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Dyeing Without Damage: The Rise of Waterless and Carbon-Neutral Solutions in Textile

Aniqa Ansari[1], Nikhila Rane[2]

[1]Master's Students, Department of Textile Science and Apparel Design, SNDT Women's University
[2]Assistant Professor Department of Textile Science and Apparel Design, SNDT Women's University

Abstract

Dyeing the textile material is essential for its aesthetic appeal. This process uses a large amount of water and releases untreated wastewater laden with hazardous chemicals. It has a major contribution to environmental pollution. Conventional dyeing methods are energy-intensive, which contributes to global greenhouse gas emissions. It is accepted that the textile industry is one of the highest water consumers. To limit this wastewater process, researchers and technologies have developed transformative alternatives. This review paper focuses on the latest advancements in waterless dyeing methods, like supercritical carbon dioxide ($scCO_2$) dyeing, plasma treatment, and digital printing, and evaluates their potential to reduce water usage and chemicals, and increase dye uptake. These dyeing technologies are sustainable and eco-friendly. The paper explores carbon-neutral strategies that aim to minimize the carbon footprint of textile coloration. Using renewable energy in dyeing units, bio-based dyes, closed-loop systems, and eco-efficient machinery are adopted to reduce the environmental impact of the dyeing process.

Keywords: Dyeing, wastewater, Supercritical carbon dioxide dyeing, plasma, sustainable, carbon neutrality.

1. Introduction

The fashion and textile industry are the world's most environmentally damaging sectors, consuming a large amount of water and energy, releasing greenhouse gas emissions, with toxic effluents. The fashion industry alone contributes 10% of global carbon emissions, while dyeing and finishing processes account for 20% of global water pollution (Kim, M., et.al. 2024). Water is considered the universal solvent and dyeing medium. The traditional textile processing involves steps like desizing, scouring, bleaching, dyeing, printing, and other finishing processes. Water consumption during the wet processing process is the highest in the bleaching process, which is 38%. The boiler takes 14% of the water intake, dyeing includes 16% and the printing process takes 8% of the water consumption (Mahmud, I., et al. 2020).

The dyeing and finishing of one kg of cotton fibers requires 125L of water to complete the process (Khalil, E. et.al. 2023). Wastewater from these processes contains heavy metals, salts, surfactants, and untreated dyes, which are difficult to eliminate and cause severe problems to aquatic life and public health. The over-increasing demand and fast fashion trends lead to more production and, in return, contribute to the environmental impact. To overcome this issue, sustainable dyeing technologies have accelerated to reduce the impact on the environment and to save water. Technology has been introduced to dye the textile material without water, called Supercritical Fluid Dyeing technology. CO_2 gas is used for dyeing that has the capacity to be in a liquid and gas state at certain temperatures and pressures (Miah, L., et al. 2013). Carbon-neutral dyeing uses renewable energy, biobased pigments, and closed-loop systems. These are emerging to lower or entirely offset carbon emissions. These approaches aim not only to reduce emissions but also to establish circular economy models within the textile supply chain. Besides this, using natural dyes and mordants, bio-based pigments, nano dye, and bacterial cellulose are other sustainable approaches towards the environment.

2. Waterless Dyeing Technologies

Traditional dyeing techniques are not only a water-intensive process but also harm the environment by generating large volumes of polluted wastewater containing dyes, salt, surfactants, and heavy metals. As a result, the textile industry needs to adopt sustainable practices in its production. Waterless dyeing technologies have emerged to eliminate or drastically reduce water use and create cleaner and more efficient dyeing systems. The technologies included in waterless dyeing are supercritical carbon dioxide ($scCO_2$) dyeing, plasma dyeing, and digital printing.

2.1 Supercritical CO_2 Dyeing

Supercritical CO_2 dyeing is a sustainable dyeing method that offers proven benefits in waterless dyeing processes. It reduces water use, effluent energy, and chemical consumption by delivering better colour quality on synthetic material. German professor Schollmeyer and his research group had first established the supercritical fluid in the late 1980_s (Mahmud, I., et al. 2020). CO_2 is the most widely used solvent in supercritical fluid due to its low cost, availability, non-flammability, and being environmentally friendly.

