"Integrating Circular Economy, SBTI, Digital LCA, and ESG Benchmarks for Sustainable Textile Dyeing: A Critical Review of Industrial Textile Practices"

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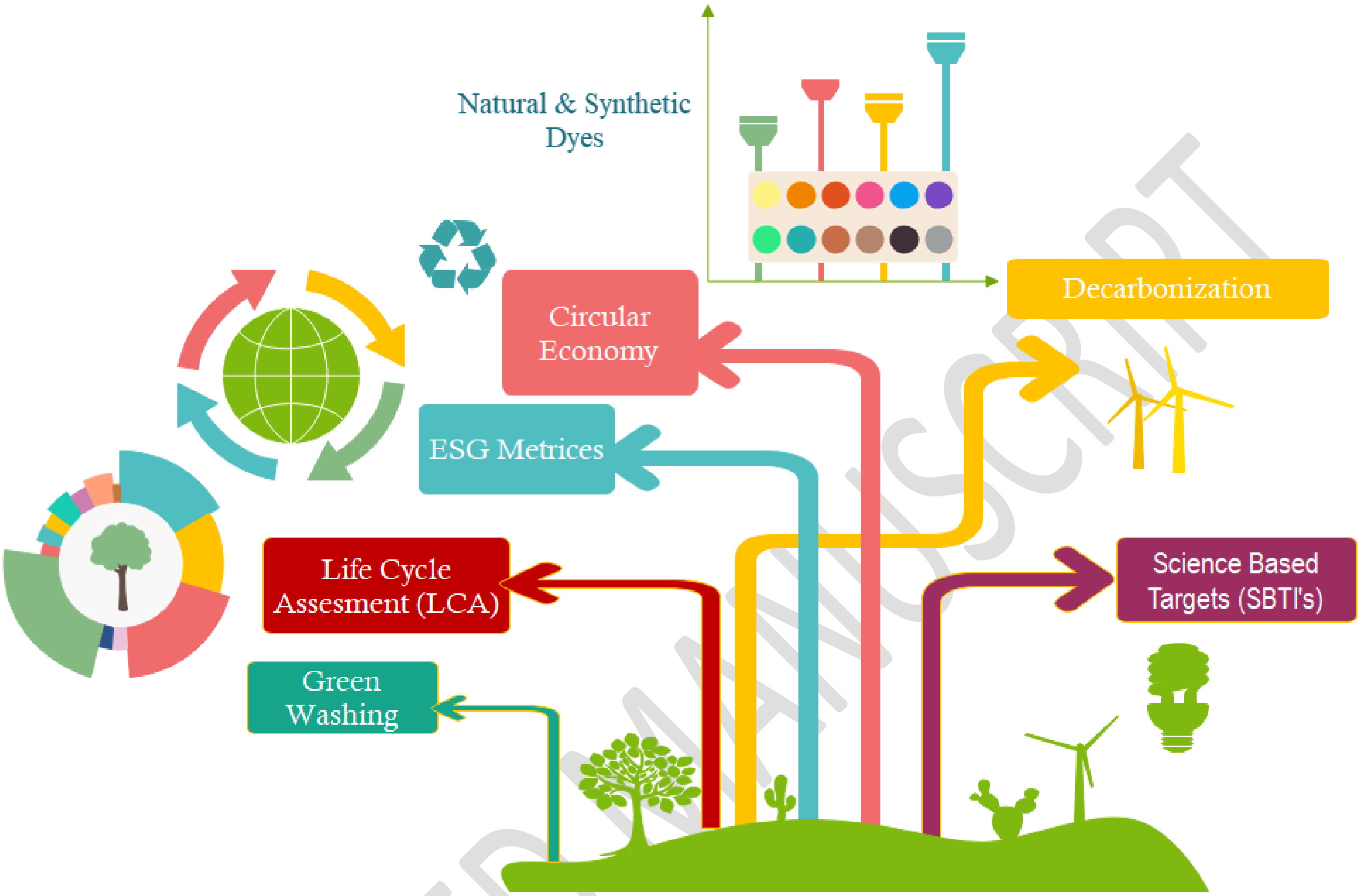
Abstract

Dyes play a crucial role in various industries, but their environmental impact and potential health risks have raised concerns. This review paper examines the classification and applications of dyes, highlighting the challenges posed by synthetic dyes and the growing interest in natural dyes. The impact of textile dyes on human health, ecosystems, water, soil, and air emissions is explored. The focus then shifts to sustainable dyeing practices in the denim industry, which can significantly reduce its environmental footprint and enhance product sustainability. The adoption of sustainable dyes aligns with circular economy principles, leading to energy and water savings. Collaboration, consumer awareness, and the integration of Life Cycle Assessment (LCA) are essential for driving sustainable dye adoption and promoting circular economy principles. The role of Environmental, Social, and Governance (ESG) factors in sustainable denim dyeing is emphasized, encompassing environmental, social, and governance considerations throughout the supply chain. The need to address greenwashing and validate sustainability claims is discussed, highlighting the importance of certifications and transparency. Chemical dyes are recognized as key contributors to achieving sustainability targets in the denim industry, aligning with the Science Based Targets initiative (SBTi) and reducing carbon emissions. The review concludes by stressing the importance of sustainable dyeing practices, considering water and energy usage, waste generation, and emissions, to minimize the denim industry's environmental impact and achieve sustainability objectives.

Keywords: Sustainable dyeing, Denim industry, Environmental impact, Collaboration, Science Based Targets Initiative (SBTI), Life Cycle Assessment (LCA), Environmental, Social, and Governance (ESG) factors

Graphical Abstract



1. Introduction

Dye is a chemical substance that bonds with a substrate to impart color [1]. Dyes find wide-ranging applications in industries such as textiles, cosmetics, plastics, paper, pharmaceuticals, and photography [2]. Within the textile industry, dyes are crucial for coloring fibers (piece dyeing), yarns, or fabrics (stock dyeing) in solution form [3]. These dyes possess four key properties: coloring ability, resistance to rubbing, substantivity, and durability against dry cleaning, washing, and light exposure [4]. In recent years, there has been a growing emphasis on natural dyes, which are environmentally friendly and non-toxic. Natural dyes have emerged as alternatives to synthetic dyes [5].

