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Sustainable Dyeing Technologies for Polyester

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Abstract

The aim of this paper is to review possible polyester dyeing method technologies in order to reduce the environmental impact of dyeing polyester fibre. It will answer the research question, what are the sustainable alternatives to conventional polyester dyeing process? Currently polyester is dyed using disperse dyes using carrier or HTHP method. Polyester fibre is the most used fibre in the textile industry, due to its physical properties, price, recyclability, and versatility however, 30% of pollutants in textile chemical processing is from dyeing and printing process. Therefore, it is the need of the hour to find sustainable alternatives to conventional polyester dyeing.

The paper reviews the following sustainable polyester alternative dyeing methods: Air Dyeing, Supercritical CO2 dyeing, Dope Dyeing and Spray Batch Dyeing. The process of dyeing as well as advantages and disadvantages are reviewed. A few alternatives such as natural dyes and thermosol dyeing is also discussed. A conclusion of each alternative dyeing method is derived from the studied literature, performance as well scope is also discussed. The sustainable polyester dyeing space has received quite a lot of attention in the past few decades. However, it still has immense potential and further investigation is required to solve problems of colourfastness and operational costs.

Keywords: Air Dye, Supercritical CO2, Dope Dyeing, Spray Dyeing, Natural Dyes, Colourfastness

1. Introduction

Textile dyeing processing faces plethora of environmental challenges, such as high water and energy consumption, air and effluent emissions, and use of global resources (Sinclair, 2014). Dyeing polyester with disperse dyes has been found to have much higher concentrations of polluting substances consequential in greater harmful effects. All these chemicals are extremely hard to biodegrade, and some are toxic too (Sharma, 2007). Therefore, it is an urgent requirement to keep water pollution-free and treat wastewater, especially during textile dyeing and hence it is essential to develop new methods which have low chemical and waste production.

Factory workers come into contact with microfibers, synthetic dyes, and petrochemicals on a daily basis through inhalation or skin contact, putting their health at risk and increasing the prevalence of respiratory disorders, including asthma and interstitial lung disease and allergies (Palacios-Mateo, 2021).

(Ivanova, 2022) mentions that LCA findings found that coloration is responsible for 21% of the total CO2-eq kg emissions, contributing to climate change. The dyeing stage holds the largest share of chemical usage. Currently, most of the dyeing industries use conventional wet chemical process for colouring fabrics. For Polyester, conventional dyeing method is using a carrier or HTHP which causes dye to enter the fibre after making it swell. According to research from the nongovernment organization Fashion for Good, a key solution to minimize environmental impact is to shift wet processing towards dry processing (FashionForGood, 2022).

Companies want to promote responsible consumption and sustainable production (SDG 12) through high-quality garments. The higher the quality, higher the colourfastness, thus increasing the lifespan of a garment. Therefore, it is also important that the sustainable technologies used to dye polyester are commercially viable and can be used on a large scale. The sustainable methods discussed in this review paper are based on advanced technologies, resource efficiency and reduced global waste.

2. Literature review

2.1. Air Dye

2.1.1. Process:

In an airflow dyeing device, the dyeing liquid is first atomized, then combined with high-pressure airflow, and then sprayed on the fabric to dye it.

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The cloth travels through an air-steam medium across the vessel, released through a blower, which is the fundamental idea of the aerodynamic system (Iqbal Mahmud, 2020).

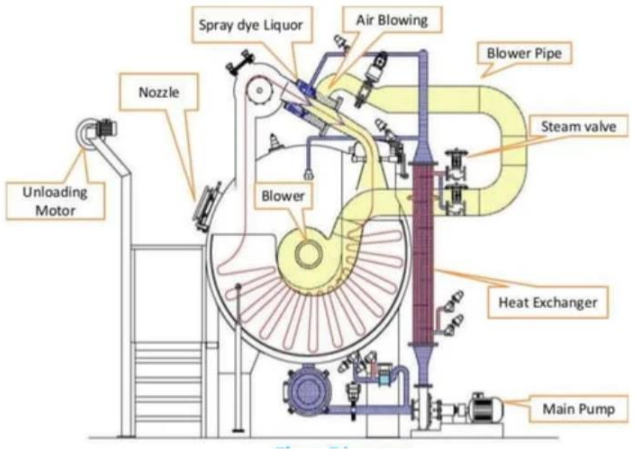

Figure 1: Air Dyeing Machine

2.1.2. Advantages:

Air Dye process is 2-sided with the possibility to independently colour each, and the hand feel of the finished fabric is luxurious and clean.

