dyeing-pollution-fashion-intl-hnk-dst-sept/index.html

Herder, R. A. (2021). *Replacing Virgin Textiles by State of Art.* Saxion University of Applied Sciences, Academy of Creative Technologies. Enschede: Saxion University of Applied Sciences.

Hurren, C. (2008). 9 - Dyeing and colouring tests for fabrics. *Fabric Testing*, 255-274. doi:https://doi.org/10.1533/9781845695064.255

imogotech. (2022). *Dye-Max*. Retrieved from imogotech: https://imogotech.com/products/dye-max.html

Jamaliniya, S. S. (2019). Using low temperature plasma for surface modification of polyester fabric: dyeing and printing improvement. *The Journal of The Textile Institute, 110*(5), 647–651. doi:https://doi.org/10.1080/00405000.2019.1569366

Jelil, R. A. (2015). A review of low-temperature plasma treatment of textile materials. *Journal of Materials Science, 50*(18), 5913-5943. doi:10.1007/s10853-015-9152-4

Kan, C. (2019). *A Novel Green Treatment for Textiles: Plasma Treatment as a Sustainable Technology.* CRC Press: Taylor & Francis Group. doi:ISBN 9780367262495

Kant, R. (2012). Textile dyeing industry an environmental hazard. *Natural Science, 04*(01), 22-26. doi:10.4236/ns.2012.41004

Ketema, A., Worku, A., & Pitsikalis, M. (2020). Review on Intermolecular Forces between Dyes Used for Polyester Dyeing and Polyester Fiber. *Journal of Chemistry*, 1-7. doi:10.1155/2020/6628404

Kiron, M. (2021, 09 24). *Reactive Dyes: Classification, Dyeing Mechanism, Application & Stripping*. Retrieved from Textile Learner: https://textilelearner.net/reactive-dyes-classification-dyeing-mechanism/

Kukka. (2021, November 05). *Living Colour - dyeing textiles with pigment producing bacteria*. Retrieved from Kukka: https://www.kukka.nl/en/portfolio/living-colour/

Kumbasar, A. (2011). *Natural Dyes.* Intechopen. doi:https://doi.org/10.5772/1817

Limhamn. (2019, May 02). *Dyeing/Finishing/Printing imogo's new Dye-Max at ITMA 2019*. Retrieved from innovation in textiles: https://www.innovationintextiles.com/imogos-new-dyemax-at-itma-2019/

M. V. Wennberg, Å. Ö. (2019). *Mistra Future Fashion Final Program: The Outlook Report .* Stockholm: Mistra Future Fashion. doi:978-91-89049-41-3

M. Vinotha, S. G. (2019). Bacterial pigments and their application in textile industries using mordants . *Journal of Advanced Scientific Research, 10*(3), 139-145.

M. Yusuf, M. S. (2022). *Emerging Technologies for Textile Coloration.* CRC Press. doi:9780367691110

Madhav, S., Ahamad, A., Singh, P., & Mishra, P. K. (2018). A review of textile industry:Wet processing, environmental impacts, and effluent treatment methods. *Environmental Quality Management, 27*(03), 31-41. doi:10.1002/tqem.21538

Mahapatra, N. (2018). *Textile Dyeing.* New Delhi: Woodhead Publishing India in Textiles. Retrieved from https://books.google.nl/books/about/Textile_Dyeing.html?id=JrR1wwEACAAJ&redir_esc=y

McKeen, L. W. (2016). Introduction to Plastics and Polymers. *Fatigue and Tribological Properties of Plastics and Elastomers*, 45-64. doi:https://doi.org/10.1016/B978-0-323-44201-5.00003-4

Mehdi, M. M. (2018). Preparation of colored recycled polyethylene terephthalate nanofibers from waste bottles: Physicochemical studies. *Advances in Polymer Technology, 37*(8), 2820-2827. doi:10.1002/adv.21954

Mendelson, D. (2017, 09 01). *Uniform Color Theory*. Retrieved from ASIS: Advancing Security Worldwide: https://www.asisonline.org/security-management-magazine/articles/2017/09/uniform-color-theory/

Muralidharan, B. &. (2011). A New Approach to Dyeing of 80 : 20 Polyester/Cotton Blended Fabric Using Disperse and Reactive Dyes. *ISRN Materials Science*. doi:https://doi.org/10.5402/2011/907493

Muthu, S. S. (2014). *Assessing the Environmental Impact of Textiles and the Clothing Supply Chain.* Woodhead Publishing.

Muthu, S. S. (2018). *Sustainable Innovations in Textile Chemistry and Dyes.* Hong Kong: Springer.

Muthu, S. S. (2021). *Sustainability in the Textile and Apparel Industries: Production Process Sustainability (Sustainable Textiles: Production, Processing, Manufacturing & Chemistry)* (1st ed. 2020 ed ed.). Switzerland: Springer.

NASA. (2010, August 20). *Technology Readiness Levels Demystified*. Retrieved from NASA: https://www.nasa.gov/sites/default/files/thumbnails/image/technology-readiness-level.gif

Naveed, M. (2018). Plasma Treatment as Green Technology for. *Trends in Textile Engineering & Fashion Technology, 2*(2). doi:10.31031/tteft.2018.02.000534

Niinimäki, K. S. (2017). Colours in a Circular Economy. *Circular Transitions Proceedings: A Mistra Future Fashion Conference on*, p. 8-19.

Nike. (2021, March 18). *Volume of freshwater use in textile dyeing and finishing by Nike from FY 2016 to FY 2020* (in liters per kilogram)*. Retrieved February 15, 2022, from Statista: https://www-statista-com.saxion.idm.oclc.org/statistics/861772/volume-of-freshwater-use-by-nike/

NUGENT, D. G., O.YARKONI, & AJIOKA, J. (2016). *UK Patent No. WO2016162657A1.* Retrieved from https://patents.google.com/patent/US11105041B2/en?assignee=Colorifix+Limited

Organisatie, D. M. (2016, 05 03). *MVO bij Defensie, Engelse versie*. Retrieved from YouTube: https://www.youtube.com/watch?v=1nhVKqTGBPo

Palacios-Mateo, C. v. (2021, January 06). Analysis of the polyester clothing value chain to identify key intervention points for sustainability. *Environmental Sciences Europe, 33*(1). doi:https://doi.org/10.1186/s12302-020-00447-x

Palich, T. (2021, November 09). *Research collaboration to reduce environmental impact of textile dyeing*. Retrieved from Deakin University: https://www.deakin.edu.au/about-deakin/news-and-media-releases/articles/research-collaboration-to-reduce-environmental-impact-of-textile-dyeing

Patnaik, A. P. (2019). *Fibres to Smart Textiles: Advances in Manufacturing, Technologies, and Applications* (1st ed ed.). Textile Institute Professional Publications: CRC Press.

Penthala, R. P. (2022). An ecofriendly dyeing of nylon and cotton fabrics in supercritical CO2 with novel tricyanopyrrolidone reactive disperse dye. *Journal of CO2 Utilization, 60*, 102004. doi:10.1016/j.jcou.2022.102004

Pereira, L., & Alves, M. (2012). Dyes—Environmental Impact and Remediation. In A. Malik, & E. Grohmann, *Environmental Protection Strategies for Sustainable Development* (pp. 111–162). Dordrecht: Springer. doi:https://doi.org/10.1007/978-94-007-1591-2_4

Periyasamy, A. P., & Militky, J. (2020). Sustainability in Textile Dyeing: Recent Developments. In S. S. Muthu, *Sustainable Textiles: Production, Processing, Manufacturing & Chemistry* (pp. 37-81). Hong Kong: Springer. doi:https://doi.org/10.1007/978-3-030-38545-3

Periyasamy, A. P., & Venkatesan, H. (2018). *Handbook of Ecomaterials.* Springer. doi:https://doi.org/10.1007/978-3-319-48281-1_55-1

Purpose, N. (2022, 03 07). *Nike Purpose: Water*. Retrieved from Nike Purpose: https://purpose.nike.com/water

Recycrom. (2022). *Tech Explained*. Retrieved February 15, 2022, from Recycrom: https://recycrom.com/tech-explained/

Ren, Y. G. (2017). Dyeing and functional properties of polyester fabric dyed with prodigiosins nanomicelles produced by microbial fermentation. *Journal of Cleaner Production, 148*, 375–385. doi:10.1016/j.jclepro.2017.01.168

Richards, P. (2015). Fabric Finishing: Dyeing and Colouring. In R. Sinclair, *Textile and Fashion: Materials, Design and Technology* (pp. 475-505). Cambridge: Woodhead Publishing Series in Textiles.

Rijksoverheid. (2018). *Towards Circular Textiles.* Categorieplan bedrijfskleding Rijk.

S. Maiti, A. P. (2022). Textile Coloration TEchnologies: Today and Tomorrow. In M. S. M. Yusuf, *Emerging Technologies for Textile Coloration* (pp. 1-10). CRC Press: Institute of Chemical Technology. doi:10.1201/9781003140467-1

S. Saxena, A. S. (2016). Natural Dyes: Sources, Chemistry, Application. In S. Muthu, *Roadmap to sustainable textiles and clothing* (pp. 37-81). Hong Kong: Springer.

Samanta, A. K. (2018). Fundamentals of Natural Dyeing of Textiles: Pros and Cons. *Current Trends in Fashion Technology & Textile Engineering, 2*(4). doi:https://doi.org/10.19080/ctftte.2018.02.555593

Saxena, S., Raja, A., & Arputharaj. (2016). Challenges in Sustainable Wet Processing of Textiles. *Textile Science and Clothing Technology*, 43-79. doi:10.1007/978-981-10-2185-5_2

Saxion. (2022). *Smart Industry*. Retrieved 02 07, 2022, from Saxion: https://www.saxion.edu/business-and-research/research/smart-industry

Saxion. (2022). *Sustainable & Functional Textiles*. Retrieved 02 07, 2022, from Saxion: https://www.saxion.edu/business-and-research/research/smart-industry/sustainable-functional-textiles/sustainable--functional-textiles

Shabbir, M. (2019). *Textiles and Clothing : Environmental Concerns and Solutions* (1 ed.). Wiley-Scrivener. doi:ISBN 9781119526315

Sihvonen, M. (1999). Trends in Food Science & Technology. *Advances in supercritical carbon dioxide technologies, 10*(6-7), 217 - 222. doi:10.1016/s0924-2244(99)00049-7

Sinclair, R. (2014). Environmental impact of dyeing. In R. Sinclair, *Textiles and Fashion: Materials, Design and Technology* (p. 496). Cambridge, UK: Woodhead Publishing Limited.

Sinclair, R. (2014). Strengths and weaknesses of natural and synthetic dyes . In *Textiles and Fashion: Materials, Science and Technology* (p. 494). Cambridge, UK: Woodhead Publishing.

SMARTEX Solution. (2019). *Environmental Product Declaration: In accordance with ISO 14025 for: Polyester fabrics (dope dyed and piece dyed versions).* Mölndal, Sweden: EPD International AB.

Tadesse, M. T. (2021). Airflow, Foam, and Supercritical Carbon Dioxide Dyeing Technologies. In A. H. L.J. Rather, *Innovative and Emerging Technologies for Textile Dyeing and Finishing* (Vol. 1, pp. 137-160). Bahir Dar, Ethiopia: Wiley-Scrivener.

TEDx Talks. (2019, 04 17). *Rethinking the way clothes are colored | Laura Luchtman & Ilfa Siebenhaar | TEDxRotterdam*. Retrieved from YouTube: https://www.youtube.com/watch?v=DXB3YtMWpoY

Textile Value Chain. (2020, November 19). *TMAS member Imogo develops new sustainable spray application technologies* . Retrieved from Textile Value Chain: https://textilevaluechain.in/news-insights/tmas-member-imogo-develops-new-sustainable-spray-application-technologies/

Today, T. (2018, 11 01). *Reforming all standards into one will help everybody to become more efficient and more sustainable*. Retrieved from Textile Today: https://www.textiletoday.com.bd/reforming-all-standards-into-one-will-help-everybody-to-become-more-efficient-and-more-sustainable/

Tušek, L. G. (2000). The Effect of Pressure and Temperature on Supercritical CO2 Dyeing of PET-Dyeing with Mixtures of Dyes. *International Journal of Polymeric Materials and Polymeric Biomaterials, 47*(4), 657–665. doi:https://doi.org/10.1080/00914030008031320

Uqaili, M. A., & Khanji Harijan. (2012). *Energy, Environment and Sustainable Development.* Wien: Springer.