Supercritical fluids operate at higher temperatures and pressures than the critical value. The critical values refer to the maximum temperature and pressure at which the substance remains in equilibrium. Their characteristics are identical to those of a gas and a liquid, and can be changed by adjusting the pressure. Its critical temperature is 31.1°C and pressure is 74 bar (Mahmud, I., et al. 2020). This state is particularly suitable for hydrophobic dyes. CO_2 becomes an excellent solvent for disperse dyes due to its low polarity molecular structure (Zheng, H., et al. 2018). The process is carried out by placing the fabric in a high-pressure vessel, and then supercritical CO_2 is passed along with dye. The dye dissolves in $scCO_2$ and penetrates the fiber due to its low surface tension and diffusivity. Pressure above 74 bar is maintained for the dyeing period of 50 to 70 minutes. After CO_2 is depressurized, excess dyes are separated and recycled.

The first waterless dyed T-shirt was produced in Thailand, developed by Dyecoo textile system (Li, S., et al. 2020). Dyecoo is also the first supplier of CO_2 dyeing equipment.

Challenges:

Despite the advantages of supercritical carbon dioxide, there are challenges associated with carrying out this process. The investment cost is high for the high-performance equipment. Skilled manpower is needed to operate the machine. The dyeing process is complex and is limited to disperse dyes and synthetic fibers.

Natural fibers are not compatible due to poor dye solubility. As the process requires high temperature and pressure, this poses safety concerns for operation.

2.2 Plasma Treatment

Plasma treatment of textiles is a highly beneficial technique that improves dyeability and reduces the consumption of water, energy, and time. It has garnered sufficient attention from the textile industry due to its economic and biodegradable nature. Plasma treatment is preferably applied as a pre-treatment before the conventional dyeing process, where the dye wastewater remains a challenge. In post-treatment, it makes a huge difference in reducing the dye wastewater (Haque, A. N. M. A., et al. 2023). Plasma is a partially ionized gas, which is also categorized as the fourth state of matter. When this is subjected to high energy, the outermost electron from an atom escapes and becomes a free negative charge, while the atom becomes positively charged. The chemical status of a substance is called plasma.

It is further classified as cold or hot plasma depending on the working pressure. Cold plasma is applied to the textile fibers for the polymer fiber because it provides thermal stability to the fiber (Das, R., et al. 2023). The most common application of plasma treatment is surface coating and cleaning. Plasma treatment provides and improves the wettability and adhesion properties of the fiber. Plasma treatment helps at the surface levels by altering roughness and removing impurities. It introduces functional chemical groups- (-COOH, -OH, NH_2) for surface activation that improve wettability and dye affinity. The plasma-treated polymerized fabric contains properties such as antibacterial finishing, UV protection coating, highly cross-linked, water repellent, etc.

In plasma treatment, the use of water is minimized by using a spraying method for both the mordanting and dyeing stages. At the pre-treatment phase, plasma treatment enhances the wettability and dye affinity of the cotton fabric with the help of the creation of new chemical groups on the cotton surface associated with the formation of cellulosic radicals, which then chemically react with plasma particles (Khalil, E., et al. 2023). Cold plasma treatment has demonstrated efficiency in natural fibers like cotton, wool, silk, and jute, with studies showing enhanced dye uptake, shrink resistance, mechanical strength, and moisture handling (Das, R., et al. 2023).

2.3 Limitations

The important limitations of plasma treatment are that designing industrial-scale, consistent plasma systems is complex. The atmospheric plasma treatment is still a challenge because of the ageing factor of plasma-treated material. The operational cost and equipment cost are high. Process standardization of different fabric types can be different, which involves fine-tuning gas types, pressure, power, and exposure time.

3. Carbon Neutral Process

Carbon neutrality means achieving a dyeing process that results in approximately zero carbon emissions by reducing greenhouse gas (GHG) emissions from dyeing and printing wastewater treatment. Printing and dyeing wastewater contains a large volume of water, high levels of organic solvents, high toxicity, high salt content, and is difficult to biodegrade (Yin, H., et al. 2025). The treatment methods are divided into physical, chemical, and biological methods. The physical methods, such as adsorption, coagulation, and membrane filtration, effectively remove dye molecules and harmful substances from wastewater. Chemical methods include electrochemical oxidation, Fenton oxidation, Ozone oxidation, and catalytic oxidation (Cui, T., et al. 2023). Biological methods mainly consist of anaerobic and aerobic processes, both of which are economically safe and environmentally friendly options for treatment.