(Dhanabalan, 2014) mentions that compared to conventional dyeing, it consumes 95% less water, 86% less energy, and 84% less greenhouse gases, depending on the fabric. Since, in contrast to a hydraulic dyeing machine, cloth transportation is not done using a dye bath or an aqueous medium. It has the lowest liquor ratio of 1:2 for man-made fibres. Nozzle pressure is extremely low compared to the jet system in which the nozzles are filled with liquor, providing the best possible protection for delicate textile surfaces. While 10% of conventionally dyed fabric is damaged during the production process, only 1% of Air-Dyed fabrics are damaged since no post-treatment or finishing is required. Overall process time is reduced by approximately 25%. The unique ability to rinse with fresh water in a running wash system and use a hot drain system drastically decreases the amount of time needed for the dyeing process. It reduces water consumption and the quantities of auxiliaries and dyes which is necessary for an optimum dyeing process, thus leading to considerable cost reduction of production and wastewater treatment.

2.1.3. Disadvantages:

The low liquor ratio could sometimes cause problems due to poor solubility of some dyes and/or during subsequent post-dyeing washing process, where higher liquor ratios is preferred.

The fabric also sometimes tends to pack on the bottom of the machine due to reduced quantity of liquor, thus leading to permanent wrinkles. This problem becomes apparent when fabrics made of synthetic fibres, have not been efficiently heat-set. (Dhanabalan, 2014).

The machine installation cost is high, and the air-dye technique is relatively new.

Little to no testing results available for the public.

2.2. Super Critical CO2 Dyeing

2.2.1. Process:

(De Giorgi, 2000) study, few decades ago, has shown that it is possible to obtain the same dyeing results using CO_2 as with aqueous dyeing in 30 min at 120°C.

CO2 is used as a fluid solvent because of its non-flammability, non-toxicity, and availability, critical temperature (Tc=31.1°C) and pressure (Pc=74 bar) are lower than that of many other fluids, recovery, reuse, and chemically inert nature, makes CO2 an attractive option (Iqbal Mahmud, 2020).

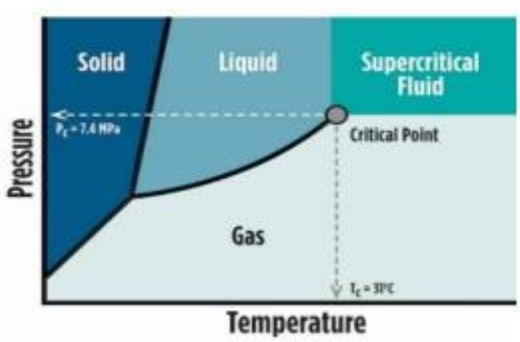

Figure 2: Phase diagram of CO2 (Tc: critical temperature, Pc: critical pressure)

ScCO2 can dissolve hydrophobic substances like disperse dyes. The ScCO2 penetrates the fibres, thus acting as a swelling agent during dyeing, i.e., increasing the diffusion of dyes in the fibres

The polyester fabrics are suspended on a stainless-steel net inside the vessel and the solid, pure dye is placed on the bottom of the vessel. When the system reaches the desired temperature (80 to 120°C) and pressure (200-250 bar), the fluid is let into the vessel. After 30 min under constant conditions, the system is expanded to atmospheric pressure and the dyed fabrics are removed.

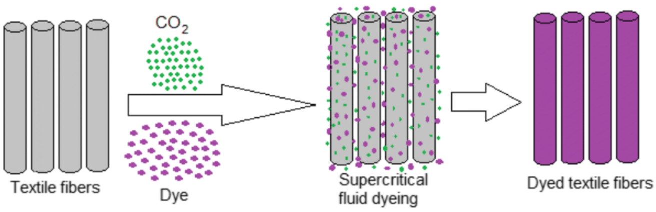

Figure 3: Dyeing process using Super Critical CO2 of Polyester

2.2.2. Advantages:

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(Iqbal Mahmud, 2020) mentioned in its paper that supercritical CO2 acts both as liquid and gas at above 31.1°C and 74 bar. Hydrophobic dyes can be more easily dissolved due to the liquid-like densities, while gas-like low viscosities and diffusion qualities can result in faster dyeing times than with water dyeing.

A good solubility, diffusivity and zero surface tension could be achieved by this method as well.