Venil, C. K. (2013). Process Biochemistry. *Bacterial pigments and their applications, 48*(7), 1065-1079. doi:https://doi.org/10.1016/j.procbio.2013.06.006

Venkatesan, A. P. (2021). Environmental Friendly Textile Processing. In O. V.-M. Kharissova, *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications* (pp. 1522 - 1539). Springer. doi:https://doi.org/10.1007/978-3-319-68255-6_55

Wang, L., Li, Y., & He, W. (2017). The Energy Footprint of China's Textile Industry: Perspectives from Decoupling and Decomposition Analysis. *MDPI Energies, 10*(10), 1461. doi:10.3390/en10101461

Y. L. Pang, &. A. (2013). Current Status of Textile Industry Wastewater Management and Research Progress in Malaysia: A Review. *CLEAN - Soil, Air, Water, 41*(8), 751–764. doi:https://doi.org/10.1002/clen.201000318

Yaseen, D. A., & Scholz, M. (2019). Textile dye wastewater characteristics and constituents of synthetic. *International Journal of Environmental Science and Technology*, 1193 –1226.

Zheng, H. Z. (2016). An industrial scale multiple supercritical carbon dioxide apparatus and its eco-friendly dyeing production. *Journal of CO2 Utilization, 16*, 272-281. doi:10.1016/j.jcou.2016.08.002

Zille, A. (2020). Plasma technology in fashion and textiles. *Sustainable Technologies for Fashion and Textiles*, 117-142. doi:https://doi.org/10.1016/B978-0-08-102867-4.00006-2

Appendices

Appendix 1 – Literature Review (Tables & Figures)

The following section represents tables and figures mentioned in the literature review.

Dye Classes

Table 9

Dye Classes accordingly to which fibre the dye is applied adapted by (NC State University: Dyeing & Dyestuff)

	Dyes on FibrEs							
Natural	**Acid**	**Basic**	**Direct**	**Disperse**	**Azoic**	**Reactive**	**Sulfur**	**Vat**
Cotton			X		X	X	X	X
Flax			X		X	X	X	X
Ramie			X		X	X	X	X
Rayon	*		X		X	X	X	X
Silk	X					X		
Wool	X					X		
Synthetic	**Acid**	**Basic**	**Direct**	**Disperse**	**Azoic**	**Reactive**	**Sulfur**	**Vat**
Polyester		*		X				
Acrylic	X	X		X				
Nylon	X			X				
Acetate				X				
PP								
PU								

**Indicate that fiber modification is required*

Reactive Dyes Auxiliaries

Table 10

Reactive Dyes Auxiliaries and their purpose in cellulose dyeing adapted by (Kiron, 2021)

Auxiliary Types	Examples	Purpose of Application
Salts	NaCl, Sulphate ions	• To increase the dye affinity • To improve the hydrolysis rate • To neutralize fabric surface electronegativity • To increase absorption of dye
Alkali	Caustic soda NaOH (as strong alkali), Soda ash Na_2CO_3 (as medium), Sodium bicarbonate $NaHCO_3$ (as weak)	• To keep proper pH in the dye bath • It is used as a dye-fixing agent
Urea	CH_4N_2O	• To achieve the required colour shade. • Darker shades require more amount of Urea, whereas lighter shades require less.
Soaping agent		• The non-fixed dyestuff is eliminated. • As a result, washing fastness performance is improved. • It increases the brightness and the stability of the dye.

Disperse Dyes: Chemicals & Auxiliaries

Table 11

Disperse Dyes Chemicals & Auxiliaries (Chavan, 2011)

Auxiliary Types	Examples	Purpose of Application
Dispersants		• Used to disperse another substance in a medium (water) • Disperse dyes contain dispersants. Additional dispersants are added to the dyeing liquor and in the final washing step.
Carriers		• When polyester is dyed under high temperature up to 100°C, carriers are used. • Due to environmental issues, carriers can be eliminated by using pressure at temperature ≤100°C.
Thickeners	Polyacrylates or alginates	• Added to the padding process
Reducing agents	Sodium Hydrosulphite	• Reducing agents are used to eliminate unfixed dyes. • It is added to Alkali solution.

Colour fastness of dyed polyester fabric with prodigiosins nanomicelles produced by microbial fermentation

The researchers tested the colourfastness properties against rubbing, washing, perspiration and light of dyed polyester fabrics. The results are represented in Figure 25. Overall, the colourfastness show considerably good propeties in terms of rubbing, washing and sweat. However, it performs poor in terms of lightfastness (grade 1).

Rubbing fastness		Washing fastness			Perspiration fastness						Light fastness
					Acid			Alkali			
Dry	Wet	CC	SP	SC	CC	SP	SC	CC	SP	SC	
5	5	4–5	5	5	5	5	5	5	5	5	1

Color change (CC), Staining on polyester fabric (SP), Staining on cotton fabric (SC).

Figure 25 Colour fastness of dyed polyester fabric. (Ren et al., 2017b)

Dope Dyeing LCA study Results

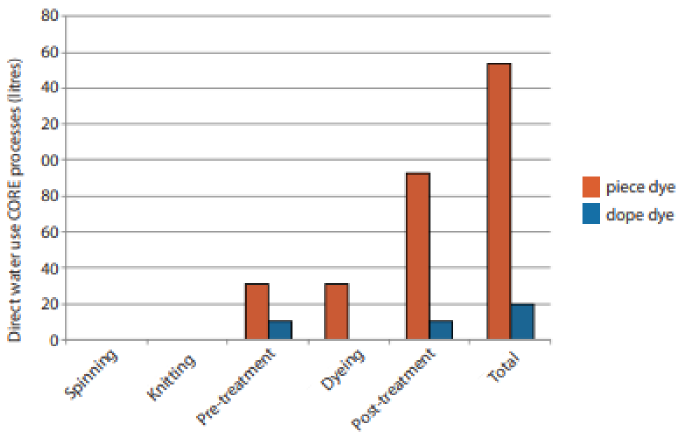


Figure 2. The water savings with the e.dye process (dope dye) compared to conventional dyeing (piece dye) for the core processes. Figures per kg of fabric.

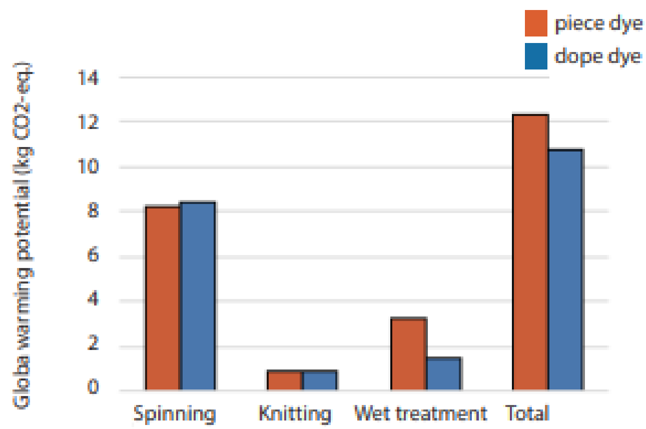


Figure 3. The global warming potential with the e.dye process (dope dye) compared to conventional dyeing (piece dye) for the core processes. Figures per kg of fabric.

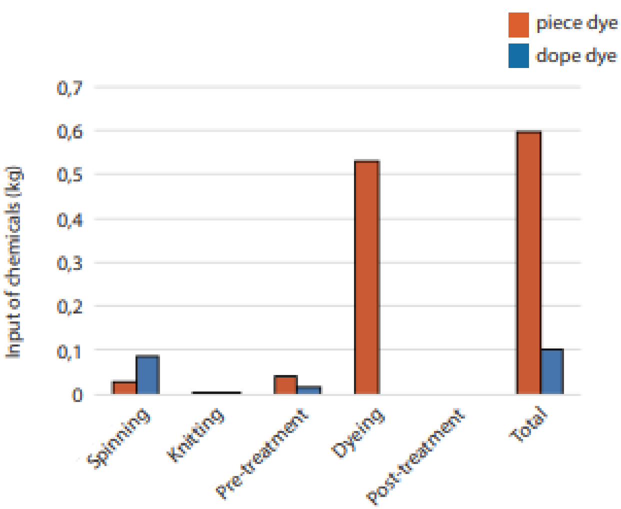


Figure 4. The amount of input chemicals for the e.dye process (dope dye) compared to conventional dyeing (piece dye) for the core processes. Figures per kg of fabric.

Figure 26 Dope Dyeing LCA study results (SMARTEX Solution, 2019)

Recycling Colour - Recycrom

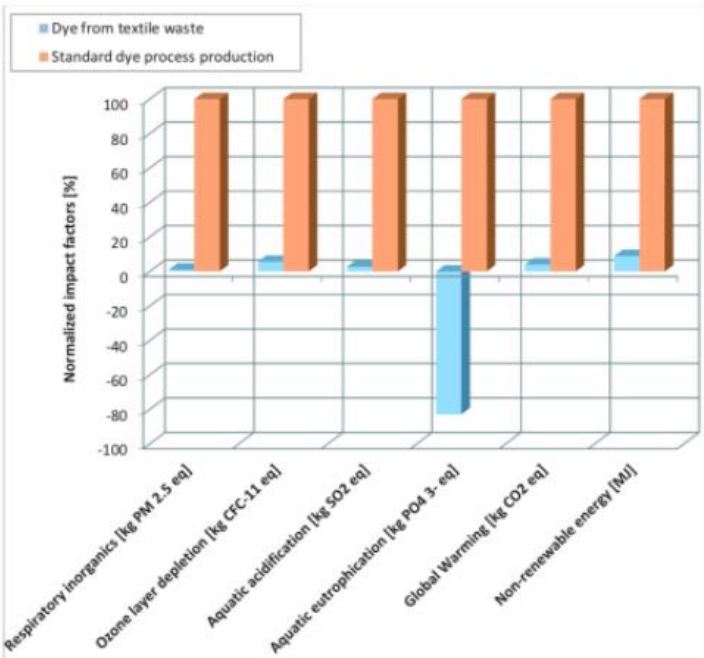


Fig. 4. Dyes production processes comparison

Figure 27 Recycrom LCA comparison (resource: TCP Engineering)

SWIFT Weave system Overview

Table 12

SWIFT Weave system: CO/PES efficient dyeing detail overview (Archroma, 2022)

Process application	Substance	Reason of efficiency
Polyester dyeing	Foron SP-WF	These disperse dyes are Alkali clearable. The unfixed dye is solubilized during the Alkaline post-bleaching step. In comparison to conventional disperse dyes, these dyes exhibit several advantageous properties, such as very good pH stability during the exhaust dyeing process, high stability to reduction, high sublimation fastness, and easy Alkali clearable.
Post-bleaching	Imerol Blue New	These agents are 'all-in-one' post bleach substances. It is free from Alkylphenol ethoxylates and phosphorous, and it is biodegradable. Further, it ensures a high degree of whiteness while preventing fibre damage. Additionally, the standard rinsing process after bleaching can be reduced or eliminated.
Cotton dyeing	Drimaren Ultimate HD	These reactive dyes provide deep shades while consuming less dyestuff and chemicals. These dyes have superior colour

		strength, excellent shade build-up, and high fixation level. Thus, it is required 31% less dyestuff to achieve the desired shade. Furthermore, this dye class guarantees reduction of salt usage by 30% and NaOH reduction by 38%.
Washing/Rinsing	Cyclon XCW Plus	This is a universal soaping agent, which is fast and efficient in removing hydrolysed dye. It achieves optimum fastness properties while using less water during rinsing.

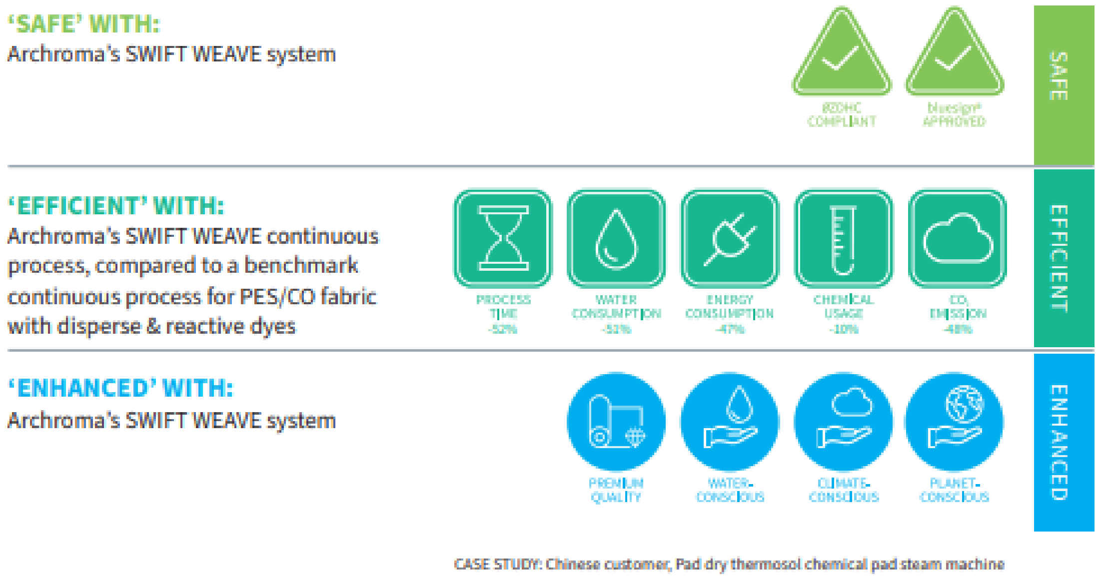


Figure 28 Swift Weave system benefits (Archroma, 2022)

Appendix 2 – Technical Requirements & Standards

List of Requirements

This section illustrates the list of requirements obtained by the conducted document analysis from *103744/06 and 105114/01*. Depending on the intended application of the final product, the textile needs to meet certain standards. In this study, colour fastness will be examined on conditions such as washing, perspiration and rubbing. The following *Table 7* represents the category of quality properties and technical standards obtained by the Categorie Bedrijfskleding Rijk. *Table 8* and *Table 9* illustrate the colourfastness requirements.

