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White Paper

Ecological Footprint of Cotton Dyeing and Review of Alternative Technological Approaches for Mitigation

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Executive Summary

Dyeing of cotton is a major contributor to the apparel industry’s environmental impact. The process consumes large amounts of water (driven by repeated washing cycles post dyeing), energy (driven by high water temperatures required to carry out washing cycles) as well as auxiliary chemistries and salt which require cumbersome effluent treatment & disposal. Furthermore, the process contributes to chemical pollution as unfixed dyes and other potentially toxic auxiliary chemical agents are released through wastewater.

This white paper explores the key drivers of the environmental impact of cotton dyeing and provides an overview and critical assessment of technological innovations and alternative processes that have been introduced to make the process more sustainable. Specifically, this white paper examines dyeing using supercritical CO2, heat- & pressure-based air dyeing technologies, microbial pigments as well as cationization technologies for their environmental impact as well as commercial viability.

Finally, this white paper introduces Livinguard’s sustainable cotton dyeing solutions portfolio consisting of Livinguard +DYE and Livinguard SFD with tremendous potential to transform the industry’s footprint while providing beneficial economics for manufacturers.

About Livinguard Technologies AG

Livinguard Technologies is a Swiss material science company focused on enhancing the functionality & performance of materials across various applications through the power of surface charge.

Livinguard’s mission is to safeguard the wellbeing of people and the environment with its high performance, sustainable technology platform. Understanding that we have one planet with limited resources has shaped Livinguard’s approach to innovation helping our partners change consumption patterns and processing parameters to limit the generation of waste and use of resources while maintaining highest standards of safety and quality.

Introduction

Humans have been coloring fabric already for millennia with the earliest record being traced back to 3500 BC. Until 1856, when W.H. Perkins discovered synthetic dyes, all dyes were made with natural pigments and oils. Nowadays it is estimated that 90% of textiles are dyed synthetically.

Current textile dyeing practices contribute significantly to the industry's poor environmental track record due to their excessive use of water, energy, and pollution. The World Bank Group has identified over 70 toxic chemicals originating solely from textile dyeing.

Scrutiny of brands and processing mills to address these issues has increased in recent years – not only from government bodies and regulators but also consumers worldwide. Consequently, the demand for solutions addressing the key drivers of ecological impact has been on the rise and various established companies, startups and research projects have proposed a broad array of alternative solutions and processes.

This whitepaper aims at providing a comprehensive overview and critical assessment of the various solution avenues and introduces Livinguard's sustainable cotton dyeing portfolio.

Environmental Impact of Cotton Dyeing

The global apparel industry with a value of USD 1.3 trillion in 2023 and employing over 300 million people along the value chain contributes significantly to many economies around the world. Global fiber production has almost doubled from 58 million tons in 2000 to 116 million tons in 2022 and is expected to continue growing to 147 million tons in 2030.

While especially the fast fashion sector is booming, increasing attention has been brought to the numerous negative environmental impacts that the apparel industry is responsible for.

- Water consumption: The fashion industry is the second-biggest consumer of water with the production of a single cotton t-shirt requiring up to 2,700 liters (about 713.26 gal) of water. Each year, the textile value chain uses 215 trillion liters of water – with fiber production having the highest impact on freshwater withdrawal due to cotton cultivation – more than 20x the global daily need for freshwater.
- Water pollution: The textile industry is responsible for 20% of global industrial wastewater and contributes significantly to chemical pollution.
- Energy consumption and carbon footprint: Energy use and resulting carbon emissions of the fashion sector are substantial. The sector accounts for 2-8% of global carbon emissions driven by energy-intense manufacturing processes and transportation in globalized supply chains. This figure supersedes emissions from the aviation and shipping industries combined and could rise to 26% by 2050 if current trends continue. Textile purchases in the EU on average caused a carbon footprint of 270kg (about 595.25 lb.) per person.
- Waste from overproduction: Between 10-40% of produced garments are not sold and end up as waste without ever having been worn even once.
- Deforestation: Around 70 million trees are cut down annually to produce fabrics like rayon and viscose exacerbating the industry's impact on global warming even further.