(Zheng, 2016) reported that the ScCO2 dyed products performed excellent colourfastness to washing, rubbing, and light, when tested accordingly to the AATCC test methods (61, 8, 16.3). It requires pure chromophores without any auxiliary chemicals. Therefore, the colourfastness properties are the same or better than water dyeing.

According to the Dutch company Dyecoo that produced the first commercial dyeing machine for SC-CO2 dyeing, the uptake of dye is 98% and the process has low operation cost, no water, no emissions of process chemicals and therefore no wastewater treatment is necessary.

In addition, (Dyecoo, 2016) affirms that 95% of used CO2 can be recycled, and the dye leftover can be easily removed by elimination of air pressure.

Several global brands and retailers that use ScCO2 such as NIKE, Adidas, Decathlon, Inditex, BonPrix, Brooks Running, and Walmart. Thus, ensuring that ScCO2 dyeing meets high-quality colourfastness standards.

Based on the NASA's Technology Readiness Level (TRL), the findings confirmed the environmental benefits of ScCO2 dyeing compared to conventional polyester processing. In addition to eliminating freshwater consumption and chemicals, dyes are also used more effectively.

An economic analysis showed that, although the purchase cost for a supercritical machine is higher (500 k€) than for an aqueous machine (100 k€), the operating cost is lower (0.35 instead of 0.99 € per kg polyester). This is caused by the higher rate of dyeing and by the simpler dye formulations that can be used in scCO2. The overall result has a 50% lower process cost for the supercritical process. Short batch cycles, efficient dye use, no wastewater treatment all contribute to significantly reduced operating costs (Kraan, 2005).

2.2.3. *Disadvantages:*

(Ivanova, 2022) mentioned that most scCO2 equipment usually had a vertical layout, which results in non-homogeneous fluid distribution, dye accumulation, and thus uneven textile dyeing caused by gravity. However, to tackle this issue Huang et al. constructed pilot-scale horizontal equipment for zipper tape dyeing in scCO2 at relatively low temperature (90 ± 2ºC) which concluded that commercialization of waterless dyeing would have great practical and strategic significance.

DyeCoo is the only technology provider that supplies ScCO2 dyeing machines. These dyeing machines operate throughout Vietnam, Thailand, South Korea, the Netherlands, and Taiwan, and purchase is pending in Turkey and India. This drives up price as demand is met by only one company, making it a monopoly.

Unless the machine is completely loaded, it is not economically viable.

The lightfastness properties can be below expectations, depending on the given requirements.

2.3. *Dope Dyeing*

2.3.1. *Process*:

Dope dyeing/Mass colouration/Solution 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 (device for extruding polymer solutions or polymer melts into fibres), the filaments are coloured.

Colour addition in polyester melt using colorants stable under elevated temperatures (260–290C) and high vacuum (pressure less than 1 torr) is widely used (Gurudatt, 2005).

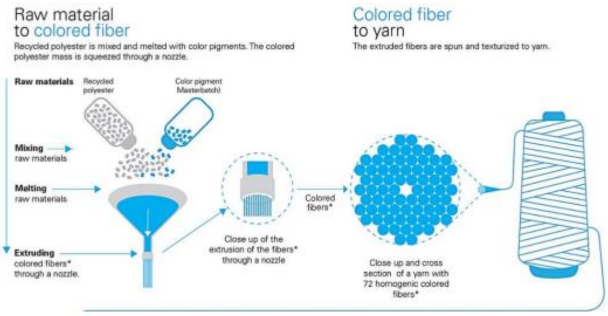

Figure 4: We aRe SpinDye® dope dyeing process

2.3.2. *Advantages*:

Dope dyeing obtains permanent colourfastness since the colour becomes part of the filament/fibre.

(Patnaik, 2019) that dope dyeing requires fewer costs, and that effluent treatment is unnecessary. (Mehdi, 2018) support this statement by listing its ecological benefits, such as saving time, energy, and chemicals, and it prevents dye loss to wastewater. Dyestuff consumption is reduced by more than 20%, the use of other chemical agents like alkaline by 80% compared to traditional dyeing.

Environmental Product Declaration following ISO 14025 for polyester fabrics conducted an LCA comparison study between dope and piece dyeing (SMARTEX, 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 CO2-eq3) of dope dyeing is still less than piece dyeing.

The cost of production of the shade by this technique is said to be about 5% of the dyeing fibre with disperse dyes (Gurudatt, 2005). According to the study by (Schuster, 2014), savings in production cost such as raw material cost and capital cost as well as labour cost are enabled by implementing spin-dyeing due to the lower input of chemicals and energy and lower amount of wastewater.