Synthetic dyes are extensively employed in industries such as textiles, food, leather, printing, and pharmaceuticals [6]. These dyes offer superior color fastness properties compared to natural dyes [7]. The Color Index (CI) lists approximately 8000 chemically synthesized dyes, with each colorant classified by a code name that signifies its color, class, and order number. For instance, Reactive Black 5, a diazo dye, serves as an example showcasing the classification based on the Color Index (CI) [8]. Dye molecules consist of auxochromic and chromophoric groups, with the arrangement and conjugation of double bonds influencing the absorption of light and color generation [9]. While dyes are widely used in the textile industry, their dyeing methods often result in low yields, leading to dye pollution in water [10]. Many textile dyes are known to be carcinogenic and pose risks to human health [11]. Efforts to treat industrial effluents containing textile dyes have employed physicochemical methods, but these have drawbacks such as harsh conditions and high costs [12]. Biodegradation methods using enzymes and microorganisms have shown promise in treating textile effluents, offering cost-effective and efficient solutions [13]. Photocatalysis technology, utilizing materials like ZrO_2, Fe_2O_3-TiO_2, and NiO nanoparticles, has also demonstrated potential in the degradation of textile dyes [14,15].

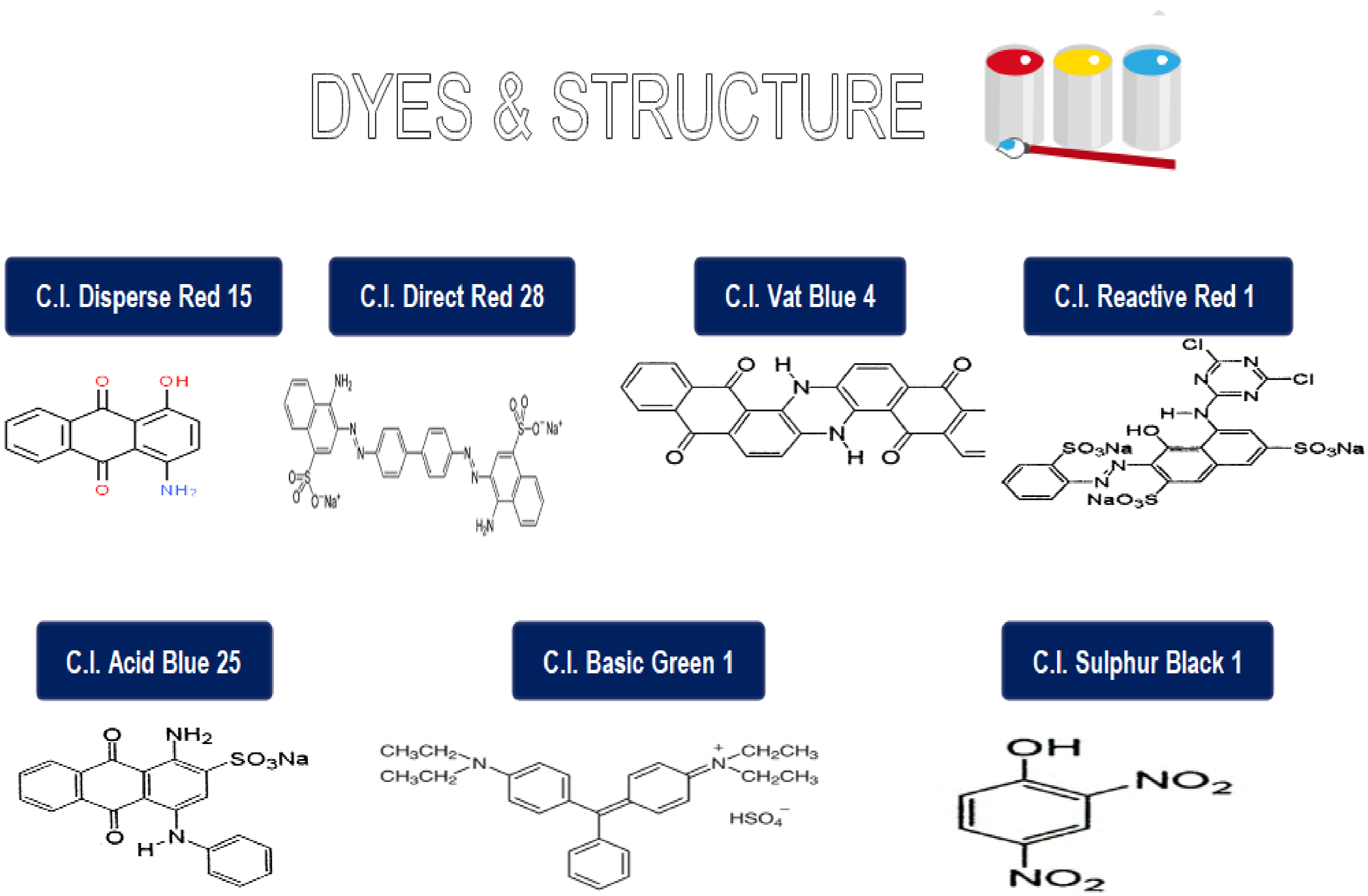


Fig1: Representative example of Industrial dyes along with structure showing classification according to CI (Color Index) [8]

This review classifies textile dyes based on color index, chemical structure, and sustainable industrial applications. It emphasizes the harm caused by dyeing effluents on ecosystems and suggests sustainable international practices to support a greener transition in the textile industry. The paper offers a brief research overview from the past two decades, underscoring sustainability's significance for the textile industry. It discusses natural and synthetic dyes, their properties, and their contribution to eco-friendly practices and decarbonization, while also addressing the role of Sustainable Business Transformation Initiatives (SBTI) in enabling a seamless transition.

2. Classification of Textile dyes: Based on Properties & Industrial Applications:

Mainly textile dyes have been classified based on their chemical structures, color index as well as applications [16]. Dyes are widely used in the textile industry due to their ability to provide vibrant and long-lasting colors. However, the chemical composition of these dyes makes them potentially harmful to both human health and the environment. The categorization of dyes based on the presence of chromophores and auxochromes within their chemical structures has led to the identification of various chromophores such as nitro, Quinonoid, nitroso, and azo [17]. Azo dyes, in particular, have been found to be the most commonly used and have been associated with adverse effects on human health and the environment [18].

Further classification of dyes into groups such as xanthene, oxazine, triphenylmethane, and diphenylmethane based on the specific chromophores they contain has enabled a better understanding of the potential environmental impacts of different types of dyes [19]. Additionally, the presence of an auxochrome enhances the coloring properties of the chromophore. Auxochromes such as hydroxyl, sulfonic, amino, and carboxyl contribute to the classification of different dyes, including phthalocyanine dyes, anthraquinone dyes, azo dyes, and triarylmethane dyes [20].