Dyeing of cotton has been identified as a major contributor and driver of the outlined environmental challenges above.

Water consumption

Dyeing cotton is a highly water intensive process. It is estimated that dyeing and finishing can use over 125 liters (about 33.02 gal) of water per kilogram of processed cotton fibers. Almost two thirds of water consumption are attributed to the repeated washing and soaping process steps after dyeing which are required to wash out unfixed dyes from the treated fabric to ensure water and washing fastness and prevent cross-staining.

Water pollution

Textile dyeing is the second-largest polluter of water globally, contributing to severe ecological impacts particularly in water-scarce regions. Usually, cotton only takes up around 70% of the dye that is being used. It is estimated that about 200,000 tons of dyes (worth 1 billion USD) are lost to effluent due to inefficient dyeing and finishing processes. This means current dyeing practices are not only wasteful of resources and money but also release toxic chemicals into freshwater sources.

Energy consumption & carbon footprint

Not only does dyeing require huge volumes of water, but it also relies on massive amounts of energy to heat up water and steam that is necessary for processing at high temperatures from bleaching, dyeing and repeated washing of the fabric. Effluent treatment requires reverse osmosis and water treatments to retrieve salt and other solids from the wastewater are further major contributors to the carbon footprint of cotton dyeing.

Review of Sustainable Dyeing Technologies

The fundamental process of cotton dyeing has not changed for decades, but mostly incremental improvements have been made through better dyestuffs, fixing agents or other auxiliary chemicals used in the process (for example soaping agents).

To mitigate the environmental impact of cotton dyeing, a variety of revolutionary alternative approaches and technologies are currently being explored ranging from waterless technologies such as supercritical CO2 or other heat & pressure-based technologies, over microbial pigmentation to finally cationization technologies.

Dyeing using Supercritical CO2

Various ventures such as the Dutch company *DyeCoo* have presented innovative closed-loop processes for dyeing using supercritical CO2. In this process, carbon dioxide is pressurized and heated above its critical point, turning it into a supercritical fluid. In this state, CO2 exhibits properties of both a liquid and a gas, making it a very good solvent for dyes. This allows the dyes to dissolve easily and penetrate deeply into the fibers, resulting in vibrant colors.

This technology possesses various advantages and environmental benefits. The process uses no water at all, eliminating wastewater and the need for water treatment. It does not only show a remarkable uptake of dyes but also avoids the use of additional chemicals such as surfactants or leveling agents, which are typically required in water-based dyeing. The “dry” process reduces the energy required for water evaporation, making it more energy-efficient compared to conventional dyeing methods.

While supercritical CO2 dyeing is well-suited for synthetic fibers like polyester and nylon, it is less commonly used for natural fibers like cotton. This is because cotton's hydrophilic nature makes it less compatible with the non-polar supercritical CO2, which is better suited for hydrophobic fibers. Cotton often requires pre-treatment with specific chemicals, such as polyethylene glycol (PEG), to improve dye uptake and fastness when using supercritical CO2. Recent advancements have demonstrated the feasibility of dyeing pure cotton on a pilot scale, highlighting the technology’s potential as a green and safe medium for textile dyeing.

Despite some commercial success and noteworthy endorsements from textile mills and brands, there are several challenges to dyeing cotton using supercritical CO2 besides compatibility with the natural fibers which have limited wide-spread deployment of the technology so far. First, the process requires specialized and expensive equipment capable of withstanding high pressures and temperatures, which are be costly to set up and maintain. Dyeing facilities can no longer use their established equipment but are required to make significant capital investments to convert their processes to supercritical CO2. Furthermore, the dyeing process requires maintaining supercritical conditions, which involve high pressures (200 to 250 bar) and temperatures (80 to 120°C). Managing these conditions can be challenging and energy intensive. Moreover, the process is not compatible with widespread continuous dyeing setups. Finally, not all dyes are soluble in supercritical CO2, which limits the range of colors and types of dyes that can be used effectively. This is particularly true for dyes traditionally used for natural fibers, which may not dissolve well in supercritical CO2.