The carbon footprint is not only produced by the dyeing process, but also through the emissions from the onsite fuel combustion released by the boilers or generators in dye production. The electricity used accounts for the indirect emissions. The use of dyes and chemicals, raw materials, cultivation, and lastly, the consumer use and disposal of dyed textiles, all contribute to the carbon emissions directly or indirectly. Researchers have found ways to prevent or limit greenhouse gas emissions by adopting natural and bio-based dyes, renewable sources of energy to replace the fossil-fuel-based sources, and closed-loop systems that recycle and eliminate waste accordingly.

3.1 Natural and Bio-Based Dyes

The use of synthetic dyes involves many chemical reactions with petrochemical-based dye intermediates (Samantha, A.K., 2020). They consume high energy for production and release toxic chemicals into the environment. To reduce the carbon footprint of dyes, the textile industry is turning towards natural and bio-based dyes obtained from renewable sources such as plants, fungi, algae, bacteria, and food or agricultural waste. Several natural sources, extraction processes, and application methodologies can provide diverse hues and biomordants, aiding manufacturers in selecting eco-friendly options for textile coloration (Pranta, A.D., 2024). Natural and bio-based dyes are a great substitute for synthetic dyes as they are environmentally friendly and sustainable. Natural dyes are biodegradable, non-toxic, and generally produced at lower energy intensities. Natural indigo, madder root, turmeric, etc, are used for dyeing cotton, silk, and wool.

Microbial dyes are pigments produced by bacteria, algae, fungi, and yeast through controlled fermentation. These are sustainable and offer low-carbon, biodegradable, and non-toxic coloration methods that align with carbon-neutral dyeing goals. Streptomyces, Chromobacterium, Pseudomonas, and Chlorella sps (Patel, H., et al. 2022) are especially engineered or optimized to increase dye yields, pigment solubility, and colour range. Microbial dyes are gaining attention for their scalability and reproducibility. As far as the limitations, colour consistency, fixation, and limited shade range still need further research and innovation.

3.2 Renewable Energy Integration

The traditional dyeing process was highly energy-intensive and relied on fossil fuels for heating, operating machines, and powering ventilation. The wet processing sector is the most energy- and water-consuming area of the textile industry (Farhana, K., et al. 2022). Extraction of fossil fuels damages the land and water resources, and hence, the combustion of fossil fuels exacerbates the greenhouse effect (Zong, S., 2023). The energy sector started to emphasize renewable energy and witnessed an increased interest in scientific research on the production of energy for the manufacturing industry (Nunes, L.J.R., et al. 2019).

Renewable energy is an alternative to fossil fuels, which are generally obtained from resources that are inexhaustible and abundant (Farhana, K., et al. 2022). Integrating renewable energy sources into dyeing processes is a key strategy for achieving carbon neutrality by eliminating or reducing emissions from energy use. The application of renewable energy in dyeing is the use of solar thermal and photovoltaic systems. They can be used in heating water, steam, and sterilization in the textile industry. This significantly reduces the use of diesel or coal-fired boilers, lowering greenhouse gas (GHG) emissions and operational costs. In India and Bangladesh, multiple small-scale dyeing units have installed solar water heaters, reducing their fossil fuel dependency by over 40% (Mahmud, I., 2020). Biogas for thermal energy generated through anaerobic digestion of organic waste can be used as a fuel source for boilers and drying systems in dyeing units. Food waste, textile cutting waste from natural fibers, and sludge from dye effluent treatment plants are common feedstocks. Compared to fossil fuels such as petroleum products, these wastes generate fewer greenhouse gas emissions; therefore, biomass is considered a sustainable type of energy (Nunes, L, J, R., 2019).

3.3 Closed-Loop Systems

Due to the increasing demand for fast fashion, the textile dyeing sector has been identified as one of the most resource-intensive and polluting segments. The conventional dyeing consumes excessive water, chemicals, and energy while generating large volumes of untreated effluents. As a shift towards carbon neutrality and environmental sustainability, the transition to closed-loop and zero-emission systems helps to minimize the ecological impact and lowers greenhouse gas emissions. A closed-loop system is a process in which used dyes, water, and auxiliary chemicals are recovered and reused, thereby minimizing or eliminating waste generation. The wastewater coming from the dyeing process can have up to 50% of the unfixed dye (Catarino, M, L., et al. 2025). Implementation of zero-liquid discharge and Effluent treatment plants uses a combination of ultrafiltration, reverse osmosis, evaporation, and crystallization to treat the wastewater so that it can be reused (Thombre, N., et al. 2025). As we discussed, the implementation of renewable energy can also help to reuse the thermal energy in preheating or other stages. Using natural dyes and bio-based materials, renewable energy sources, and adapting circular manufacturing processes that align with the closed-loop system will help contribute to for better environment and a sustainable approach.