Table 13

Quality Research: Category and ISO standards (Translated from Dutch)

Category	**Tests**	**ISO standards**
Colour fastness	Part C06: Colour fastness to domestic and commercial laundering	NEN-EN-ISO 105-C06:2010
Colour fastness	Part E04: Colour fastness to sweat	NEN-EN-ISO 105-E04:2013
Colour fastness	Part X12: Colour fastness to rubbing	NEN-EN-ISO 105-X12:2016(E)
Colour fastness	Part B02: Colour fastness to artificial light: Xenon arc fading lamp test	NEN-EN-ISO 105-B02

Table 14

Colourfastness requirements of man's long-sleeve shirt uniform – Product A & B (Translated from Dutch)

Description	**Technical requirement**	**Document Test Method**	**Number/Place**
Colorfastness	Fastness against: Light: ≥ 5-6 Rub, dry: ≥ 5 Rubbing, wet: ≥ 4-5 Sweat: ≥ 4-5 Wash at 60 ºC: ≥ 4 Ironing and pressing: ≥ 4	NEN-EN-ISO 105: B02. x12. x12. E04. C06. x11	All parts of the man's shirt in white and light green

Table 15

Colourfastness requirements for OPS Kmar trousers – Product C (Translated from Dutch)

Description	Technical requirement	Document Test Method	Number/Place
Colorfastness	Lightfastness: ≥ 5. Fastness: water, wash 60°C, sweat, rub Dry, rub wet: ≥4.	ISO 105 A t/m Z	All materials part of trousers

Appendix 3 – Expert Interviews

The following section presents the purpose of each interview, transcript, and coded interviews.

Table 16

Interviewee participants: Sample explanation

Topic	Interviewee Sample selection
$ScCO_2$ Dyeing	To understand the state-of-art supercritical carbon dioxide dyeing, Expert 1 and Expert 2 were reached out for expert interview. The results are used to determine if $ScCO_2$ dyeing is a feasible alternative technology for the selected garments. In 2010, a Dutch company *DyeCoo* invented the commercial machinery for industrial scale textile dyeing with 98% uptake of pure dyes on 100% PES textiles (CO2 Dyeing, 2019).
Spray Dyeing	Expert 3, a textile processing expert at Imogo tech, was interviewed to get insights into digital spray dyeing. Further, the participant is a lecturer at the Textile School of Boras as an expert on processes for pre-treatment, dyeing and finishing of textiles. Thus, the interviewee shared insights into resource efficient dyeing technologies. The results were used to determine the role of digital spray dyeing as a resource-efficient dyeing alternative technology. Additionally, the company Alchemie Technologies was reached out to discuss Endeavour waterless smart dye technology. Unfortunately, the company did not proceed with an interview.
Plasma technology	Expert 4, a researcher at TNO, is interviewed to gain a better understanding of plasma technology. The interview results are used to determine the opportunities and challenges of implementing plasma before conventional dyeing. The researcher was involved in a study investigating the plasma effect on the adhesion of coatings to high-tech textiles (Šlmor et al., 2010).
Microbial pigmentation	To understand the state-of-art of microbial pigmentation's possibilities, several experts in bacteria and microorganism processing were interviewed. - Expert 5: A researcher at Research Group Ambient Intelligence, lecturer and microbiologist was interviewed to obtain insight information on growing colour-producing microorganisms and colour extraction principle. Lavrič obtained his bachelor's degree in Microbiology at the University of Ljubljana and did his thesis on genetics. - Expert 6: London-based textile-driven researcher and creative resident of Colorifix was approached to gain more insight into the state-of-art in dyeing with microorganisms. Ruth Lloyd's work explores sustainable, circular, and regenerative colour systems. Lloyd conducted practise-based research on the potential of microbial pigmentation as part of her master's thesis at the Royal College Art. - Expert 7: A transdisciplinary design research studio was approached for further information regarding bacterial pigmentation. In their research, Post Carbon Lab has developed zero-waste bacterial-based dyes that function by harnessing photosynthesis to eliminated CO2 emissions (Prendergast, 2021). Lastly, Colorifix was reached out to obtain more qualitative data on colour performance and dyeing technology. However, the company did not proceed with an interview.
Recycrom	Expert 8 was interviewed to get in-depth insights on the patented technology to derive pigment from pre-consumer textile scraps. Recycrom

	is the most recent sustainable development of the chemical, dyes and auxiliaries supplier Officina 39+.
Textile supplier	Expert 9&10: The chosen company, KLOPMAN, is well-known for the high-quality products supplying on the market of workwear fabrics, including corporate workwear. Furthermore, the company is committed to the Sustainable Development Goals to improve their environmental and social impact. The supplier was interviewed to obtain in-depth insight information regarding the current environmental challenges of conventional dyeing in their production, as well as the opportunities and challenges to opt for alternative dyeing solutions.
Workwear	Workwear suppliers were interviewed to obtain detailed information regarding their current environmental challenges facing during the dyeing stage of their production and state-of-art sustainable dyeing methods within their collection lines. Also, the workwear companies explored their opportunities and challenges to opt for the listed alternative technologies. - Expert 11: FRISTADS is a one of the interviewee participants chosen due to their green collection, in which some of the articles are dope dyed. - Expert 12: HAVEP is the second interviewee participant chosen due to their promise to obtain 95% circularity by 2025.
Corporate wear	Expert 13 & 14: An interview with a corporate fashion company ETP was conducted to obtain insight information their current environmental challenges facing during the dyeing stage of their production and state-of-art sustainable dyeing methods within their collection lines. Also, the corporate wear company explored its opportunities and challenges to opt for the listed alternative technologies. In 2021, the company released a 100% circular collection for ABN AMRO (ETP, 2022).

Interview Transcript & Coding attachments are located in the separate Appendix file.

Appendix 4 – Quality Research

A List of Tested Materials

Table 17 Tested Materials Overview

Sample Code	Tested material	Dyeing method	Dyed class	Composition	Construction	Supplier
B1	Benchmark Product A	Conventional	White, OBA	60% CO / 40% PES	Plain 2-ply	Ministry of Defence
B2	Benchmark Product B	Conventional	Light Green, missing	60% CO / 40% PES	Plain 2-ply	Ministry of Defence
B3	Benchmark Product C	Conventional	Dark Blue, missing	50% CO / 48% PES / 2% EL	Twill 2/2 Z	Ministry of Defence
NB	Natural Indigo Blue	Natural Dyeing	Pale Blue, Natural indigo	100% Wool	Fine plain	Ecological Textiles
RB	Reactive Blue	Conventional	Blue, Reactive	100% Wool	Fine plain	Ecological Textiles
A1	Digital Spray dyed 1	Spray batch 18h	Yellow, Reactive	100% Cotton	Panama	Imogo Tech
A2	Digital Spray dyed 2	Spray batch 18h	Black, Reactive	100% Cotton	Panama	Imogo Tech
A3	Digital Spray dyed 3	Spray batch 18h	Grey, Reactive	100% Tencel	Twill	Imogo Tech
A4	Digital Spray dyed 4	Spray batch 18h	Black, Reactive	97%CO / 3% EL	Twill	Imogo Tech
A5	Digital Spray dyed 5	Jet + DWR vax type finish	Grey, Disperse	100% PES	Velvet	Imogo Tech Lab scale
A6	Digital Spray dyed 6	Spray batch 18h	Navy Blue, Reactive	58% TEN / 39% CO / 3% EL	Twill	Imogo Tech
A7	Spun dyed	e.dye solution dyeing + undyed	Melange effect, e.dye polyester, undyed cotton	CO/PES blend	Twill	FRISTADS
A8	sCO2 dyeing	CO2 dyeing	Dark blue, disperse pure	100% PES	Knit	DyeCoo
A9	Recycrom 1	Textile waste pigment dyeing	Recycrom Orange	100% Cotton	Twill	Officina +39
A10	Recycrom 2	Textile waste pigment dyeing	Eco marble	CO/PES blend	Twill	Officina +39

Note. Images of the tested materials can be seen in the separate Appendix file

Quality Testing Methods

This following section describes the methods applied during the quality research.

Colourfastness to washing

The test is performed according to the NEN – EN - ISO - 105-C06:2010 (E) standard. The objective is to determine the degree of washing influence on the color of a textile and staining on other materials.

Procedure

Tested samples (*10 cm x 4 cm*) were attached to a multifiber adjacent fabric, complying with ISO 105-F10. The multifibre fabric contains acetate, cotton, nylon, polyester, acrylic, and wool fibers. Then, each sample was placed in a stainless-steel container. Later, the steel container was filled with 1:50 material to liquid ratio and 5 g per 1 litre of the detergent solution. The detergent solution complies to the Dye Transfer Test Detergent ISO C-06 with Phosphate. Further, 10 non-corrodible (stainless) steel balls (6mm diameter) were added to each steel container. The containers were inserted into the suitable mechanical device Mathis Labomat. The machine rotates the steel containers at a constant temperature at approximately 40 revolutions per minute. Initially, the test was performed for 45 min at 40°C temperature. Then, second washing test was performed for 45 min at 60°C temperature. Lastly, the test was performed for 45 min at 90°C temperature. The objective is to find out how the colour changes gradually with increasing the temperature. Also, it is crucial to study the colour durability. In the end, colour change and staining are graded by using the greyscale for accessing under Day Light. ***Figure 29*** illustrates the greyscale used for evaluating the degree of colour change (ISO 105-A02) and staining (ISO 105-A03). The higher the number, the greater the colourfastness result.

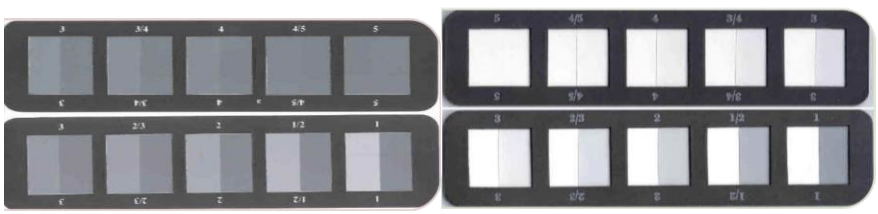


Figure 29 (1) Greyscale for colour change (ISO 105-A02); (2) Greyscale for colour staining (ISO 105-A03)

The test is performed accordingly to the NEN – EN - ISO 105 - X12:2016 standard. The aim of this test is to determine the resistance of the color to rubbing off and staining on other materials. The tested samples are the only materials that met the Dutch Ministry of Defense's technical requirements from previous test.

Procedure

Test samples are cut in both warp and weft direction with the size of 22 cm x 8 cm. A special machine called Crockmeter is used to apply rubbing onto textile surface. The machine has a finger that needs to rub in a straight line of 10 cm at pressure of 9N. The fabric that must be tested is used in the warp and weft direction. Furthermore, the test is performed by using both dry and wet pieces of unbleached cotton by rubbing it against the textile surface. The rubbing fastness cloth is 5 cm x 5 cm, desized, bleached, and without finishes. The cloth is moisturized by using demineralized water (distilled water). Finally, the color change and staining are evaluated by using greyscale for accessing. The tested samples are attached to the crockmeter's main surface in such a way that it cannot move. Firstly, one warp and one weft sample are tested with dry rubbing. Secondly, the rest samples are tested with wet rubbing. The wet cotton piece of cloth is moisturized at approximately 100%. The test was performed at 10 rubs at 10 seconds. Wet samples are air dried at room temperature. Unfortunately, it was not possible to do double testing for reliability due to limited fabric. Colour change and staining are accessed by using the grey scale under Day Light.

Colorfastness to perspiration

The test is performed accordingly to the NEN - EN – ISO - E04:2013 standard. The objective of this test is to determine the colour resistance of textiles to all types of human perspiration.