Heat- & Pressure-based Air Dyeing Technologies

The Japan-based company *AirDye* (formerly *Colorep*) and UK-based *Endeavour Alchemie* have introduced a process that transfers color to textiles through a molecular-level process driven by heat and pressure. The dyeing process involves a spray-type technique where dye is atomized and mixed with high-pressure air. This mixture is then sprayed onto the fabric, allowing the dye to penetrate the fibers deeply. The UK-based company *xefco* has introduced a plasma dyeing process and equipment to apply color to a variety of substrates which works on a similar mode of action.

These innovative technologies drastically reduce water and energy consumption, as fabrics no longer require repeated soaking and heat-drying. They also reduce greenhouse gas emissions by up to 85% and minimize hazardous waste. For example, *AirDye* claims an impressive reduction compared to traditional dyeing methods, consuming 90% less water and 85% less energy, making it a game-changer in sustainable textile coloring. The *AirDye* technology furthermore allows for simultaneous printing or dyeing on both sides of the fabric, offering a broad range of design possibilities.

Similar to the supercritical CO2 technology, these heat- and pressure-based processes are primarily used for synthetic fibers such as polyester and are not or less suitable for natural fibers like cotton without specialized pre-treatments. Also, these technologies are reported to have very limited adoption due to the need for expensive, specialized equipment completely substituting existing machinery. The corresponding capital expenditures as well as challenging cost implications for processing mills essentially render these technologies economically unfeasible. Finally, the process furthermore is only suitable for smaller batch processing but cannot cover the massive scale required by most processing mills catering to global brands.

Technologies based on Microbial Pigments

Various companies such as England-based *Colorifix* or *Faber Futures*, and research projects like Dutch *LivingColour* or Austrian *Vienna Textile Lab*, are pioneering the exploration of microbial dyes. Companies like *huue* have developed a process to create an indigo blue dye for application in the denim industry that is based on cultivating special microbes on a sugar-based medium. These technologies involve fermenting microbes or other organisms to produce natural dyes removing industrial synthetic dyestuffs and chemicals or salts to infuse color into textiles. For example, *streptomyces coelicolor* is a microbe that naturally changes color based on the pH of the medium it grows inside.

The process of dyeing with microbes typically starts by autoclaving a textile to prevent contamination. Then a liquid medium filled with bacterial nutrients is poured over the textile. The textile is then exposed to bacteria and is left in a climate-controlled chamber for a couple of days. During this time, the bacteria is changing the color of the fabric. Finally, the textile is rinsed and laundered to wash out the smell of the bacterial medium.

Microbial pigments offer a promising alternative to synthetic dyes due to their biodegradability and lower environmental impact. Cotton, being a natural fiber, does not always interact well with microbial pigments as the binding affinity of these pigments to cotton fibers is reported to be less effective compared to synthetic dyes, often-times requiring additional treatments to improve adherence and color intensity.

Despite many promising properties, there are several challenges associated with using microbial pigments for dyeing cotton: First, the extraction of pigments from microbial sources can be complex and costly. It often requires specific conditions and substrates to optimize pigment production, which has been a major barrier to large-scale application so far. Furthermore, microbial pigments do not always provide the same level of color fastness as synthetic dyes resulting in colors that fade more quickly when exposed to washing, light, or other environmental factors. Moreover, while microbial pigments are generally considered non-toxic and environmentally friendly, there are regulatory hurdles related to their use in textiles, particularly concerning safety and potential allergens. Finally, scaling up the production of microbial pigments to meet industrial demands has proven to be challenging.

Cationization Technologies

Cationization technologies are based on the chemical modification of either the cotton fiber / fabric or the dye itself to make the substrate more receptive to dyestuffs and create a bond between the fiber and dye. This approach promises to eradicate the need for salt in the dyeing process while improving dye-uptake and limiting required washing post dyeing.