2.3.3. *Disadvantages*:

(Maiti, 2022) acknowledges that this technology is feasible for colours with large market volumes, such as dark blue, black, brown, and red. It requires to make early colour decision. Involves efforts in cleaning of the units, which is a complicated, time consuming process before changing shade. Especially in post spinning operations, deposition of colorant or coloured dust necessitates more efforts in cleaning

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

2.4. *Spray Batch Dyeing*

2.4.1. *Process:*

Spray batch dyeing technology utilizes capillary forces and natural absorbency of materials to get deeper penetration

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 (ApparelResources, 2020).

DyeMax's water usage is 0.5 litre per kilo, process speed is 5 – 50 m/min and application can be one or two sided (Limhamn, 2019).

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.

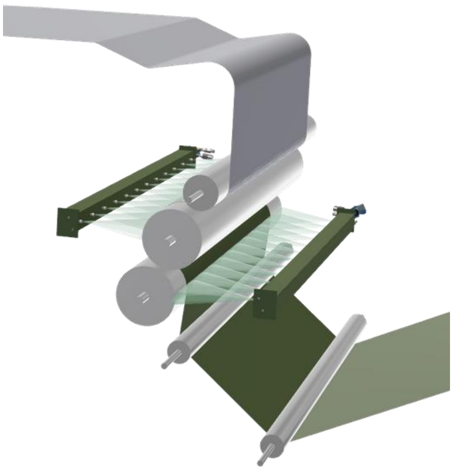

Figure 5: Dye-Max configuration for woven

2.4.2. *Advantages:*

This technology significantly decreases the use of water, energy, chemicals, and generated wastewater due to a low-liquor ratio (TextileValueChain, 2020). The technology allows spraying the exact amount of dye required on the fabric surface and it also produced on demand.

The system is a feasible replacement of pad and jet machines, but also it can be integrated into a pad continuous line system. This technology can be quickly implemented by the industry.

DyeMax can work with diverse pigments, all types of dyestuff, and finishing chemicals.

Impact of DyeMax on dyeing process compared to jet process:

Water consumption reduced with	> 90%
Energy consumption reduced by	> 90%
Wastewater reduced by	> 90%
Reduce Co2 emissions by	> 90%
Productivity increases by	> 100%

Table 1: Impact of DyeMax compared to Jet dyeing process

2.4.3. *Disadvantages*:

According to (Ivanova, 2022), Spray batch has low colourfastness performance in wet rubbing and lightfastness.

Polyester dyeing is still on lab-scale, with low volume of production.

Companies needs investment to further optimize the process.

Not yet suitable for knitted fabrics, as the machinery needs improvements with respect to loading process.

2.5. *Other Alternatives*

2.5.1. *Natural Dyes*

The use of renewable dyes and auxiliary components is a possible approach to lower the environmental impact. However, (Bide, 2016) claims that synthetic dyes are the best to use for polyester since these colorants require less water and energy consumption and provide better wash fastness properties.

(Saxena, 2016) mentioned that many natural resources for dyestuff, such as plants and fruits, are seasonal and require large volumes of water to grow.

(Ivanova, 2022) mentioned that colourfastness results are not as satisfying as the synthetic dyes and the colour is not as durable as synthetic dyes. Low wash fastness properties since the colour fades after several washes and exposure to light

There are also further challenges such as the volume of chemical binders, budget, and high-level equipment costs.

For all the above reasons, this review paper will not be going into use of natural dyes for polyester dyeing since a lot of research is ongoing, involving different methods which is beyond the scope of this paper.

2.5.2. Thermosol Dyeing

In research from (Rashedul Islam, 2011), Thermosol method is continuous methods of dyeing with disperse dye where dyeing is performed at high temperature like 180-220°C in a close vessel, sublimation of dye from solid to gas takes place. It requires only a few seconds to 1 min and temperature about 200-230°C.

Padding > Drying> Thermo fixing >After Treatment

There are a lot of variables to control to get the require shade, such as when time of treatment is prolonged, there can be loss of fibre strength.

It requires special machine arrangement since shade may change due to sublimation at high temperature, which is expensive. Therefore, maintaining colourfastness is tricky.

Pre-treatment is prerequisite because of very short contact time with dye. It also requires various chemicals such as dispersing agent, wetting agent, migration inhibitor, pH stabilizers, diffusion accelerant etc.