Procedure

Two test samples with the dimensions of 4 cm x 10 cm are attached to a multifiber adjacent fabric complying with ISO 105-F10. Furthermore, two sweat solutions are freshly prepared – alkaline and acidic sweat. The alkaline solution is made using grade 3 water, 0,5 grams per liter of L-histidine monohydrochloride monohydrate ($C6H9O2N3 \cdot HCl \cdot H2O$), 5 grams per liter of sodium chloride (NaCl), and 2,5 grams per liter of disodium hydrogen orthophosphate dodecahydrate ($Na2HPO4 \cdot 12H2O$). The acidic solution is made with grade 3 water, 0,5 grams per liter of L-histidine monohydrochloride monohydrate ($C6H9O2N3 \cdot HCl \cdot H2O$), 5 grams per liter of sodium chloride (NaCl), and 2,5 grams per liter of monosodium phosphate ($Na2HPO4 \cdot 12H2O$). The test specimens are placed in a cup filled with 1:50 ml of sweat solution. Thus, 50 ml of 1sweat solution for every gram of the test sample. The test samples are left in a room temperature for 30 minutes. Then, the samples are placed between two Perspex acrylic plates in the perspirometer with a pressure of 5kg weight on it (***Figure 30***). The perspirometer device is placed in an oven at 37°C for 4 hours. Later, the test specimens are open dry at 60°C in the oven. After drying, the colour change and staining was evaluated by using the grey scale under day light.

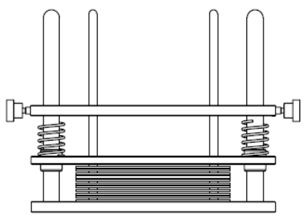


Figure 30 Sweat testing device

Colorfastness to artificial light

The test is performed accordingly to the NEN - EN – ISO – B02:2014 standard. The objective of this test is to determine the impact of light on the colour of the dyed fabric.

Procedure

Test samples with dimensions of 1 cm x 4 cm are illuminated in a Xenon light tester for 300 hours. The light exposure in the Xenon light tester for three weeks evaluates the colour change which happens for approximately of five years in the Netherlands sun light exposure.

Detecting Optical Brightening Agents

Placing the Product A’s fabric under an UV light source, can easily detect whether the fabric contains Optical Brightening Agent (Hurren, 2008). Thus, the B1 sample was placed under UV light source to detect whether OBA is used for whitening.

Quality Research Results

Natural vs. Reactive dyes

Figure 30 visualizes the significant difference of colorfastness performance between naturally and synthetically dyed wool. NB lost completely the color derived from natural indigo immediately after the 60° degree washing test, whereas the RB slightly changed the blue shade. ***Figure 31*** represents the evaluated color change results from the two tests performed on both Natural Blue (NB) and Reactive Blue (RB) samples.

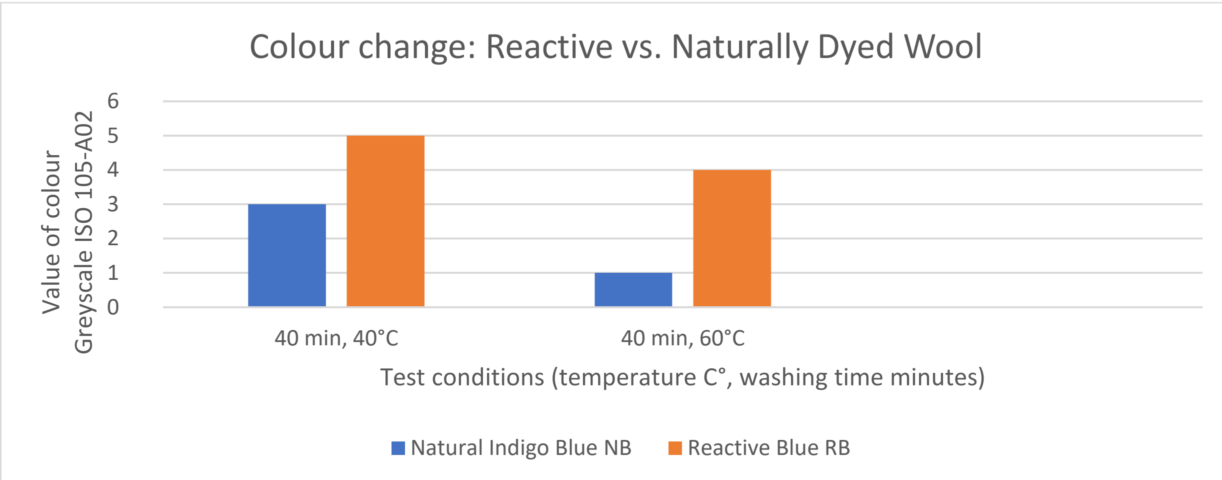


Figure 31 Colour Change Results graph: Reactive vs Naturally Dyed Wool

Primarily, natural dyestuff did not meet the technical requirements from the Dutch Ministry of Defence. For instance, the sample's colour faded away completely after increasing the temperature from 40 degrees to 60 degrees during washing. Meanwhile, the synthetic reactive blue dyestuff performed great at 40 degrees, but it still changed its colour at 60 degrees. On the other hand, ***Figure 32*** shows the colour staining on the attached multifibre fabric. It is evident that the synthetic dyestuff transfer colouration significantly on wool and nylon fibres, whereas the natural dyestuff did not stain seriously. Notably, the reactive dyes significantly coloured the water within the container during the washing test.

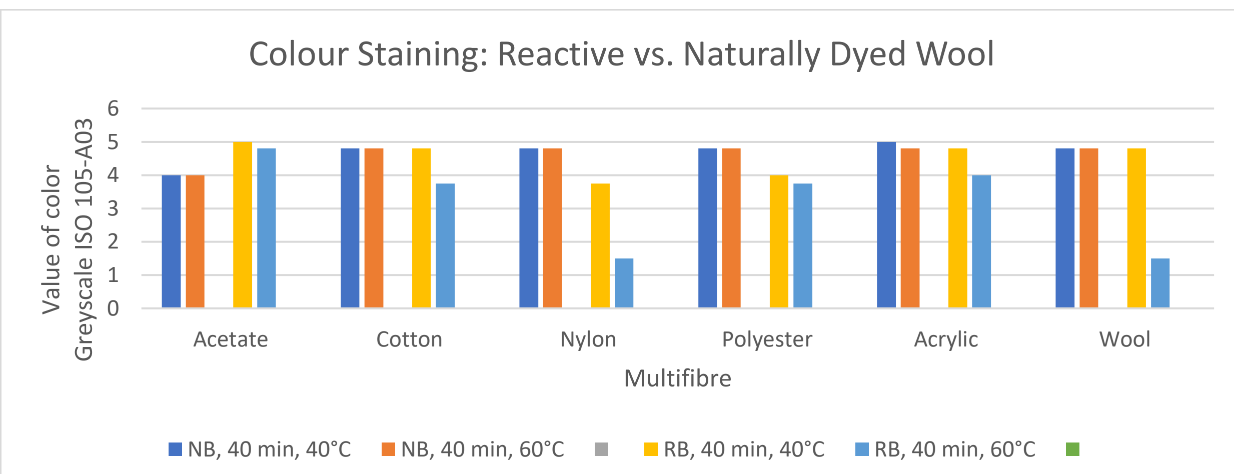


Figure 32 Colour Staining: Reactive vs. Naturally Dyed Wool

Washing Colourfastness Results

The following ***Table 18*** presents the washing test results on all alternative and original benchmark samples.

Table 18 Washing Colourfastness Results

Alternative													Benchmark		
Materials		NB	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	B1	B2	B3
Test 1,105-C06:2010 (40°, 40 minutes)															
Colour Change		3	5	5	4	5	5	5	5	5	4	5	5	4-5	5
Staining	Acetate	4	5	4-5	5	5	4	5	5	5	5	5	5	5	4-5
	Cotton	4-5	4-5	4-5	4-5	4-5	4-5	4-5	4-5	5	3-4	3-4	4	5	4-5
	Polyamide	4-5	5	4-5	4-5	4-5	4-5	5	5	4-5	5	5	5	5	4-5
	Polyester	4-5	4-5	4-5	5	4-5	4-5	4-5	4-5	5	5	4-5	5	5	4-5
	Acrylic	5	4-5	4-5	4-5	4-5	4-5	4-5	5	4-5	5	5	5	5	4-5
	Wool	4-5	4-5	4-5	4-5	4-5	4-5	5	5	5	4-5	5	5	5	4-5
REQ A ≥4		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes		
REQ B ≥4		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No		Yes	
REQ C ≥4		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No			Yes
Test 2,105-C06:2010 (60°, 40 minutes)															
Colour Change		1	4-5	5	4	4-5	4-5	4-5	5	5	3-4	4	5	4-5	5
Staining	Acetate	4	5	4-5	5	5	3	5	5	5	5	5	5	4-5	4-5
	Cotton	4-5	4-5	4-5	4-5	4-5	4-5	4-5	4-5	4-5	3	3-4	2	4-5	4-5
	Polyamide	4-5	5	4-5	4-5	4-5	3	5	5	4-5	5	5	4-5	4-5	3-4
	Polyester	4-5	4-5	4-5	5	4-5	4-5	4-5	4-5	4-5	5	4-5	5	4-5	4
	Acrylic	5	4-5	4-5	4-5	4-5	4-5	4	5	4-5	5	5	5	4-5	4
	Wool	4-5	4-5	4-5	4	4-5	4	4-5	5	4-5	4-5	5	5	4-5	4
REQ A ≥4		No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	No		
REQ B ≥4		No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No		Yes	
REQ C ≥4		No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No			No
Test 3,105-C06:2010 (90°, 40 minutes)															
Colour Change		N/A	4-5	5	4	4-5	4-5	4-5	5	5	2-3	3-4	5	4	5
Staining	Acetate	N/A	5	4-5	5	5	1-2	5	5	1-2	5	5	5	4-5	3-4
	Cotton	N/A	4-5	4-5	4-5	3-4	4-5	3-4	4-5	4	2	3-4	2	4-5	4-5
	Polyamide	N/A	5	4-5	4-5	4-5	1-2	4-5	5	1	5	5	4	4-5	3
	Polyester	N/A	4-5	4-5	4-5	4-5	4	4	4-5	2-3	5	4-5	5	4-5	4
	Acrylic	N/A	4-5	4-5	4-5	4-5	4-5	4	4-5	4-5	5	5	5	4-5	4-5
	Wool	N/A	4-5	4-5	4	4-5	4-5	4-5	4-5	3	4-5	4-5	5	4-5	4
REQ A ≥4		N/A	Yes	Yes	Yes	No	No	No	Yes	No	No	No	No		
REQ B ≥4		N/A	Yes	Yes	Yes	No	No	No	Yes	No	No	No		Yes	
REQ C ≥4		N/A	Yes	Yes	Yes	No	No	No	Yes	No	No	No			No

Rubbing Fastness Results

The following ***Table 19*** and ***20*** present the rubbing colourfastness test results evaluated in terms of colour change and staining.

Table 19 Rubbing Colourfastness Results: ISO 105 - X12:2016 Staining on unbleached cotton

Alternative									**Benchmark**	
Samples	A1	A2	A3	A4	A6	A7	A8	A10	B2	B3
Warp Wet	4-5	1-2	3-4	1-2	1-2	4	4	2-3	5	3-4
Warp Dry	5	4	4-5	3-4	4	4-5	4-5	5	5	4-5
Weft Wet	4-5	1-2	4	1-2	2	4	4	4-5	5	3
Weft Dry	5	4	4-5	3-4	4	5	4-5	5	5	4
REQ A ≥ 5 (dry) ≥ 4-5 (wet)	Yes	No	No	No	No	No	No	No		
REQ B ≥ 5 (dry) ≥ 4-5 (wet)	Yes	No	No	No	No	No	No	No	Yes	
REQ C ≥ 4 (wet, dry)	Yes	No	No	No	No	Yes	Yes	No		No

Table 20 Rubbing Fastness Results: ISO 105 - X12:2016 Colour Change

	Alternative Dyeing Samples								**Benchmark**	
Samples	A1	A2	A3	A4	A6	A7	A8	A10	B2	B3
Warp Wet	4-5	3	4-5	3-4	4	4-5	4	4-5	4-5	4
Warp Dry	5	4-5	4-5	4	4	5	4-5	5	5	4-5
Weft Wet	4-5	3-4	4-5	4	4	4	4	4-5	5	4
Weft Dry	5	4-5	4-5	4-5	4	5	4-5	5	5	4-5
REQ A ≥ 5 (dry) ≥ 4-5 (wet)	Yes	No	No	No	No	No	No	Yes	-	-
REQ B ≥ 5 (dry) ≥ 4-5 (wet)	Yes	No	No	No	No	No	No	Yes	Yes	-
REQ C ≥ 4 (wet, dry)	Yes	No	Yes	No	Yes	Yes	Yes	Yes	-	Yes

Sweat Test Results

The following section depicts the colourfastness results of the conducted sweat test.