4. Challenges and Limitations

Innovations in textile wet processing have shown a significant potential in pressing environmental challenges by reducing water, energy, and chemical consumption. Despite the promising benefits of the new technologies, the industrial adoption remains limited due to high investment costs, process scalability, and further optimization (Catarino, M, L., 2025). It needs a high capital investment, which is difficult for small and mid-sized textile manufacturers. Some technologies are restricted to the type of fabric used, like supercritical CO_2 dyes well with hydrophobic synthetic fibers, but limits its application to natural fibers. Implementing renewable and carbon-neutral dyeing systems demands technical abilities and specialized infrastructure. A strong operational understanding is required to operate the machine with proper requirements to ensure safety and reproducibility.

There is a lack of global acceptance for the emerging dyeing techniques in the market. Certifications like Oeko-Tex, GOTS, etc, exist for conventional eco-textile and do not specifically address waterless or carbon-neutral certifications. It creates a gap between the customer and the manufacturer. Hence, successful implementation of these sustainable technologies will depend on combining financial support, training programs, and standardization to overcome these barriers.

5. Conclusion and Future Directions

The global textile industry is undergoing a transformative shift towards environmentally responsible practices to overcome the issue of wastewater management. Waterless as well as carbon-neutral dyeing technologies are at the forefront of this evolution. Conventional dyeing methods are water-intensive and contribute to global pollution and carbon emissions. Whereas, innovations such as supercritical CO_2, plasma treatment, and the use of bio-based or microbial dyes offer alternatives by reducing or eliminating the need for water, toxic chemicals, and fossil fuel-based energy sources. These are helping in biodegradable and low-carbon alternatives, helping close the loop in textile production. The integration of renewable energy, such as solar or biogas, in dyeing units further enhances the carbon neutrality of these processes. Closed-loop or zero-emission systems support the goal of circularity in textile manufacturing.

Despite their advantages, these technologies are hindered by several challenges. High capital investment, fiber limitations, skilled workforce, and certifications have constrained industry-wide implementation. Future research should prioritize large-scale studies for actual industrial implementations. Research in bio-dye optimization will help to reduce greenhouse gas emissions. Future government incentives for water reuse are expected to play a pivotal role in promoting sustainable water management practices by putting regulations, public-private partnerships, capacity building programs, and development of international standards can accelerate sustainable dyeing technologies.

Reference

1. Kim, M., Shim, J.Y., Lim, S. et al. (2024). Reduction of greenhouse gas emissions by optimizing the textile dyeing process using digital twin technology. Fash Text 11, 17. https://doi.org/10.1186/s40691-024-00384-w
2. Khalil, E., Sarkar, J., Rahman, M. M., Shamsuzzaman, M., & Das, D. (2023). Advanced technology in textile dyeing. In Advanced technology in textiles: fibre to apparel (pp. 97-138). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-2142-3_4
3. Miah, L., Ferdous, N., & Azad, M. M. (2013). Textiles material dyeing with supercritical carbon dioxide (CO2) without using water. Chem. Mater. Res, 3(5), 2224-2226.
4. Mahmud, I., & Kaiser, S. (2020). Recent progress in waterless textile dyeing. Journal of Textile Science & Engineering, 10, 1–3. https://doi.org/10.37421/jtese.2020.10.421
5. Galdino Jr., C. J., Medeiros, A. D., Amorim, J. D., Nascimento, H. A., Henrique, M. A., Costa, A. F., & Sarubbo, L. A. (2021). The future of sustainable fashion: Bacterial cellulose biotextile naturally dyed. Chemical Engineering Transactions, 86, 1333–1338. https://doi.org/10.3303/CET2186223
6. Abou Elmaaty, T., & Abd El-Aziz, E. (2018). Supercritical carbon dioxide as a green media in textile dyeing: A review. Textile Research Journal, 88(10), 1184-1212. https://doi.org/10.1177/0040517517697639