While the basic concept of cationization for dyeing has already been around and explored for years, there are various challenges that have so far limited widespread adoption:

- Uneven dyeing and shade variations: High levels of cationization can lead to rapid dye adsorption which may result in uneven dye distribution and shade variations on the fabric. This is particularly problematic when using dye mixtures as it makes it difficult to achieve uniform color distribution, especially for light to medium shades.
- Chemical consumption and efficiency: The cationization process requires a substantial amount of chemicals, such as CHPTAC, for effective treatment. However, the chemical efficiency is often low, with only a small portion of the cationizing agent being fixed onto the cotton fibers. This high chemical consumption can negatively impact the ecological profile of the dyeing process and overcompensates potential cost savings in salt and dyestuffs.
- Dye fixation and color fastness: Achieving successful dye fixation and issues like constant bleeding of the dye during washing resulting in low water fastness has been a major drawback and limitation of cationization technology thus far. Furthermore, cationized dyeing is known to have fastness challenges with exposure to light.
- Unpleasant odor: Cationized fibers have been reported to have an unpleasant odor due to the characteristics of certain cationic compounds used in the process.
- Cost and required process adjustments: Although cationized dyeing reduces the need for salt and alkali, the process involves additional steps and costs associated with the chemical treatment of cotton. It is estimated that the most common cationization approaches result in 10-15% higher total dyeing costs. Adapting existing dyeing facilities to incorporate cationization have thus far presented a logistical and financial challenge.

In recent years, there has been advancements to overcome these limitations as this technological approach has shown the highest promise of providing a commercially viable solution that can be deployed across dyehouses globally at scale. Currently, there are three major avenues for cationization pre-treatment explored.

Cationization of Fibers

The US-based company *ColorZen* has introduced in 2012 a technology based on a cationization pre-treatment of cotton before spinning in order to positively charge the fiber making it more receptive to uptake dyestuffs in subsequent processing.

The approach promises to revolutionize the dyeing process, achieving remarkable reductions of up to 90% in water usage, up to 75% in energy consumption, and up to 90% in chemical usage compared to traditional cotton dyeing methods. Through the pre-cationization, the process eliminates the need for salt in the dyeing process and lowers dyeing time and dyeing process costs.

After strong recognition and initial PR, the process did not gain much commercial traction, most likely attributable to the pre-processing requirements and their substantial implications on sourcing and supply chains of producing mills. Implementing ColorZen's technology requires coordination across various stakeholders in the supply chain, from raw cotton producers to end-product manufacturers. Establishing these global production pathways has turned out to be a significant challenge not compatible with how the industry operates today.

Cationization of Fabric

The international chemical company *Dow* introduced in 2018 a cationic treatment called *Ecofast Pure* to enhance sustainability and efficiency of cotton dyeing.

The process begins with a pre-treatment of cotton fabrics used to modify the cotton fibers and make them more receptive to dyes to enhance dye uptake and reduce the need for excess dye washing and other chemicals. The solution promises up to 90% reduction in chemicals use and the eradication of salt in the dyeing process, up to 50% less water due to fewer rinses needed and faster cycle times. Furthermore, up to 50% less dyestuff is required due to improved dye uptake and the process allows for room-temperature dyeing. The treatment is compatible with existing dyeing equipment, which facilitates its integration into current manufacturing processes without the need for capital expenditures due to new machinery.

While the process and technology presented by Dow can use existing equipment, it still requires changes in supply chain practices and collaboration across various industry stakeholders adopt practices and dye recipes, besides a major increase in cost of production. This has been so far a major barrier to rapid implementation. Initial implementation costs to adopt the processes, for example to train staff, have been a further limitation to widespread adoption. While the Ecofast technology promises increases in productivity and efficiency, it is said to be priced high which has further limited adoption in a highly cost sensitive environment. The process introduced is said to require a thermal drying and curing step after the cationization phase which posed a major roadblock in established processes. Finally, there have been reports of unevenness of the dyeing which most likely limited the adoption of this disruptive solution so far.