Table 21 Perspiration Colourfastness Results

	Alternative Dyeing Samples										Benchmark		
Samples	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	B1	B2	B3
	Alkaline sweat solution												
Colour Change	4-5	4-5	4	5	-	5	5	5	-	4	5	5	5
Acetate	4-5	5	5	5	-	5	5	5	-	5	5	5	4-5
Cotton	4-5	4	5	4	-	4-5	5	5	-	4-5	4	4-5	4-5
Nylon	5	4-5	5	5	-	5	5	5	-	5	4-5	5	5
Polyester	5	5	5	5	-	5	5	5	-	5	5	5	5
Acrylic	5	4-5	5	5	-	5	5	5	-	5	5	5	5
Wool	4-5	4-5	5	4-5	-	5	5	5	-	5	5	5	5
REQ A ≥ 4-5	Yes	No	No	No	-	Yes	Yes	Yes	-	No	No	-	-
REQ B ≥ 4-5	Yes	No	No	No	-	Yes	Yes	Yes	-	No	-	Yes	-
REQ C ≥ 4	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	-	Yes	-	-	Yes
	Acidic sweat solution												
Colour change	5	4-5	4-5	5	-	5	5	5	-	4	5	4-5	5
Acetate	5	5	5	5	-	5	5	5	-	5	5	5	5
Cotton	4-5	3-4	5	4-5	-	4-5	5	5	-	4-5	2	5	5
Nylon	5	4-5	5	5	-	5	5	5	-	5	4	5	5
Polyester	5	4-5	5	5	-	5	5	5	-	5	5	5	5
Acrylic	5	4-5	4-5	4-5	-	4-5	5	5	-	4-5	5	5	5
Wool	4-5	4-5	4-5	4-5	-	5	4-5	5	-	4-5	5	5	5
REQ A ≥ 4-5	Yes	No	Yes	Yes	-	Yes	Yes	Yes	-	No	Yes	-	-
REQ B ≥ 4-5	Yes	No	Yes	Yes	-	Yes	Yes	Yes	-	No	-	Yes	-
REQ C ≥ 4	Yes	No	Yes	Yes	-	Yes	Yes	Yes	-	Yes	-	-	Yes

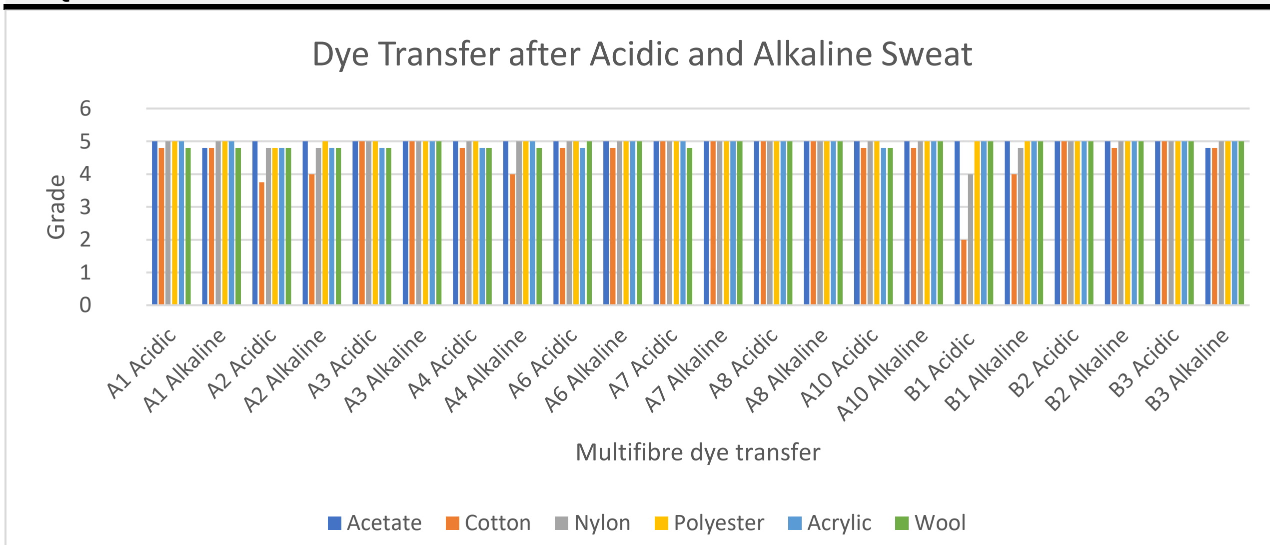


Figure 33 Dye Transfer on multifibre

Lightfastness Test Results

The following section depicts the colourfastness results of the conducted lightfastness test.

Table 22 Lightfastness results

	Alternative Dyeing Samples											Benchmark		
Samples	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	NB	B1	B2	B3
Grade	4	N/A	4	4	5	4	8	3	1	1	1	7	6	7
REQ A ≥ 5-6	No		No	No	Yes	No	Yes	No	No	No	No	Yes		
REQ B≥ 5-6	No		No	No	Yes	No	Yes	No	No	No	No		Yes	
REQ C ≥ 5	No		No	No	Yes	No	Yes	No	No	No	No			Yes

Figure 34 Lightfastness results: samples

Appendix 5 – Environmental impact assessment

Input Data MODINT Ecotool 3.0

Kmar Trousers (lifespan 3 years)

Materials - Fibre materials	Cotton, conv. (China)	Polyester (PES/PET)	Elastane fibre
Water (litre)	6970	0	82
Land (m2)	7.8	0.0	0.0
Chemicals, pesticides (kg)	0.01		
Total energy content (CED), fossil	33	78	94
Total energy content (CED), non-fossil	18.9	0.4	1.6
Process emissions GHG (kg CO2--equivalent)	3.5	2.7	4.2
Mass of fibre material (kg)	500.0	480.0	20.0

Construction, benchmark	Extrusion	Rotor spinning/open-end spinning	Shearing and sizing of yarn	Weaving, >25 tex
Electricity (kWh)		0.80	0.03	2.50
Steam (kg)			3	
Water (litre)	0		0	
Chemicals, starches (kg)			0.05	
Chemicals, inorganic salts (kg)			0.04	
Total energy content (CED), fossil	10			
Total energy content (CED), non-fossil	1.3			
Process emissions GHG (kg CO2--equivalent)	0.5			
Mass of fibre material (kg)	480.0	500.0	500.0	1000.0

Pre-treatment	Singeing & desizing cotton	Mercerization	Cont. Scouring/bleaching, heat exch.	Use of drying cylinder
Electricity (kWh)		0.04		
Steam (kg)			1.2	1.0
Gas (m3)	0.02	0.00		
Water (litre)	3.0	5.7	5.5	
Chemicals, starches (kg)	0.05			
Chemicals, H2O2/NAOH (kg)		0.04		
Chemicals, sodium dithionite (kg)			0.04	
Chemicals, complexing/sequestering agent (kg)			0.004	
Chemicals, inorganic pigments (kg)			0.02	
Product loss (%)	1.00%			
Mass of fibre material (kg)	480.0	500.0	500.0	1000.0

Colouring	Dyeing (cotton/PES)	Cont. washing, heat exchange	Use of drying stenter PES	Use of drying stenter cotton/viscose
Electricity (kWh)	0.05		0.12	0.12
Steam (kg)	2.0	2.1		
Gas (m3)	0.06	0.00	0.18	0.25
Water (litre)	0.8	35.0	0.5	0.7
Chemicals, coating (kg)	0.08			
Chemicals, complexing/sequestering agent (kg)		0.01		
Mass of fibre material (kg)	1000.0	1000.0	480.0	500.0

Finishing	Finishing cotton	Use of drying stenter cotton/viscose	Finishing PES	Use of drying stenter PES
Electricity (kWh)		0.12		0.12
Gas (m3)	0.05	0.25	0.01	0.18
Water (litre)	0.5	0.7	0.3	0.5
Chemicals, inorganic salts (kg)	0.05	0.05	0.05	
Mass of fibre material (kg)	500.0	500.0	480.0	480.0

Product Assembly	Sewing
Electricity (kWh)	0.300
Product loss %	15%
Mass of fibre material (kg)	1000.0

HOME SUCAM	Washing, 60° efficient load	Drying	Ironing, 1000W
Electricity (kWh)	0.16	0.71	0.01
Water (litre)	12		
Chemicals, tensides (kg)	0.02		
Mass of fibre material (kg)	1000.0	1000.0	1000.0

Shirt (lifespan 2 years)

Materials - Fibre materials	Cotton, conv. (China)	Polyester (PES/PET)
Water (litre)	6970	0
Land (m2)	7.8	0.0
Chemicals, pesticides (kg)	0.01	
Total energy content (CED), fossil	33	78
Total energy content (CED), non-fossil	18.9	0.4
Process emissions GHG (kg CO2--equivalent)	3.5	2.7
Mass of fibre material (kg)	600.0	400.0

Construction, benchmark	Extrusion	Rotor spinning/open-end spinning	Shearing and sizing of yarn	Weaving, <17 tex
Electricity (kWh)		0.80	0.03	6.00
Steam (kg)			3	
Water (litre)	0		0	
Chemicals, starches (kg)			0.05	
Chemicals, inorganic salts (kg)			0.04	
Total energy content (CED), fossil	10			
Total energy content (CED), non-fossil	1.3			
Process emissions GHG (kg CO2--equivalent)	0.5			
Mass of fibre material (kg)	400.0	600.0	600.0	1000.0

Pre-treatment	Singeing & desizing cotton	Mercerization	Cont. Scouring/bleaching, heat exch.	Use of drying cylinder
Electricity (kWh)		0.04		
Steam (kg)			1.2	1.0
Gas (m3)	0.02	0.00		
Water (litre)	3.0	5.7	5.5	
Chemicals, starches (kg)	0.05			
Chemicals, H2O2/NAOH (kg)		0.04		
Chemicals, sodium dithionite (kg)			0.04	
Chemicals, complexing/sequestering agent (kg)			0.004	
Chemicals, inorganic pigments (kg)			0.02	
Product loss (%)	1.00%			
Mass of fibre material (kg)	600.0	600.0	600.0	1000.0

Colouring	Dyeing (cotton/PES)	Cont. washing, heat exchange	Use of drying stenter PES	Use of drying stenter cotton/viscose
Electricity (kWh)	0.05		0.12	0.12
Steam (kg)	2.0	2.1		
Gas (m3)	0.06	0.00	0.18	0.25
Water (litre)	0.8	35.0	0.5	0.7
Chemicals, coating (kg)	0.08			
Chemicals, complexing/sequestering agent (kg)		0.01		
Mass of fibre material (kg)	1000.0	1000.0	400.0	600.0

Finishing	Finishing cotton	Use of drying stenter cotton/viscose	Finishing PES	Use of drying stenter PES
Electricity (kWh)		0.12		0.12
Gas (m3)	0.05	0.25	0.01	0.18
Water (litre)	0.5	0.7	0.3	0.5
Chemicals, inorganic salts (kg)	0.05	0.05	0.05	
Mass of fibre material (kg)	600.0	600.0	400.0	400.0

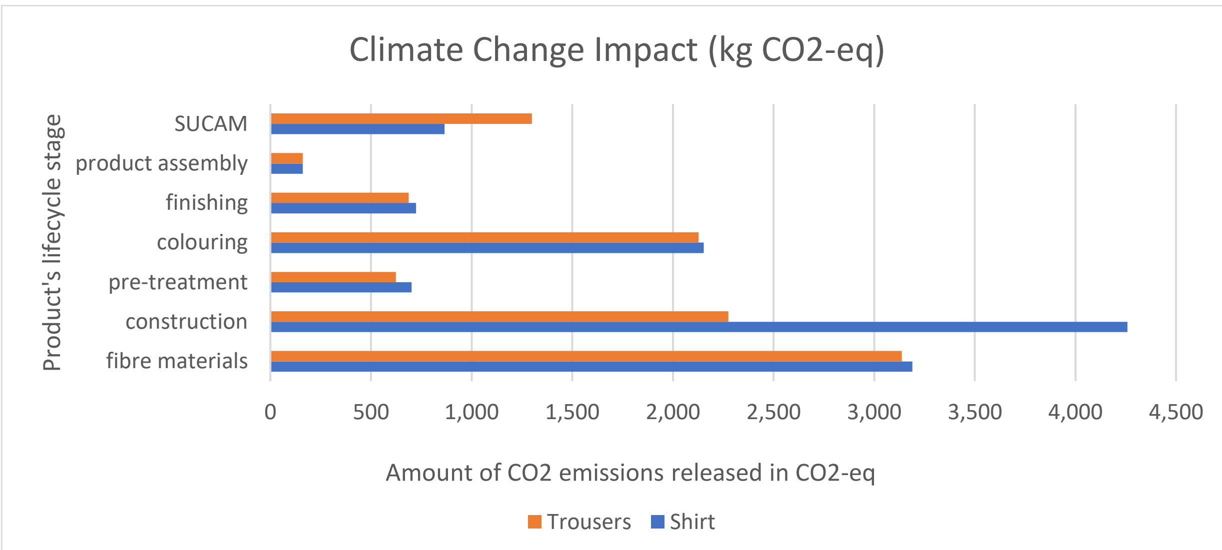
Product Assembly	***Sewing***
Electricity (kWh)	*0.300*
Product loss %	*15%*
Mass of fibre material (kg)	*1000.0*