Studies have shown that the discharge of textile dyes into water bodies can lead to the contamination of aquatic ecosystems and negatively impact aquatic life [21]. Furthermore, the presence of textile dyes in soil can cause soil degradation and reduce soil fertility [22]. Textile dye emissions into the air can also contribute to air pollution and harm human health [23]. With the increasing demand for textiles and clothing, it is essential to address the environmental and health concerns associated with the use of textile dyes. All colorants are given to a color index (C.I.) which is composed of generic name as well as chemical constitution number. Color Index allots (CI) generic names to many commercial dyes. By using color index, different commercial dyes have been classified; figure 1 highlights the different aspect of dyes along with properties and 2-D structures [24].

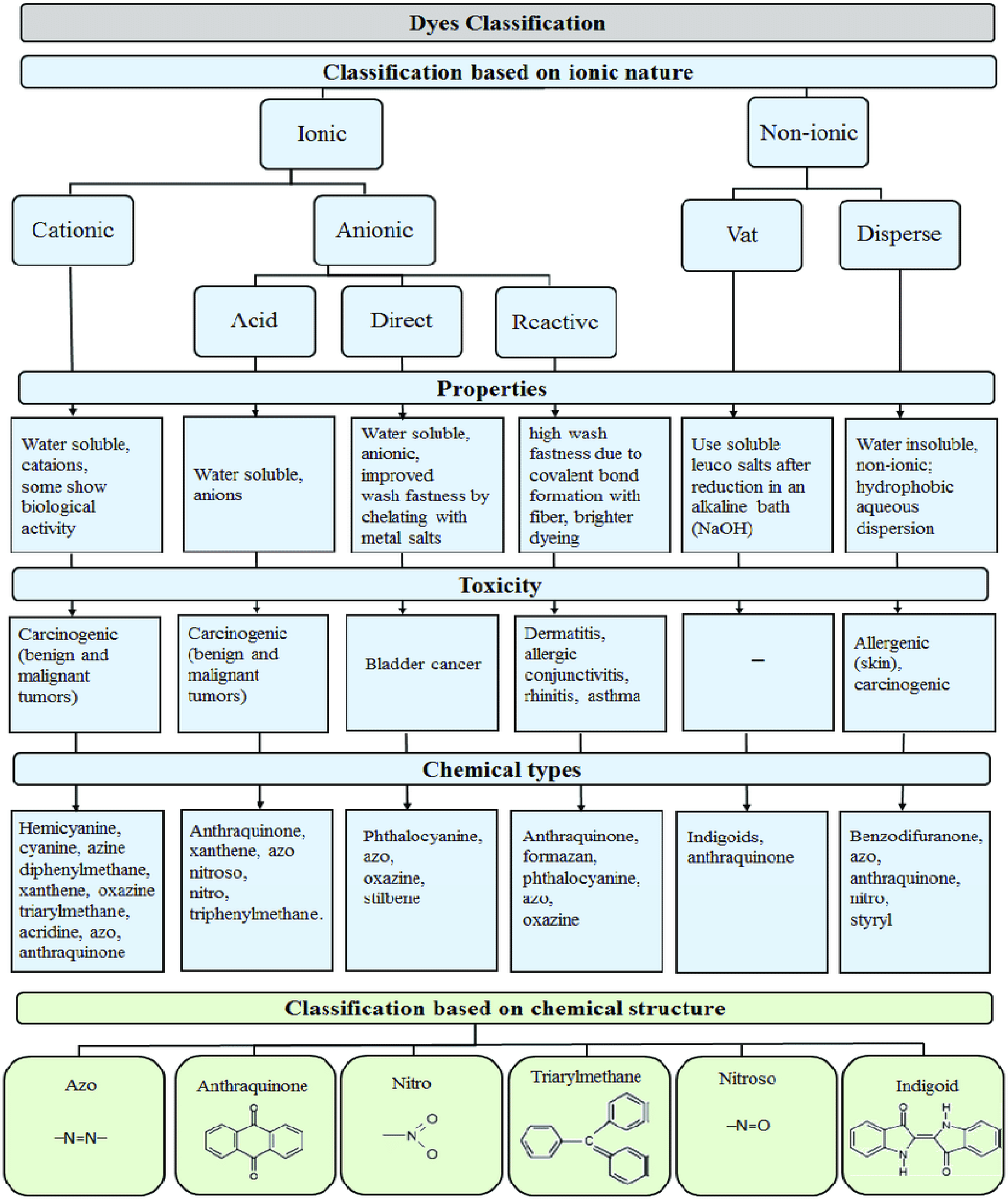


Figure 1: Classification of dyes based on chemical structure for types, properties, and toxicity [24]

On the basis of applications in textile industries, dyes are classified into mordant, vat, disperse, acidic, basic, direct as well as Sulphur dyes [25]. Disperse dyes, commonly used for polyester fibers, have low molecular weight, high volatility, and are insoluble in water [26, 27]. They offer excellent properties such as high exhaustion and color fastness [27], but are non-biodegradable [28]. Adsorption of disperse dyes onto polyamide fibers occurs at polar sites, resulting in stronger bonds compared to polyester fibers. Examples of disperse dyes include C.I. Disperse Blue 27, C.I. Disperse Violet 1, C.I. Disperse Orange 1, and C.I. Disperse Red 15 [29].

Direct dyes, including congo red, lack strong bonding with functional groups, leading to moderate light and washing fastness properties [30]. Classified direct dyes include Direct Black 38, Direct Orange 26, Direct Blue 6, Direct Blue 86, Direct Red 2, and Direct Red 28 [31]. Vat dyes exhibit exceptional fastness properties, especially on cellulosic fibers [32]. The dyeing process using vat dyes involves reduction, dye-uptake, leuco oxidation, and soaping treatment. They offer a wide range of colors and applications in the textile industry [33]. Approximately 50% of reactive dyes are utilized for textile coloration due to their water solubility, excellent wet fastness, wide range of shades, and vibrant colors [34]. Reactive dyes are preferred for their binding ability and stable reactive groups [35]. Khatri et al. [36] reported that reactive dyes with different reactive groups exhibit varying levels of reactivity, with the order being as shown in figure 2:

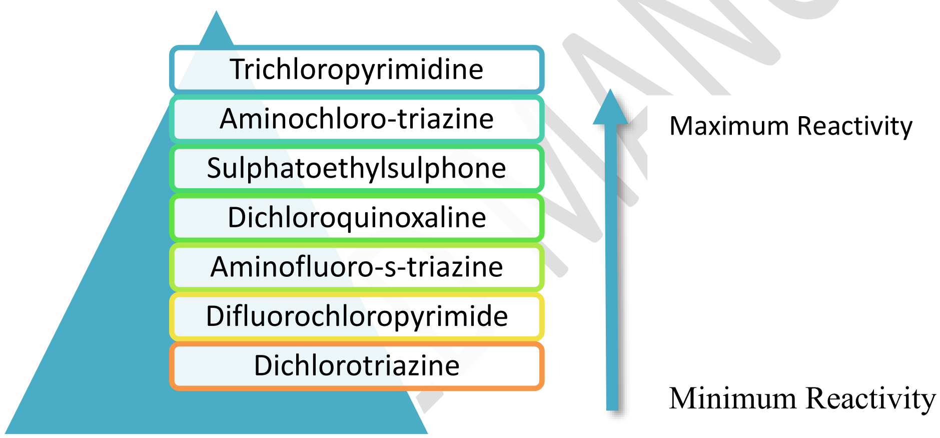


Figure 2: The reactivity levels of reactive dyes, which possess different reactive groups, vary in a specific order from minimum to maximum reacitivity.