It is a good method, with short dyeing times, brighter shades, good dye utilization (75-90%) and it has also been researched well. However, still no solution has been found for the variation in the shade range and loss of strength with the slightest change in temperature.

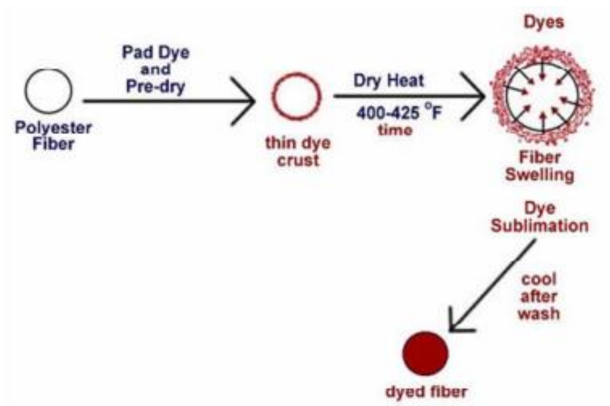

Figure 6: Dyeing Polyester with thermosol process

3. Conclusion

Conventional dyeing of polyester with carriers and high temperature and pressure are wet processes which have a large climate impact due to large amounts of energy, heat, and water requirements. Air, ScCO2, colour pigments at yarn production and spray dyeing are alternatives to such wet processes since they consume less water, chemicals and produce less waste.

Table 2 provides a better understanding of the position of different sustainable polyester dyeing technologies. In order to get a close comparison between the different dyeing methods, colourfastness results from sample discontinuous dyeing with dark solid colours have been taken. The quality of colour fastness was tested using AATCC test methods: AATCC 15 Colourfastness to Perspiration, AATCC 82 Colourfastness to Crocking, AATCC 61 Colourfastness to Laundering, AATCC 16 Colourfastness to Light.

For different end usage, a different method might be chosen. Such as, dope dyeing is one of the best resource-saving polyester dyeing processes and the technology itself is not new and it has proven its system in an operational system, however, the colour range is limited to darker colours like blacks, blues and browns and therefore would not be recommended for a collection that requires bright or lighter colours.

Not enough testing has been done on AirDye to support its colourfastness performance and no information was available on its lightfastness, therefore AirDye will be a hard recommendation to make and requires further research and testing.

Supercritical CO2 dyeing is an excellent choice for a circular economy as CO2 can be reused, however the lightfastness properties can sometimes be below requirements. This can be improved by adopting other environment friendly methods in dyeing such as plasma pre-treatment. According to (Özdoğan, 2009), treating fabrics with air and argon plasma at high exposure durations, showed higher lightfastness. According to new research (Elmaaty, 2019), the light fastness properties of polyester dyed with polyester is 5/5.

Similarly, spray dyeing has to guarantee better colourfastness performance with respect to rubbing and lightfastness, this can be achieved either by creative pre-treatment or finishing as well as further investment into research and development of this technology is required as polyester dyeing is still lab-scale.

In contrast, natural dyes are at the moment irrelevant alternatives for garments mainly due to the limited colourfastness performance and non-commercial ability while the environmental benefits of natural dyes being insignificant.

It is crucial to implement methods into the production that gives the best possible results. In order to do this, accurate information about colourfastness of waterless dyed fabrics should be provided to consumers for their wise choice in purchasing and consuming environmentally conscious textile products. Additional textile testing, such as colourfastness to burnt gas fumes, dry-cleaning, light, chlorine bleach, and non-chlorine, should be conducted for more detailed information about the product’s colourfastness. Further research is also suggested for fabrics with different fibre blends and finishing methods to improve colourfastness as well as to expand the use of sustainable dyeing for the environment.

	Air Dye	ScCO2 Dyeing	Dope Dyeing	Spray Batch Dyeing (DyeMax)
Water	95% less water	Co2 is used instead which is 90% recycled.	89% less water consumption	90% reduction of water consumption
Energy	86% less energy	80% less energy	63% less energy consumption	90% reduction in energy consumption
Colourfastness Performance (Ivanova, L. I., 2022 and Lowe et al., 2020)	Wash fastness: 3 Rubbing: 3.5 Dry, 1.8 Wet Perspiration: 2.5 Dark Solid Colour	Wash fastness: 5 Rubbing: 4-5 dry, 4 wet Perspiration: 5 Lightfastness: 6 Dark blue	Wash fastness: 5 Rubbing: 4-5 dry, 4 wet Perspiration: 5 Lightfastness: 8 Dark blue	Wash fastness: 4-5 Rubbing: 4-5 dry, 3 wet Perspiration: 4-5 Lightfastness: 4 Dark Grey
Commercial Viability	The machine installation cost is high.	Machinery cost is higher than traditional ones, but the production costs are 50% lower and more beneficial due to the current high energy and gas prices.	Already used in the industry	Quickly implemented in industry however, polyester spray dyeing in still lab scale.