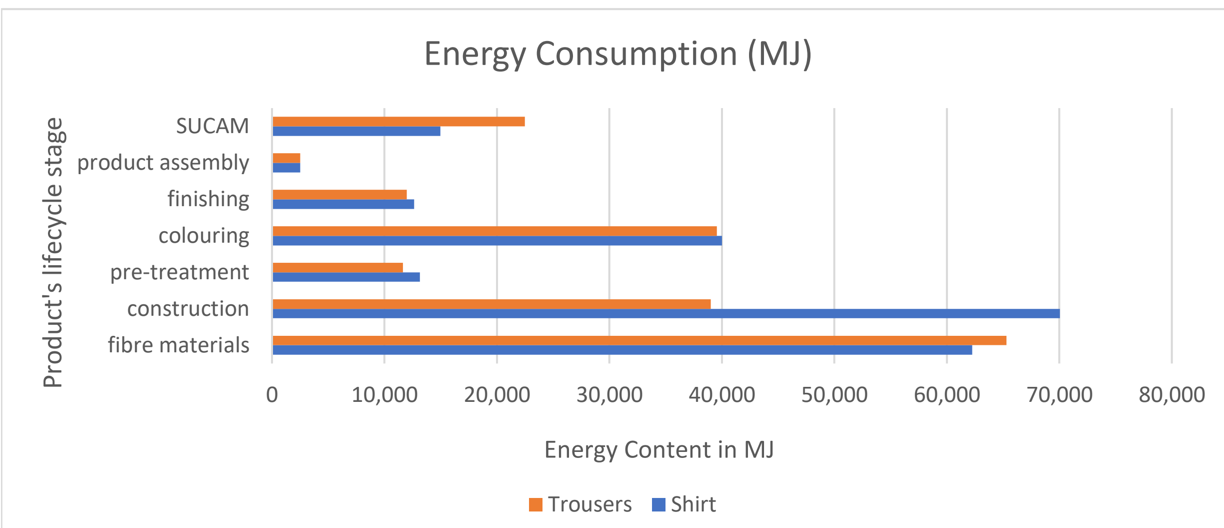
HOME SUCAM	***Washing, 60° efficient load***	***Drying***	***Ironing, 1000W***
Electricity (kWh)	*0.16*	*0.71*	*0.01*
Water (litre)	*12*		
Chemicals, tensides (kg)	*0.02*		
Mass of fibre material (kg)	*1000.0*	*1000.0*	*1000.0*

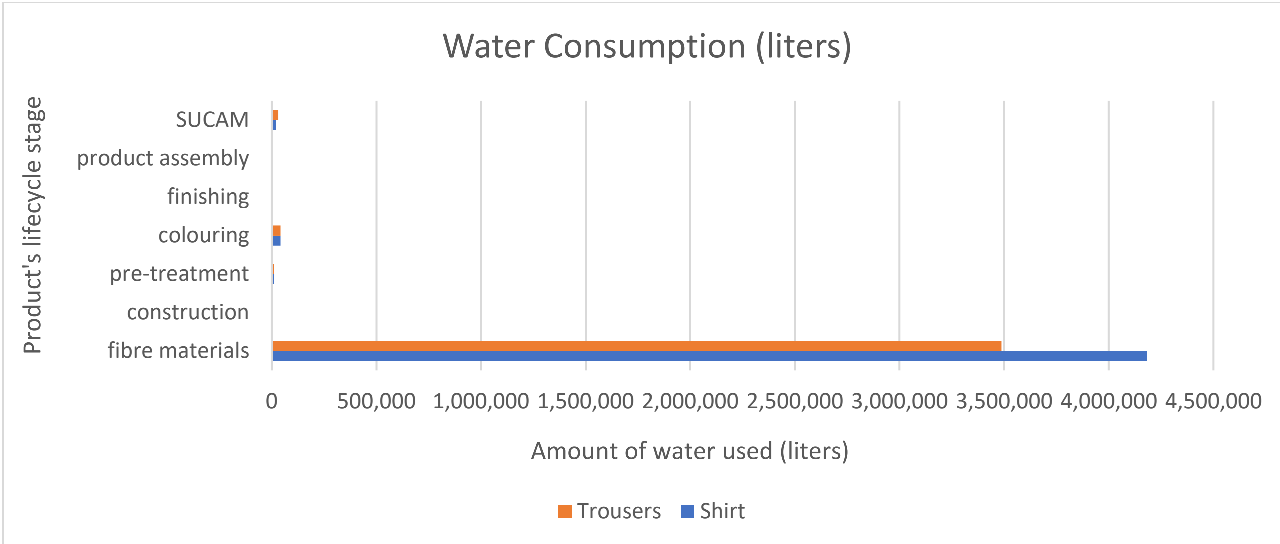
Environmental impact: Scorecard Analysis on original garments

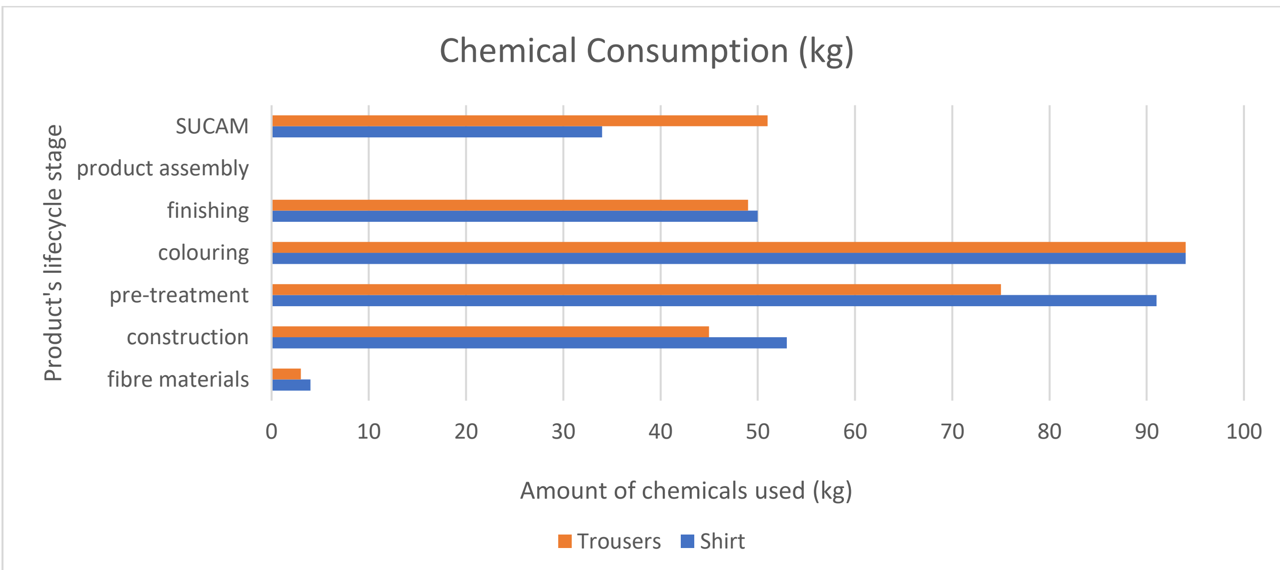
The following section contains graphs comparing the total footprint of the alleged trousers and shirt. The data is obtained based on the scorecard output data from the Modint Ecotool.

Figure 35 Scorecard Trousers vs Shirt






Water Consumption (liters)
Product's lifecycle stage
SUCAM
product assembly
finishing
colouring
pre-treatment
construction
fibre materials
0
500,000
1,000,000
1,500,000
2,000,000
2,500,000
3,000,000
3,500,000
4,000,000
4,500,000
Amount of water used (liters)
Trousers
Shirt


Chemical Consumption (kg)
Product's lifecycle stage
SUCAM
product assembly
finishing
colouring
pre-treatment
construction
fibre materials
0
10
20
30
40
50
60
70
80
90
100
Amount of chemicals used (kg)
Trousers
Shirt

Alternative Dyeing Processing Input Data

The following section describes the methods and data inserted in the Modint Ecotool.

Kmar Alternative – dope dyeing and undyed cotton

Mueller et al. (US Patentnr. USOO7687568B2) reveal the polyester colorant concentrate during spin dyeing. The inventors specify that the spinning solution contains polyester carrier material, and 0.5 to 1.5 dyes/pigments parts by weight per part of a co-polyester. The Ecotool database do not have dope dyeing as an option. Thus, own process is created in the construction phase, as dope dyeing. Colorant of 0.5 is added to the extrusion process. The lifespan, fibre materials, pre-treatment, finishing, assembly, and home SUCAM are not included since they are the same as the benchmark input data. The colouration is taking place in the construction during polyester extrusion (*See own process spin dyeing*), and cotton is undyed. Thus, colouration step is eliminated.

Construction	***Own process (Spin dyeing)***	***Rotor spinning/open-end spinning***	***Shearing and sizing of yarn***	***Weaving, >25 tex***
Electricity (kWh)		*0.80*	*0.03*	*2.50*
Steam (kg)			*3*	
Water (litre)			*0*	
Chemicals, starches (kg)			*0.05*	
Chemicals, organic colouring, other (kg)	*0.5*			
Chemicals, inorganic salts (kg)			*0.04*	
Total energy content (CED), fossil	*10*			
Total energy content (CED), non-fossil	*1.3*			
Process emissions GHG (kg CO2--equivalent)	*0.5*			
Mass of fibre material (kg)	*480.0*	*500.0*	*500.0*	*1000.0*

Kmar Alternative – dope dyeing and spray dyeing cotton

Imogo Tech conducted a LCA study between DyeMax and Jet Dyeing processes. The interviewee participant shared EcoChain tool output data, which was used to create *Own colouring process* (spray dyeing cotton) in the Ecotool. The polyester part is dope dyed, thus the input data for construction is same as the table above.

Colouring	***Spray dyeing cotton***	***Use of drying stenter cotton/viscose***
Electricity (kWh)	*0.025*	*0.12*
Steam (kg)	*0*	
Gas (m3)		*0.25*
Water (litre)	*0.875*	*0.7*
Chemicals, Soda ash	*0.021*	
Chemicals, organic colouring (reactive dye) (kg)	*0.020*	
Chemicals, complexing/sequestering agent (kg)	*0*	
Chemicals, coating (kg)	*0.001*	
Mass of fibre material (kg)	*500.0*	*500.0*

Shirt Alternative – dope dyed polyester, spray dyed cotton

Construction	Own process (Spin dyeing)	Rotor spinning/open-end spinning	Shearing and sizing of yarn	Weaving, <17 tex
Electricity (kWh)		0.80	0.03	2.50
Steam (kg)			3	
Water (litre)			0	
Chemicals, starches (kg)			0.05	
Chemicals, organic colouring, other (kg)	0.5			
Chemicals, inorganic salts (kg)			0.04	
Total energy content (CED), fossil	10			
Total energy content (CED), non-fossil	1.3			
Process emissions GHG (kg CO2--equivalent)	0.5			
Mass of fibre material (kg)	400.0	600.0	600.0	1000.0

Colouring	Spray dyeing cotton	Use of drying stenter cotton/viscose
Electricity (kWh)	0.025	0.12
Steam (kg)	0	
Gas (m3)		0.25
Water (litre)	0.875	0.7
Chemicals, Soda ash	0.021	
Chemicals, organic colouring (reactive dye) (kg)	0.020	
Chemicals, complexing/sequestering agent (kg)	0	
Chemicals, coating (kg)	0.001	
Mass of fibre material (kg)	600.0	600.0