Acid dyes, accounting for 30-40% of total dye consumption [37], are primarily used for silk and wool fibers under acidic conditions [38]. Their high solubility and vibrant color shades make them popular in industries such as dye printing, textiles, leather, paper, and pharmaceuticals [39]. Acid dyes offer a diverse range of colors and find extensive applications in various sectors [40].

Basic dyes, characterized by a positive charge on an ammonium group or a delocalized charge on the dye cation [39], are water-soluble and commonly used for nylon, paper, and acrylic dyeing [40]. Different basic dyes provide a wide range of vibrant colors and find applications in various industries [41]. Sulfur dyes, containing ─S=S─ linkages, are commonly used for men's clothing, providing brown and black shades [42]. They are insoluble in water and require reducing agents to convert them into a soluble form [43]. The application of sulfur dyes involves a series of reactions, as demonstrated in previous studies [44]. Examples of sulfur dyes include C.I. Sulphur Green 3, C.I. Sulphur Black 1, C.I. Sulphur Red 14, and C.I. Sulphur Blue 15 [45].

3. The Multifaceted Impact of Textile Dyes: Examining Health, Ecosystems, Water, Soil, Air Emissions, and Human Well-being

The textile industry is widely recognized as one of the largest global polluters due to its substantial consumption of chemicals and fuels [46]. Within this industry, the use of synthetic dyes has been linked to potential health risks, including cancer and various diseases, in living organisms [47]. The textile dyeing industry contributes significantly to water pollution, with a lack of proper wastewater treatment plants in the majority of textile sectors [48]. Textile effluents contain a mixture of organic and inorganic chemicals, and some unfixed colors from the dyeing process end up in discharged wastewater [49]. The presence of dyes in water can lead to waterborne diseases, health issues, and economic instability in affected areas, highlighting the need for sustainable dyeing processes and water quality preservation [50].

Textile effluents entering agricultural fields obstruct soil pores, reducing soil productivity [51]. The high levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), micronutrients, salts, heavy metals, and dissolved solids in textile effluents have detrimental effects on crops, hindering plant growth and diminishing carbon dioxide absorption and protein content [52] [53]. Excessive water consumption associated with synthetic dyes exacerbates soil pollution [54]. Textile industries contribute to air pollution through various emissions, including solvent mists, oil fumes, boiler exhaust, odors, acid vapors, dust, and lint [55] [56]. Hazardous substances such as ethyl acetate, formaldehyde, styrene, and dichlorobenzene are generated during the dyeing process, leading to unpleasant odors and respiratory diseases [57]. Dust particles generated during fiber processing can also cause respiratory issues when inhaled [58].

Many textile dyes used for fabric dyeing have harmful effects on human health, contributing to respiratory problems, skin irritation, and other health issues [59]. Unfixed colors can wash out and release metals like copper, chromium, zinc, and arsenic, leading to medical problems such as dermatitis and nausea [60]. Certain azo dyes are known to be harmful and can cause genetic mutations [61].

4. SUSTAINABLE DYES AND ROLE IN CIRCULAR ECONOMY FOR DENIM INDUSTRY

The denim industry has faced criticism for its environmental impact due to the use of synthetic dyes that harm the environment and human health [62]. Sustainable dyes offer a solution by utilizing eco-friendly methods like plant-based materials and recycled water [63]. By adopting sustainable dyes, the denim industry can reduce its environmental footprint and enhance product sustainability. These dyes enable the creation of easily recyclable or reusable denim products, aligning with circular economy principles [64]. Additionally, sustainable dyes promote an ethical and responsible supply chain by reducing harmful chemical use and encouraging natural materials [65]. This fosters transparency, accountability, and sustainability, benefiting all stakeholders in denim production. Sustainable dyeing processes also lead to significant energy and water savings, with water savings of up to 50% and energy savings of 50-60% [64]. To drive sustainable dye adoption, collaboration and initiatives among industry stakeholders are crucial [66]. This encourages innovation, knowledge sharing, and the development of sustainable practices throughout the supply chain. Consumer awareness and demand for sustainable denim products play a pivotal role in motivating brands and manufacturers to prioritize eco-friendly dyeing processes [67]. Sustainable dyes have the potential to facilitate the denim industry's transition to a circular economy, minimizing its environmental impact, improving supply chain ethics, and creating products suitable for recycling and reuse. Embracing sustainable dyes is a significant step towards a more sustainable future for the denim industry and the planet as a whole [67]. Sustainable dyes are biodegradable, non-toxic, and have a minimal environmental impact, making them an ideal alternative to conventional synthetic dyes [68]. It also promote an ethical and responsible supply chain, leading to a more sustainable and transparent industry that benefits all stakeholders.