Table 2: Comparison of different sustainable polyester dyeing technologies

4. References

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

2. Bide. (2016). Roadmap to Sustainable Textiles and Clothing: Environmental and Social Aspects of Textiles and Clothing Supply Chain. *SpringerLink*.

3. De Giorgi, C. M. (2000). Dyeing polyester fibres with disperse dyes in supercritical CO2. Dyes and Pigments. *45(1)*, 75-79. Retrieved from https://doi.org/10.1016/s0143-7208(00)00011-5

4. Dhanabalan, S. &. (2014). *Air-Dyeing Technology-A Review*. Textile Today.

5. Dyecoo. (2016). *CO2 Dyeing*. Retrieved from http://www.dyecoo.com/co2-dyeing

6. Elmaaty, T. A. (2019). Green Approach to Dye PET and Nylon 6 Fabrics with Novel Pyrazole Disperse Dyes under Supercritical Carbon Dioxide and Its Aqueous Analogue. Fibers and Polymers. *20(12)*. Retrieved from https://doi.org/10.1007/s12221-019-1208-7

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

8. Gurudatt, R. B. (2005). Dope-dyed Polyester Fibers from Recycled PET Wastes for Use in Molded Automotive

   Carpets. *Journal of Industrial Textiles*, *34(3)*, 167-179. Retrieved from https://doi.org/10.1177/1528083705049053

9. Iqbal Mahmud, &. S. (2020). Recent Progress in Waterless Textile Dyeing. *Journal of Textile Science & Engineering*, *10(6)*, 1-3. Retrieved from https://doi.org/10.37421/2165-8064.2020.10.421

10. Ivanova, L. I. (2022). Circular Workwear: Alternative Textile Dyeing Processes [Bachelor Thesis]. *Saxion University of Applied Sciences*.

11. Kraan, V. D. (2005). Process and Equipment Development for Textile Dyeing in Supercritical Carbon Dioxide. *Technische Universiteit Delf*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:7548fc15-db85-44b4-8ae4-58facf60900c/datastream/OBJ/download

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

13. Lowe, V. Z. (2020). A Case Study of Colourfastness of Waterless Dyed Fabrics Sustainable for the Environment. Pivoting for the Pandemic. Retrieved from https://doi.org/10.31274/itaa.11760

14. Maiti. (2022). Textile Coloration TEchnologies: Today and Tomorrow. In M. S. M. Yusuf, Emerging Technologies for Textile Coloration. *CRC Press: Institute*, 1-10.

15. Manea, B. (2020). Polyester Dyeing and its Environmental Impact. *IOP Conference Series: Materials Science and Engineering, 877(1), 012062*. Retrieved from https://doi.org/10.1088/1757-899x/877/1/012062

16. Mehdi. (2018). Preparation of colored recycled polyethylene terephthalate nanofibers from waste bottles: Physicochemical studies. *Advances in Polymer Technology*.

17. Özdoğan, D. K. (2009). EFFECTS OF ATMOSPHERIC PLASMA ON THE PRINTABILITY OF WOOL FABRICS. *Tekstil Ve Konfeksiyon, 19(2),*, 123-127.

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

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

20. Rashedul Islam, U. K. (2011). Comparative Study Among Different Dyeing Methods of Polyester Fabric with Disperse Dyes. *Department of Wet Processing Engineering.*

21. Saxena. (2016). Challenges in Sustainable Wet Processing of Textiles. *Textile Science and Clothing*.

22. Schuster, P. T. (2014). Environmental assessment of coloured fabrics and opportunities for value creation: Spin-dyeing versus conventional dyeing of modal fabrics. . *Journal of Cleaner Production, vol. 72*.

23. Sharma, K. (2007). Pollution hazards in polyester dyeing and role of acid in monitoring. *Current World Environment, 2(2)*, pp. 175-182. Retrieved from https://doi.org/10.12944/cwe.2.2.12

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

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

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

27. Zheng. (2016). An industrial scale multiple supercritical carbon dioxide apparatus and its eco-friendly dyeing production. *Journal of CO2 Utilization*.