7. Zheng, H., Zhong, Y., Mao, Z., & Zheng, L. (2018). CO2 utilization for the waterless dyeing: characterization and properties of Disperse Red 167 in supercritical fluid. Journal of CO2 Utilization, 24, 266-273. https://doi.org/10.1016/j.jcou.2018.01.014
8. Li, S., Zheng, H., Su, Y., Zhao, Y., He, T., & Zheng, L. (2020). Effect of fluid field on the eco-friendly utilization and recycling of CO2 and dyes in the waterless dyeing. Journal of CO2 Utilization, 42, 101311. https://doi.org/10.1016/j.jcou.2020.101311
9. Haque, A. N. M. A., & Naebe, M. (2023). Zero-water discharge and rapid natural dyeing of wool by plasma-assisted spray-dyeing. Journal of Cleaner Production, 402, 136807. https://doi.org/10.1016/j.jclepro.2023.136807
10. Das, R., Dash, C., & Bisoyi, D. K. (2023). A review of cold plasma treatment on textile fibre. Trends in Textile Engineering & Fashion Technology, 7(5), Article TTEFT.000675. https://doi.org/10.31031/TTEFT.2023.07.000675
11. Mohamed, H., El-Halwagy, A. A., & Garamoon, A. A. (2019). Plasma application in textiles. Journal of Textiles, Coloration and Polymer Science, 16(1), 15-32. 10.21608/jtcps.2019.5428.1006
12. Zille, A., Oliveira, F. R., & Souto, A. P. (2015). Plasma treatment in textile industry. Plasma processes and Polymers, 12(2), 98-131. https://doi.org/10.1002/ppap.201400052
13. Arumugam, A., Ramesh Babu, V., & Sundaresan, T. D. (2024). Sustainable dyeing techniques: Advancements and innovations in the textile industry. Melliand Int, 30(1).
14. Yin, H., Yang, C., & Tang, Z. (2025). Assessing GHG emissions and carbon neutral strategies in dyeing and printing wastewater treatment and reuse. Journal of Environmental Chemical Engineering, 13(2), 116004. https://doi.org/10.1016/j.jece.2025.116004
15. Cui, T., Wang, X., Chen, Y., Chen, Y., Fu, B., & Tu, Y. (2023). Reverse Osmosis coupling Multi-Catalytic Ozonation (RO-MCO) in treating printing and dyeing wastewater and membrane concentrate: Removal performance and mechanism. Water Resources and Industry, 30, 100217. https://doi.org/10.1016/j.wri.2023.100217
16. Samanta, A. K. (2020). Bio-dyes, bio-mordants and bio-finishes: scientific analysis for their application on textiles. Chemistry and technology of natural and synthetic dyes and pigments, 3-42. https://doi.org/10.5772/intechopen.92601
17. Pranta, A. D., & Rahaman, M. T. (2024). Extraction of eco-friendly natural dyes and biomordants for textile coloration: a critical review. Nano-Structures & Nano-Objects, 39, 101243. https://doi.org/10.1016/j.nanoso.2024.101243
18. Patel, H., Yadav, V. K., Yadav, K. K., Choudhary, N., Kalasariya, H., Alam, M. M., ... & Jeon, B. H. (2022). A recent and systemic approach towards microbial biodegradation of dyes from textile industries. Water, 14(19), 3163. https://doi.org/10.3390/w14193163
19. Mia, R., Mofasser, A. Z. M., Bhat, M. A., Howlader, M. I., Sayed, N. I., & Bakar, M. A. (2024). Utilizing neem wood waste as a natural dye in the development of bio-based functionalized colored jute fabric. Sustainable Chemistry and Pharmacy, 38, 101489. https://doi.org/10.1016/j.scp.2024.101489
20. Farhana, K., Kadirgama, K., Mahamude, A. S. F., & Mica, M. T. (2022). Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability. Materials Circular Economy, 4(1), 15. https://doi.org/10.1007/s42824-022-00059-1

21. Zong, S. (2023). The systematic application of plant dyeing techniques based on sustainable energy systems in ecological textile design. Cleaner Environmental Systems, 11, 100143. https://doi.org/10.1016/j.cesys.2023.100143
22. Nunes, L. J. R., Godina, R., & Matias, J. C. D. O. (2019). Technological innovation in biomass energy for the sustainable growth of textile industry. Sustainability, 11(2), 528. https://doi.org/10.3390/su11020528
23. Catarino, M. L., Sampaio, F., & Gonçalves, A. L. (2025). Sustainable Wet Processing Technologies for the Textile Industry: A Comprehensive Review. Sustainability, 17(7), 3041. https://doi.org/10.3390/su17073041
24. Thombre, N., Patil, P., Yadav, A., & Patwardhan, A. (2025). A short review on water management and reuse in textile industry–a sustainable approach. Discover Water, 5(1), 1-17. https://doi.org/10.1007/s43832-025-00215-z