Case Study	Description	Reference
Dyecoo Technology	G-Star RAW uses supercritical carbon dioxide to dye denim fabric, eliminating the need for water and reducing energy consumption, while also creating a closed-loop system for CO_2.	[65]
Indigo Juice	Spanish start-up, Royo Group, has developed a technology that extracts indigo dye from the wastewater of denim production, creating a sustainable and circular supply chain.	[66]
Natural Dyeing	Kassim Denim has started using natural dyes, such as indigo and madder, in its production process, reducing the use of synthetic dyes and promoting a more sustainable supply chain.	[67]
Waterless Dyeing	Jeanologia has developed a waterless dyeing technology, called "E-Flow," which uses ozone to dye denim fabric, reducing water usage and eliminating the need for harmful chemicals.	[68]
Closed-Loop Dyeing	The company, Archroma, has developed a closed-loop dyeing process that uses 90% less water and produces 30% less CO2 emissions than traditional dyeing methods. The process also enables the recovery and reuse of up to 99% of dyes and chemicals.	[69]
Bio-Based Dyes	Colorifix has developed a technology that uses genetically engineered microorganisms to produce bio-based dyes, eliminating the need for petroleum-based dyes and reducing the environmental impact of dye production.	[70]
Textile Recycling	The Renewcell company uses a chemical recycling process to transform discarded textiles into a new material that can be used to create new textiles. The process saves water, energy, and reduces waste.	[71]
Upcycling	The fashion company, Eileen Fisher, has launched a program called "Renew," which collects used Eileen Fisher garments and upcycles them into new garments. This program helps to reduce waste and promote circularity in the fashion industry.	[72]
AirDye	AirDye is a technology developed by the company, Colorep, which uses air instead of water to dye textiles, reducing water usage, energy consumption, and eliminating the need for wastewater treatment.	[73]
Mushroom Dyeing	The textile company, MycoWorks, has developed a technology that uses mushrooms to dye textiles. The process is sustainable and eliminates the need for harmful chemicals in the dyeing process.	[74]
Solar Dyeing	The Indian textile manufacturer, Himatsingka, has implemented a solar dyeing process, which uses solar panels to power the dyeing machines and eliminates the need for fossil fuels. The process also uses less water and chemicals than traditional dyeing methods.	[75]

Table 1: Industrial sustainable dying technologies and practices.

5. The Role Of Life Cycle Assessment For Textile Dyes In Terms Of Increasing Sustainable Practices, Circular Economy:

Life Cycle Assessment (LCA) evaluates the environmental impacts of a product from raw material extraction to end-of-life disposal [76]. In the textile dyeing industry, LCA identifies environmental hotspots and improvement opportunities, guiding strategies for mitigating impacts throughout the dye's life cycle [72]. It helps identify sustainable options, minimizing resource consumption, waste generation, and emissions [73]. LCA assesses the benefits of using alternative and sustainable dyeing technologies, like natural dyes [76]. It identifies improvement opportunities in raw material selection, process efficiency, energy consumption, and waste management [77]. LCA supports decision-making, promoting sustainable practices and circular economy principles [78]. It enables eco-design strategies for dyes, integrating sustainability into product development [79]. LCA identifies resource reduction, improved recyclability, and minimized environmental burdens in dye production and use. It enables comparison of dye formulations, application techniques, and processes for environmental performance and sustainability.

LCA allows for the identification of environmental hotspots and helps guide decision-making processes towards more sustainable practices. Through LCA, researchers and industry practitioners can compare different dye formulations, application techniques, and dyeing processes to determine their environmental performance and sustainability.

Several studies have been conducted to evaluate the environmental impact of dyeing processes in denim production. One study [80] aimed to compare the environmental impact of natural and synthetic dyes. The results showed that natural dyes had a lower environmental impact than synthetic dyes in all studied impact categories, including global warming potential, acidification potential, eutrophication potential, and human toxicity potential. Another study [81] assessed the environmental impact of a new dyeing process for denim production. The findings revealed that the new dyeing process had a lower environmental impact compared to traditional dyeing processes, with reductions in water consumption and wastewater discharge.

In a comparative analysis of different dye types [82], it was found that acid dyes had the highest environmental impact in terms of energy consumption, water use, and greenhouse gas emissions, while reactive dyes had the lowest environmental impact. The environmental impact of natural dyes for cotton production was evaluated in a study [83], which found that using ultrasound technology for the dyeing process resulted in reduced energy use, water consumption, and greenhouse gas emissions.

The assessment of a novel dyeing process for denim production [84] showed that it had a lower environmental impact than traditional dyeing processes, including reduced water consumption, wastewater discharge, energy consumption, and greenhouse gas emissions. Investigating the environmental impact of recycled cotton denim production using natural dyes [85] revealed that natural dyes had a lower environmental impact than synthetic dyes in terms of energy consumption, water use, and greenhouse gas emissions. Furthermore, recycled cotton denim production was found to have a lower environmental impact compared to conventional cotton denim production.

The environmental impact of indigo dyeing for denim production was assessed [86], indicating a high environmental impact, particularly in terms of water consumption, energy use, and greenhouse gas emissions. A study on different dyeing methods for denim production [87] demonstrated that reactive dyeing had a lower environmental impact compared to sulfur dyeing and direct dyeing, especially in terms of water consumption and wastewater generation.

These studies employed various software tools for their assessments, such as SimaPro [84], GaBi [85], OpenLCA [86], Ecoinvent [87], and Umberto NXT [88]. This provides valuable insights into the environmental impact of different dyes and dyeing processes for denim production, which can inform sustainable practices and promote circularity in the industry.

5.1 Comparative Life Cycle Assessments (LCAs) of Dyes in Denim Industry: Environmental Impacts and Dye Types:

The table below presents a collection of studies that have investigated the life cycle assessment (LCA) of dyes sustainability in the denim industry. The studies have examined various types of dyes, including synthetic and natural, and have evaluated their impact on different LCA impact categories, such as global warming potential, acidification potential, eutrophication potential, and human toxicity. The table also includes references for each study, allowing readers to delve deeper into the research and findings. Overall, this table provides valuable insights into the sustainability of dyes used in denim production and can serve as a useful reference for researchers, industry professionals, and anyone interested in sustainability in the fashion industry.