Cationized Dyestuffs

The international specialty chemical company *DyStar* introduced in 2023 a solution for eco-advanced Indigo dyeing eradicating the use of inorganic salt. The technology promises to reduce water usage by up to 90% and energy consumption by up to 30% as well as substantially decrease the effluent load in Denim production. The technology can be applied to the indigo traditional dyeing process, for sulfur dyes, and colored denim. There is limited further information on DyStar’s technology available publicly.

Livinguard Sustainable Dyeing Portfolio

Livinguard's mission is to safeguard the wellbeing of people and the environment with its high performance, sustainable technology platform. Understanding that we have one planet with limited resources has shaped Livinguard's approach to innovation - helping partners change consumption patterns and processing parameters to limit the generation of waste and use of resources while maintaining highest standards of safety and quality.

With this mission in mind, the company has investigated various approaches to tackle the disastrous environmental impact of cotton dyeing for multiple years. This investment that has now paid off after a series of recent technological breakthroughs, Livinguard has taken steps towards the commercialization of two technologies for sustainable cotton dyeing.

Livinguard +DYE

Livinguard +DYE is an additive used to reduce the number, duration and temperature of wash and soap cycles needed to remove unfixed dyes in an otherwise conventional wet dyeing process for 100% cotton/viscose and cotton/Lycra blends.

The solution promises disruptive sustainability and cost impact for mills with up to 30% water savings and up to 70% energy & CO2 savings while providing up to 35% increase in productivity and full compatibility with established equipment. Furthermore, the technology allows for up to 20% lower dosing of dyestuffs due to increased color depth, the partial or complete substitution of other chemical additives such as soaping agents, and higher production up-time even during water shortages.

Livinguard understands that sustainable technologies will have only limited adoption unless they provide not only environmental benefits but also interesting economics for processing mills. Based on initial calculations and estimates, the adoption of the Livinguard +DYE technology has the potential to decrease the total cost per processed volume by 5-10%.

The Livinguard +DYE technology has been successfully validated at laboratory and bulk scale as well as various field trials with renowned textile mills. Currently, Livinguard Technologies is working towards commercialization at scale with various early adopters evaluating the solution in their production environment.

Livinguard SFD

Livinguard SFD is a breakthrough new approach enabling completely salt-free dyeing and reducing required RO treatments to recover salt after dyeing and eradicating all washing post dyeing without any capital expenditures. The technology's approach is built on cationization of the fabric before dyeing. Whereas the process and approach overall resembles *Dow's Ecofast* solution, Livinguard SFD leverages a cationic molecule that provides significantly higher efficiency in the process, allows for a wet-on-wet process (aka does not require interim drying of the fabric before dyeing) and is priced more favourably to drive rapid adoption of the technology.

Livinguard SFD environmental and economical savings are comparable to Livinguard +DYE – however this technology also addresses the impact of salt in the process.

Technical feasibility has been established for Livinguard SFD and the technology has been successfully tested for performance at laboratory scale. While still at an earlier stage of development, testing for safety and bulk-scale tests are currently being initiated.

Transformative Impact

Shifting the entire addressable global production of around 7 million tons of processed cotton annually to Livinguard's sustainable dyeing solutions could have a transformative environmental impact. Based on initial estimates, Livinguard's technology portfolio could save up to 190 billion liters (about 52 billion gallons) of water and 7 million tons of CO2 annually. Other sustainability benefits such as additional greenhouse gas savings from production, transportation and discarding/ insinuation of salt, dyestuffs and other chemistries have not yet been considered in these estimates.

Beyond the outlined environmental impact and cost savings for processing mills, Livinguard's sustainable dyeing portfolio also provides tangible benefits for apparel brands as they can make tangible progress towards their scope 3 greenhouse gas emission goals. Furthermore, brands can mitigate reputational risk stemming from production of goods sold and greenwashing while improving their brand positioning around sustainability and corporate social responsibility.

Conclusion

Due to increasing demand driven by higher scrutiny on brands and processing mills to decrease the environmental impact of cotton dyeing, various potential solution avenues for sustainable cotton dyeing have emerged in recent years. These range from supercritical CO2, heat- and pressure-based air dyeing, microbial pigments to cationization technologies.