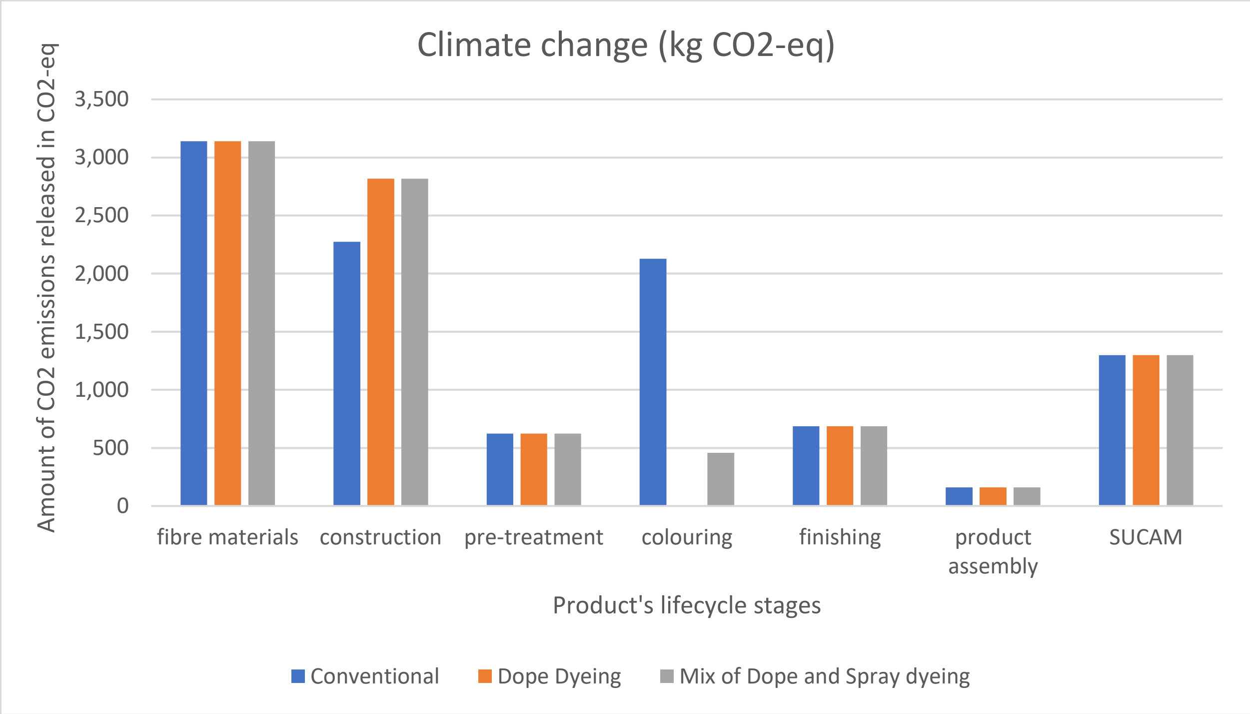
Shirt Alternative – CO/PES spray dyeing

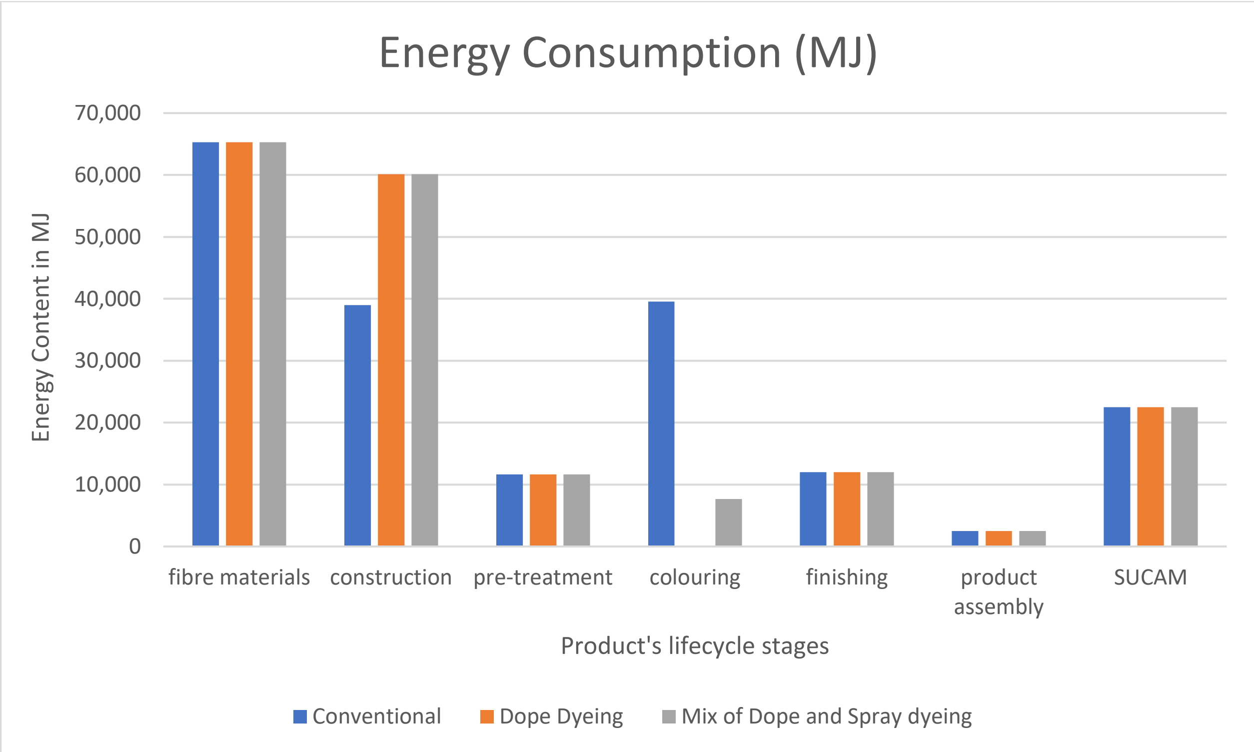
Colouring	CO/PES Spray dyeing	Use of drying stenter cotton/viscose	Use of drying stenter PES
Electricity (kWh)	0.025	0.12	0.12
Steam (kg)	0		
Gas (m3)		0.25	0.18
Water (litre)	0.875	0.7	0.5
Chemicals, Soda ash	0.021		
Chemicals, organic colouring (reactive dye) (kg)	0.020		
Chemicals, complexing/sequestering agent (kg)	0		
Chemicals, coating (kg)	0.001		
Mass of fibre material (kg)	100.0	600.0	400.0

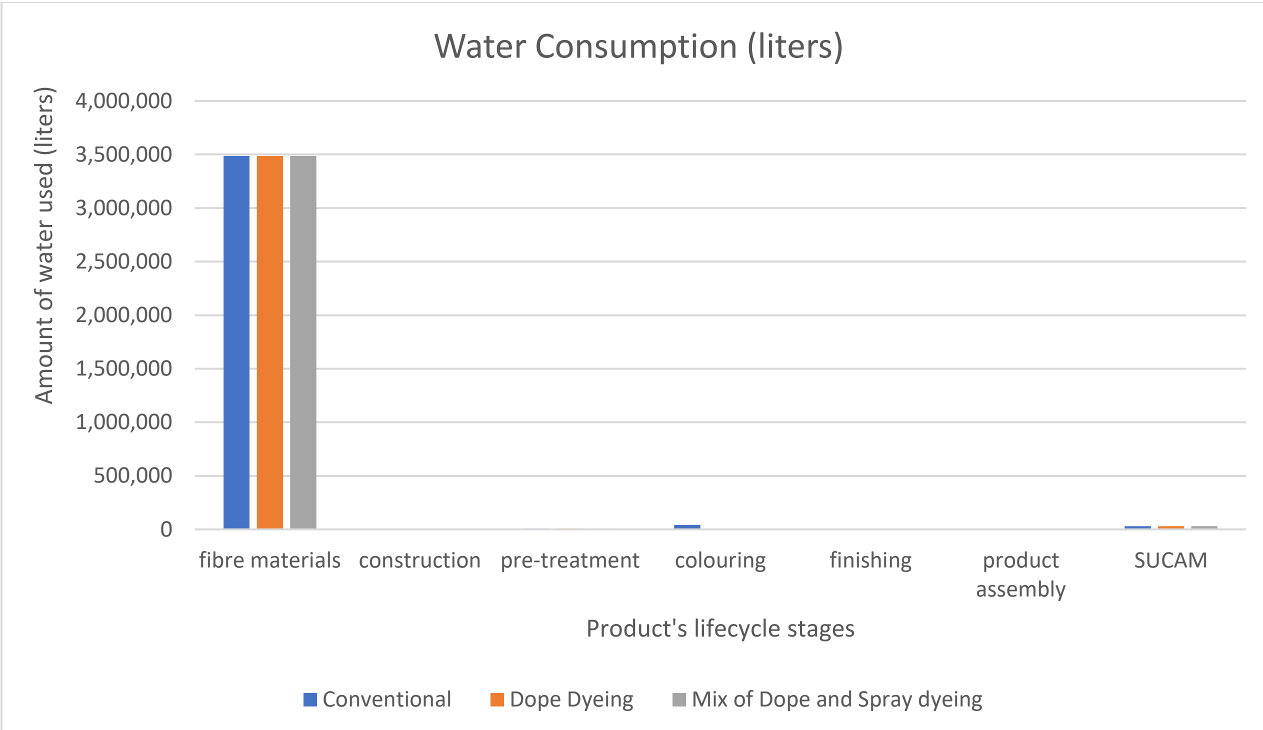
Environmental impact Alternatives for KMAR trousers

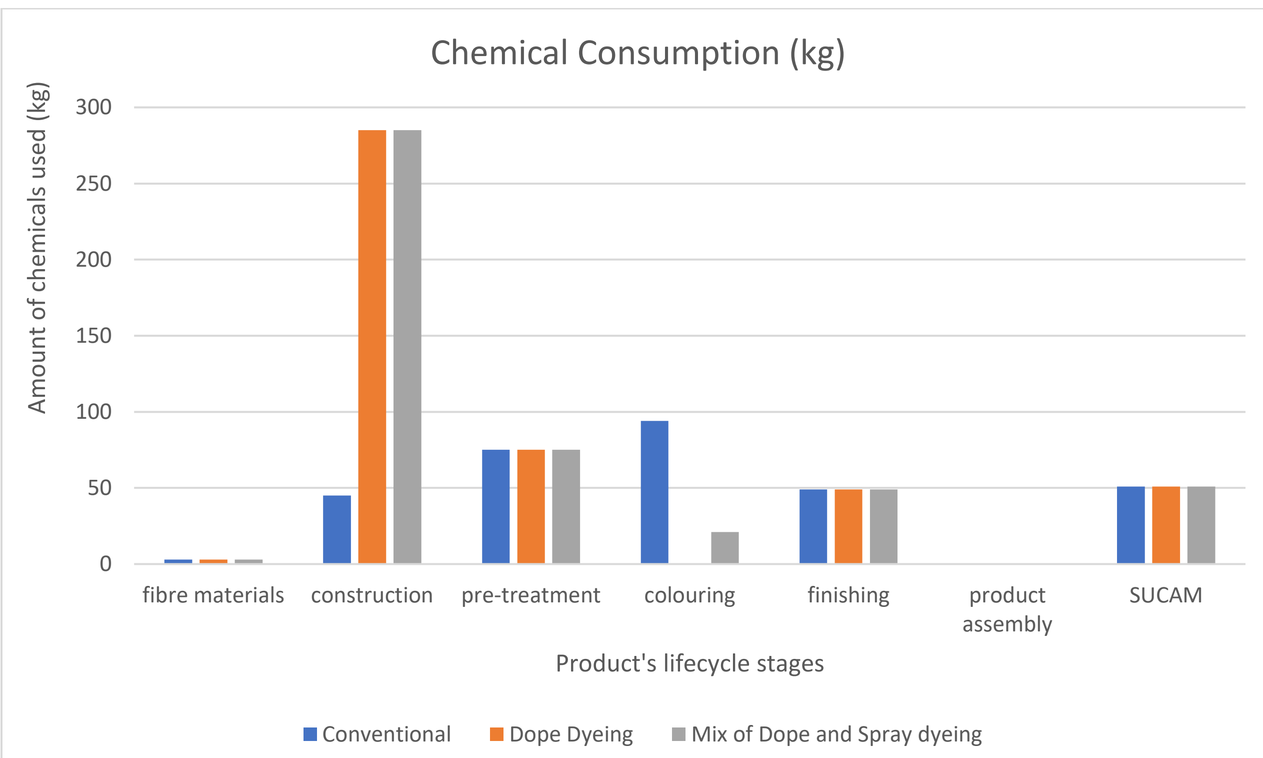
The following section illustrates the outcome of the inserted alternative dyeing technologies, compared to the original trousers footprint.