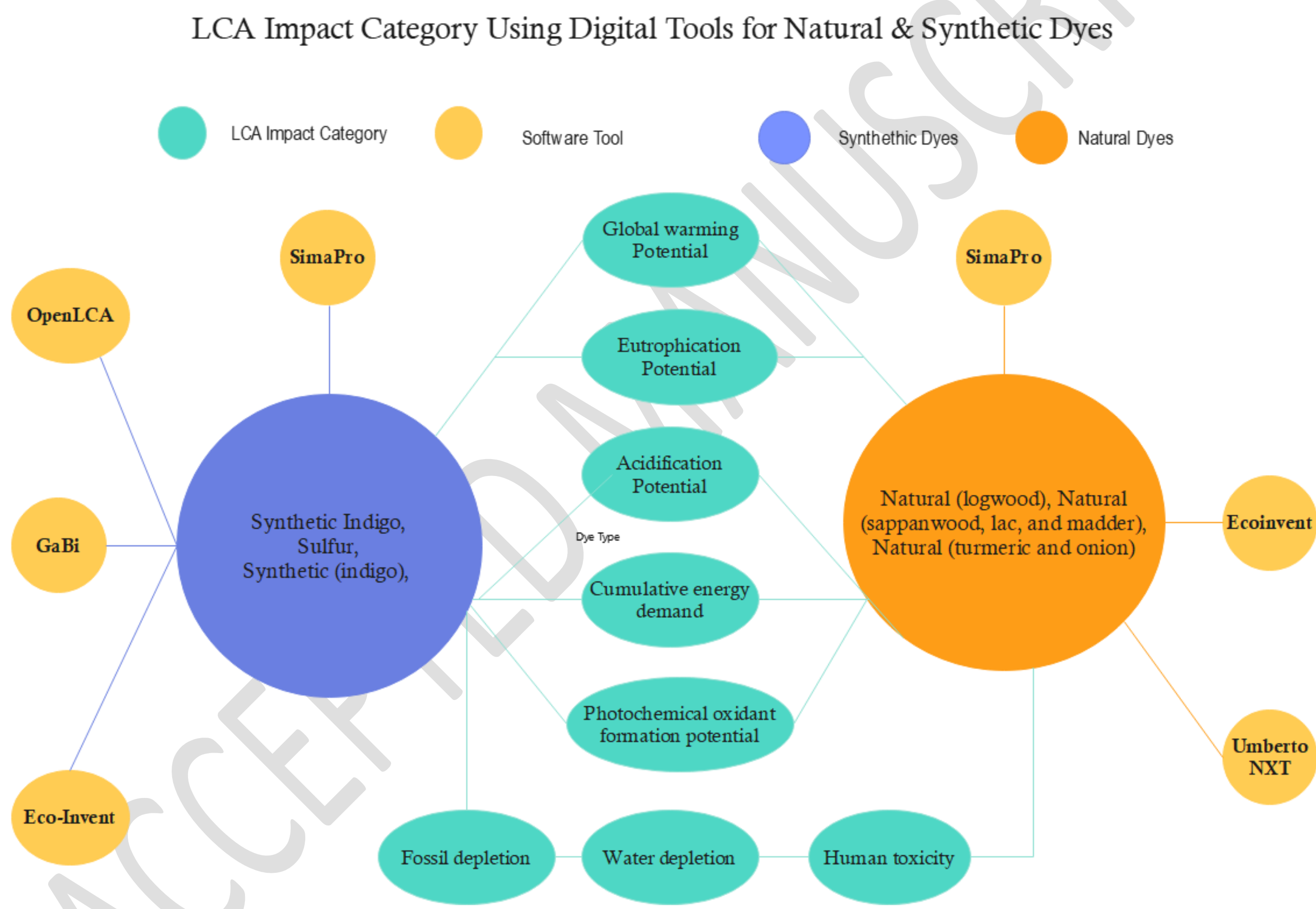


Figure 3: a relationship mind-map for the assessment of natural and synthetic dyes based on LCA impact category and software tools

6. Role of Dyes Advancing Sustainability, Decarbonization ESG Practices and Green Washing Elimination in the Denim Industry

Dyes play a crucial role in the denim industry's sustainability and decarbonization efforts [89]. Adopting sustainable practices and decarbonization strategies can mitigate the environmental impact of dye production and use. Sustainable dye production involves using eco-friendly and low-carbon dyeing processes, such as natural dye extraction from plant-based sources like indigofera tinctoria and madder roots [90]. Natural dyes offer benefits such as biodegradability and reduced toxicity, providing a sustainable alternative to synthetic dyes [67]. Decarbonization efforts aim to reduce greenhouse gas emissions associated with the dyeing process. Innovative technologies like solar and wind power, energy-efficient equipment, and process optimization strategies help minimize carbon footprints in dye production [91]. Circular economy principles are also being explored in the denim industry to enhance dye sustainability. Designing dyes and dyeing processes for easier recycling and reusability reduces waste generation and resource consumption. Implementing closed-loop systems where dyes are recovered, treated, and reused aligns with circular economy principles [92]. These sustainable dyeing techniques, decarbonization strategies, and circular economy principles contribute to a more sustainable future for the denim industry [93].

The use of biodegradable and non-toxic synthetic dyes can reduce the environmental impact of the dyeing process [94]. Enzymatic and microbial treatments eliminate the need for harsh chemicals, reducing the environmental impact and water consumption [95]. Incorporating renewable energy sources such as solar and wind power helps reduce the carbon footprint of the dyeing process and supports industry decarbonization [96]. Upcycling and repurposing textile waste minimize the environmental impact of dyes by promoting reuse [97]. Green chemistry principles, including the use of renewable raw materials and the reduction of energy consumption, reduce the environmental impact and waste [98]. Waterless dyeing technologies, such as air dyeing and foam dyeing, eliminate the need for large quantities of water, reducing the environmental impact, energy consumption, and waste [99]. Biodegradable dyes, derived from renewable materials and broken down by microorganisms, further reduce the environmental impact of the dyeing process [98]. Sustainability assessment tools like life cycle assessment (LCA) support decision-making toward more sustainable practices [88]