While all these approaches promise a transformative environmental impact by drastically reducing water, energy and chemical consumption, none of these technologies have so far seen broad commercial adoption. Despite prominent endorsements and PR success, it is understood that the challenges involved around commercial feasibility, operational complexity and higher costs have been the biggest challenges to widespread adoption.

Livinguard pioneered the development and is driving the commercialization of two solutions that promise to deliver impact for the environment while providing disruptive economics for processing mills.

References

Abedin, Ashik (2021). Comparative study between cationic cotton dyeing and conventional dyeing: An approach towards sustainability.

Agarwal, Bipin J. (2015). Supercritical Carbon-dioxide Assisted Dyeing of Textiles: An Environmental Benign Waterless Dyeing Process.

Beltrame, Luigi & Castelli, Antonella & Mossa, Andrea & Selli, Elena & Testa, Giovanni & Bonfatti, Anna Maria & Seves, Alberto (1998). Dyeing of Cotton in Supercritical Carbon Dioxide.

De Oliveira Barreto, Joao Vitor & Casanova, Livia Marques & Neves, Athayde & Vermelho, Alane Beatriz (2023). Microbial Pigments: Major Groups and Industrial Applications.

Choudhury, A.K. Roy (2014). Coloration of Cationized Cellulosic Fibers–A Review.

Elmaaty, Abou & Kazumasa, Hirogaki & Elsisi, Hanan & Mousa, Abdalla & Sorour, Heba & Gaffer, Hetem & Hori, Teruo & Hebeish, Ali & Tabata, Isao & Farouk, Reham (2020). Pilot scale water free dyeing of pure cotton under supercritical carbon dioxide

Fu, Sha (2016). Studies on Cationized Cotton.

Gao, Dan & Yang, Da-fa & Cui, Hong-sheng & Huang, Ting-ting & Lin, Jin-xin Lin (2015). Supercritical Carbon Dioxide Dyeing for PET and Cotton Fabric with Synthesized Dyes by a Modified Apparatus.

Goñi, María L. & Gañán, Nicolás A. & Martini, Raquel E. (2021). Supercritical CO_2-assisted dyeing and functionalization of polymeric materials: A review of recent advances.

Jha, Joti & Meenu, Kumari (2017). Microbial pigment as an alternative to synthetic dye.

Kannan, Subramanian & Mariappan, Gopalakrishnan Senthil (2006). Influence of cationization of cotton on reactive dyeing.

Mahmud, Iqbal & Kaiser, Shantanu (2020). Recent Progress in Waterless Textile Dyeing.

Rather, Luqman Jameel & Mir, Shazia Shaheen & Ganie, Showkat Ali & Islam, Shahid-ul-Islam & Li, Qing (2023). Research progress, challenges, and perspectives in microbial pigment production for industrial applications - A review.

Setthayanond, Jantip & Netzer, Felix & Seemork, Kattika & Suwanruji, Potjanart & Bechtold, Thomas & Pham, Tung & Manian, Avinash P. (2023). Low-level cationisation of cotton opens a chemical saving route to salt free reactive dyeing.

Thomas, M. (2019). Water and chemical free dyeing with CO2.

Walker, Alissa (2009). AirDye's Ecological Dyeing Process Makes the Future of Textiles Bright.

Willis, Sofia (2023). How sustainable dyeing is changing the textile industry.

Wilson, Adrian (2024). Eco-Dyes are on the rise.

Zhang, Han & Fu, Ranran & Zheng, Qiumeng & Song, Xiaoping & Wu, Jing & Ren, Yanfei (2024). Continuous mode of color and functionality construction for cotton by bacterial pigment based on nano-suspension system.

Zhang, Tingting & Zhang, Song & Qian, Wei & He, Jinxin & Dong, Xia (2021). Reactive Dyeing of Cationized Cotton Fabric: The Effect of Cationization Level.

Company & project websites of referenced technologies