Figure 36 Environmental Impact Scorecard: Kmar's vs Alternatives



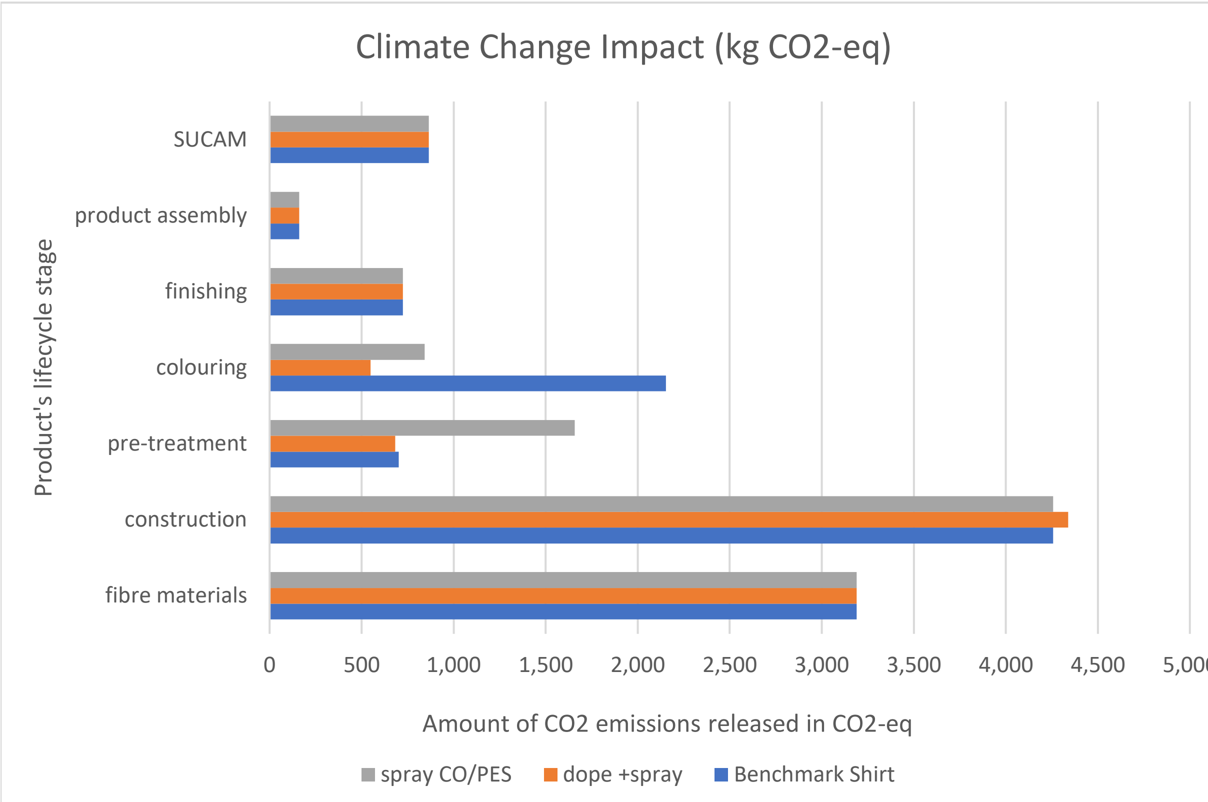


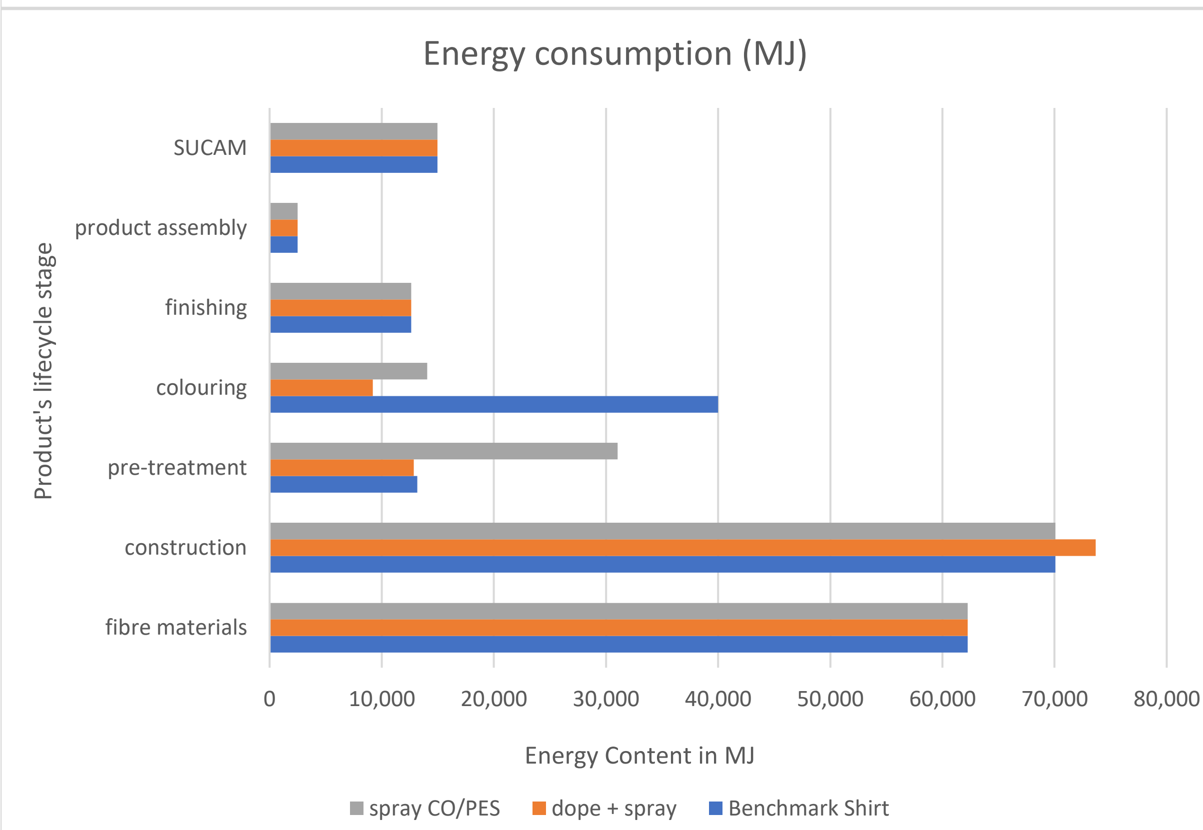

Water Consumption (liters)
Amount of water used (liters)
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
fibre materials
construction
pre-treatment
colouring
finishing
product assembly
SUCAM
Product's lifecycle stages
Conventional
Dope Dyeing
Mix of Dope and Spray dyeing

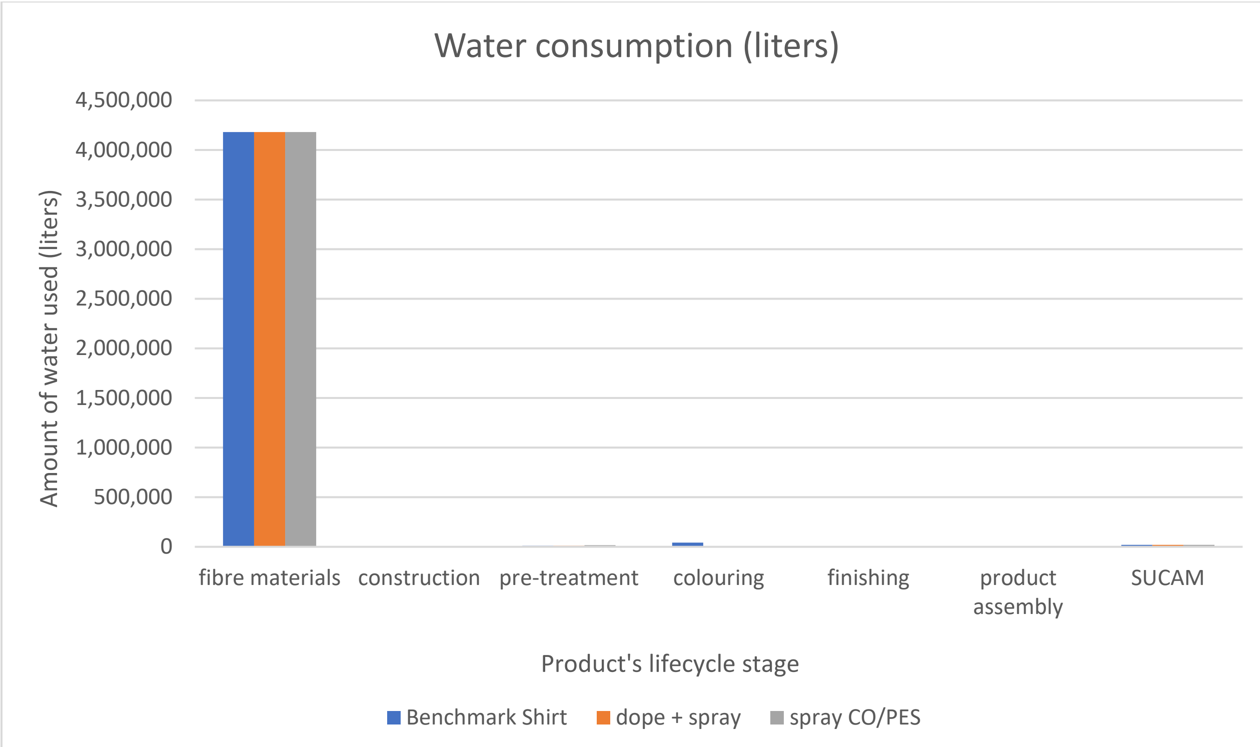

Chemical Consumption (kg)
Amount of chemicals used (kg)
300
250
200
150
100
50
0
fibre materials
construction
pre-treatment
colouring
finishing
product assembly
SUCAM
Product's lifecycle stages
Conventional
Dope Dyeing
Mix of Dope and Spray dyeing

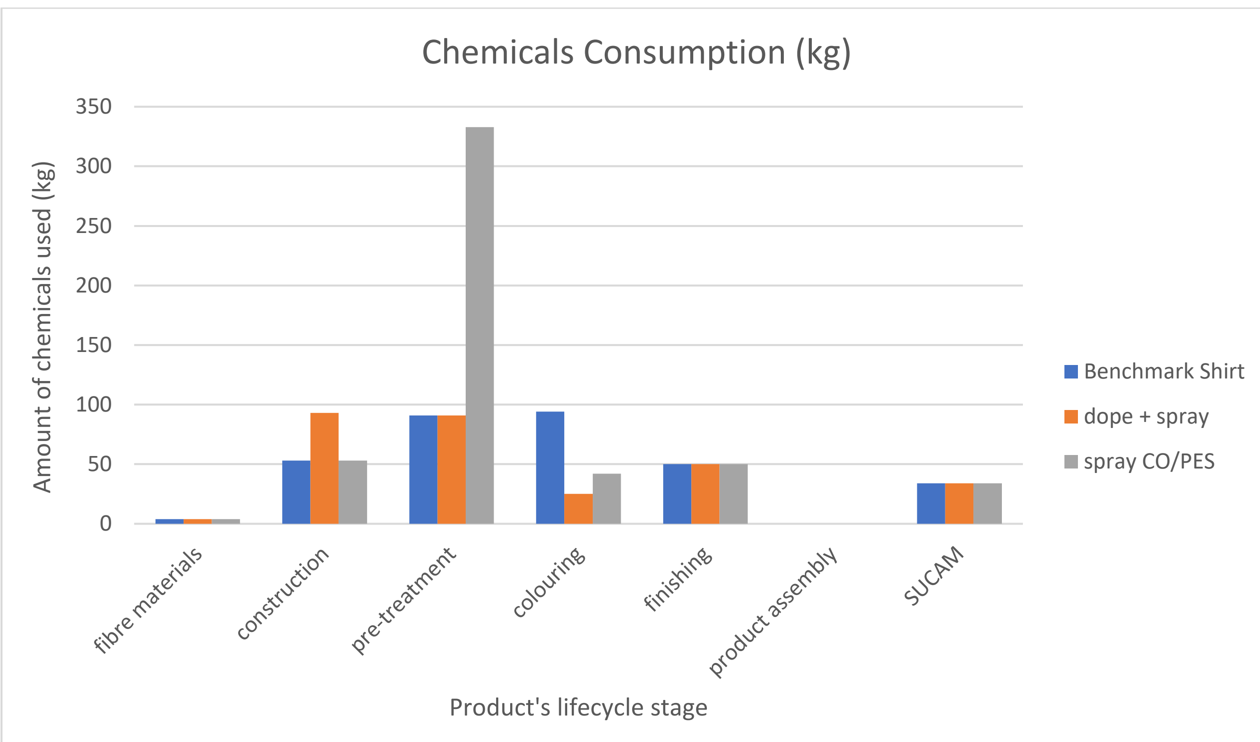
Environmental impact Alternatives for shirts

Figure 37 Environmental Impact Scorecard: Shirt's vs Alternatives






Water consumption (liters)
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
Amount of water used (liters)
fibre materials
construction
pre-treatment
colouring
finishing
product assembly
SUCAM
Product's lifecycle stage
Benchmark Shirt
dope + spray
spray CO/PES


Chemicals Consumption (kg)
350
300
250
200
150
100
50
0
Amount of chemicals used (kg)
fibre materials
construction
pre-treatment
colouring
finishing
product assembly
SUCAM
Product's lifecycle stage
Benchmark Shirt
dope + spray
spray CO/PES