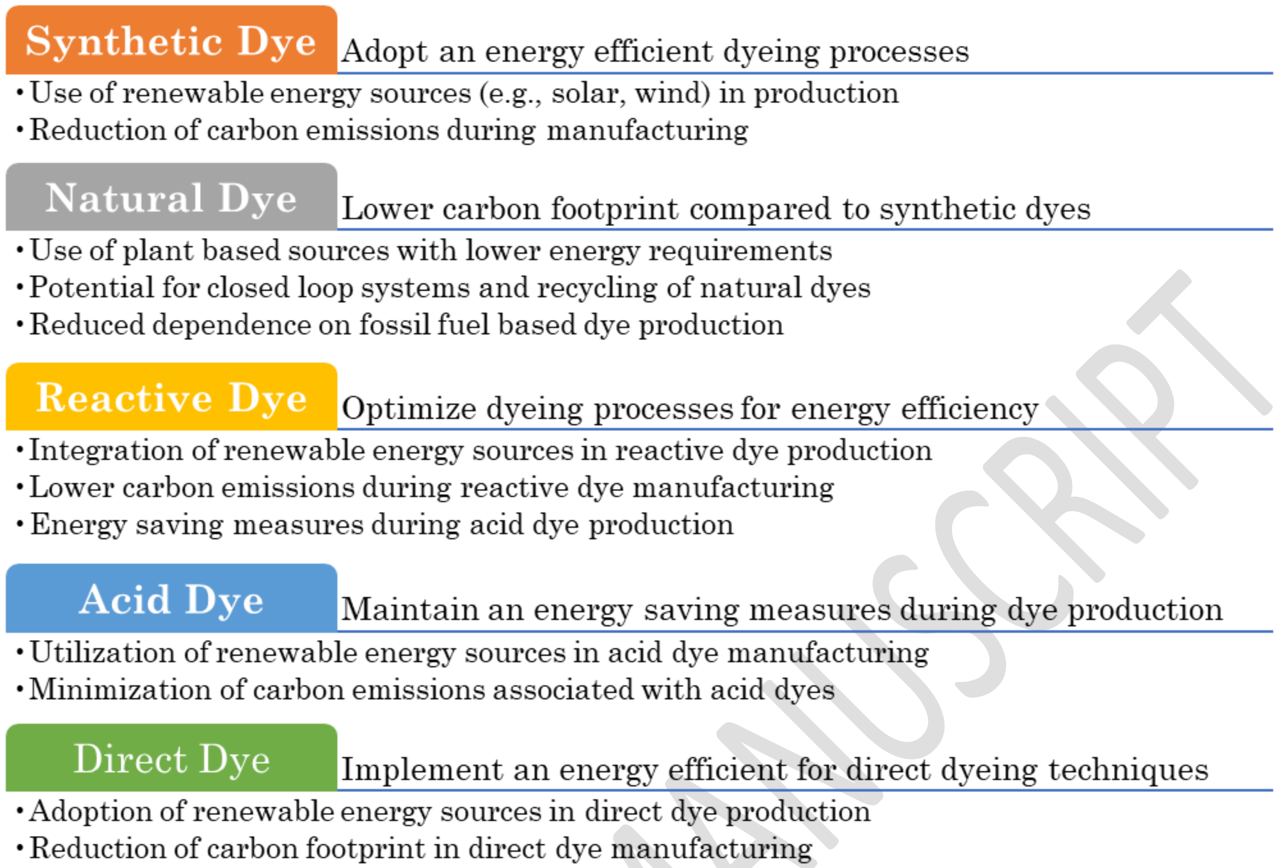


Figure 4: A diagram for comparing how different types of dyes support the Decarbonization efforts in the Denim Industry

6.1 Dying Process Role for Green Washing Elimination:

Greenwashing is prevalent in the textile industry, including the dyeing sector, where sustainability claims may lack proper certification or evidence [88] [96]. To ensure accurate sustainability claims, rigorous evaluation based on environmental, health, social, and economic impact criteria is necessary. Studies have addressed greenwashing in the dyeing industry, emphasizing the importance of regulations and certifications [95]. Independent certifications and third-party audits can enhance transparency and consumer trust [100]. Implementation of recognized sustainability standards and verification processes can promote sustainability throughout the supply chain. The denim industry has embraced sustainable practices to reduce its environmental impact, such as low-impact dyes, ozone technology, water and energy-efficient processes, natural or eco-friendly finishing processes, circular economy practices, and renewable energy sources [95].

A greenwashing matrix can be created for dyes by evaluating criteria such as raw materials, manufacturing process, disposal and waste management, environmental impact, and transparency and certifications [91]. The matrix can be used to evaluate the sustainability of different types of dyes, from traditional synthetic dyes to natural and plant-based dyes [93]. This evaluation can be based on a score or ranking system to determine which dyes are the most sustainable and eco-friendly.

By using a greenwashing matrix for dyes, consumers and businesses can make more informed decisions about the products they purchase and promote the use of sustainable and environmentally friendly dyes in the denim industry. To calculate the sustainability of dyes in the denim industry below matrix are adapted and modified to suit the specific needs and goals of different businesses and organizations. They can also be used in combination with other sustainability metrics, such as life cycle assessment (LCA) and cradle-to-cradle (C2C) certification[101].

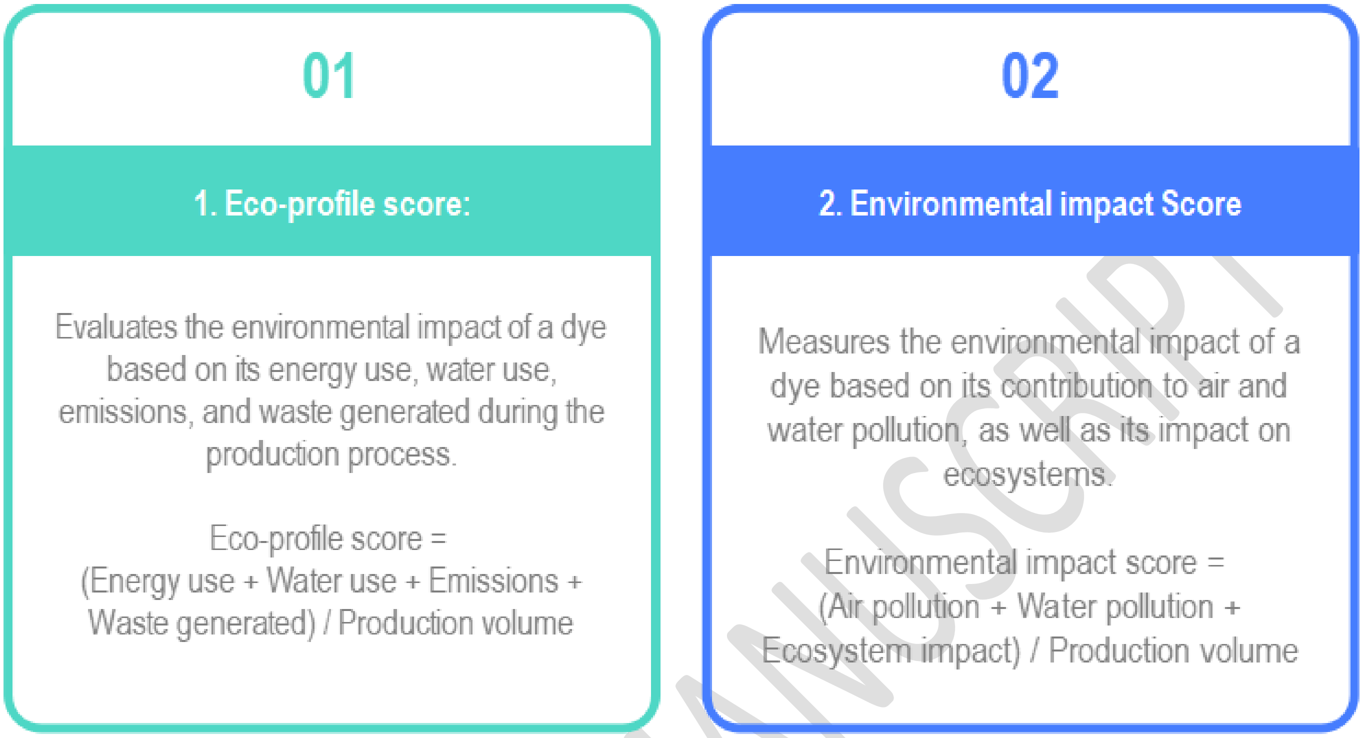


Figure 5: Green washing elimination score calculations and key performance metrics

6.2 ESG Methods, Metrics and Calculations for Sustainable Dying Operations:

The role of Environmental, Social, and Governance (ESG) factors in sustainable denim dyeing is vital for driving sustainability practices. ESG encompasses criteria that assess the environmental impact, social responsibility, and governance practices of organizations [102]. ESG principles guide the development and adoption of sustainable dyeing technologies and influence best practices across the supply chain.

1. Environmental Considerations: ESG encourages the adoption of environmentally friendly dyeing techniques and materials to minimize the industry's ecological footprint. This includes reducing water consumption, energy use, and adopting low-impact dye formulations [103].
2. Social Considerations: ESG principles emphasize the social aspects of sustainable dyeing practices, focusing on worker safety, fair labor practices, and ethical sourcing of raw materials. Ensuring the well-being of communities affected by dyeing operations is also a key consideration [104].
3. Governance Considerations: Good governance practices are vital for ESG implementation. This involves adhering to regulations and standards, implementing proper waste management, and ensuring responsible supply chain management throughout the dyeing industry [105].

By incorporating ESG considerations into decision-making processes, the denim industry can enhance its sustainability performance and promote responsible business practices. Companies can prioritize the well-being of workers involved in the dyeing process, implement ethical labor practices, and provide fair wages, and support health and safety [106]. Adhering to regulations and standards related to waste disposal can minimize the environmental impact of dyeing operations and demonstrate responsible governance. Seeking certifications such as the Global Organic Textile Standard or the Bluesign system can validate adherence to sustainable practices and provide assurance to consumers and stakeholders [101]. Engaging with stakeholders can help align dyeing practices with ESG principles and ensure that the industry meets societal expectations. These examples illustrate how ESG considerations drive sustainable dyeing practices in the denim industry, fostering environmental stewardship, social responsibility, and responsible governance.

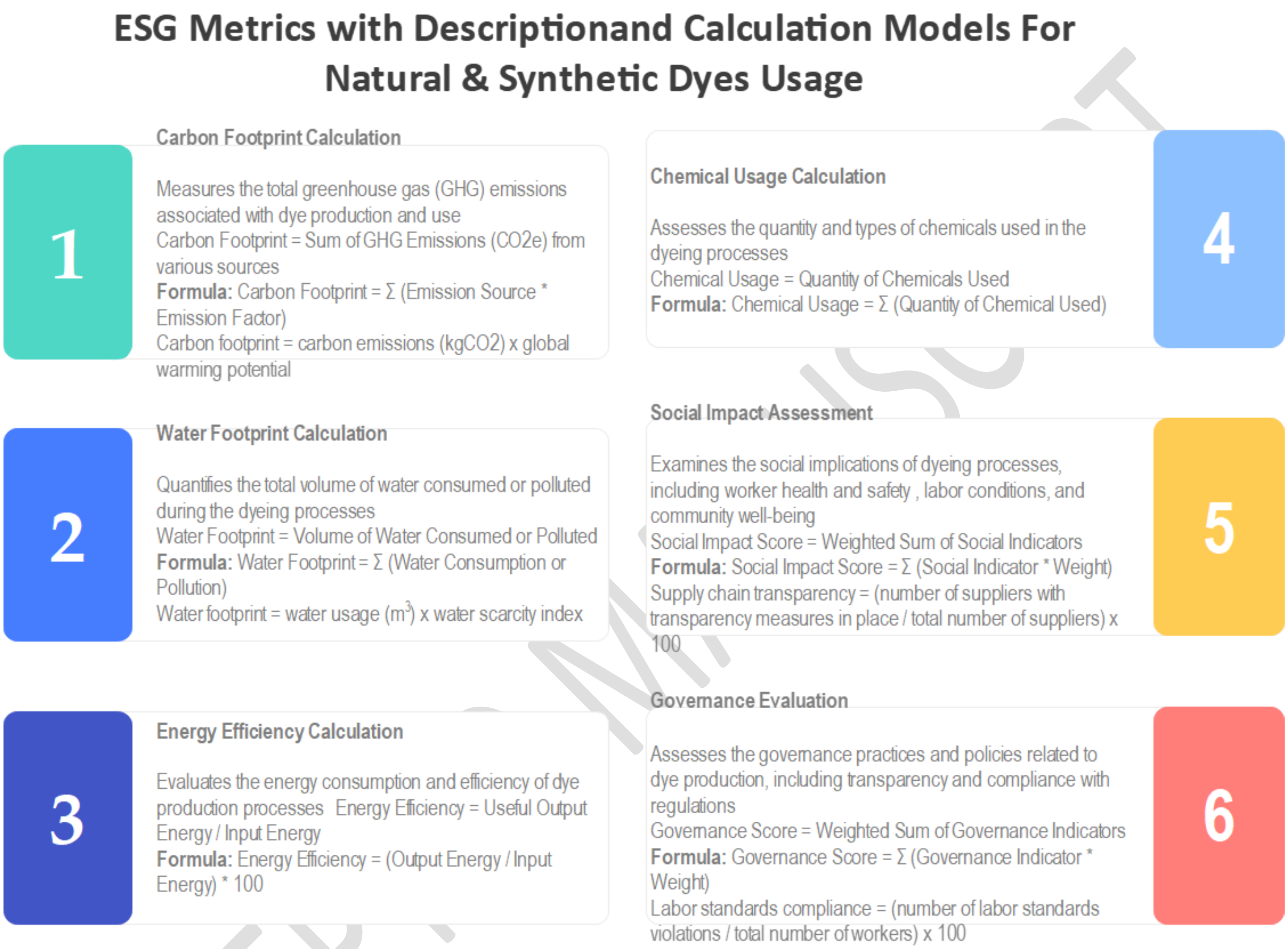


Figure 6: ESG calculations and role of chemicals and dyes in it for denim industries based on the Evaluation models and metrics respectively.

It is important to note that these limitations and considerations are general in nature. When applying the formulas and conducting sustainability assessments for denim industries, it is advisable to use specific guidelines, standards, and industry-specific data to ensure accuracy and relevance.

In addition to using metrics and calculations to evaluate ESG performance, there are also various best practices and standards that denim industry players can adopt to minimize the environmental and social impact of chemical and dye use, including like using safer chemicals and dyes that have a lower environmental and social impact or adopting closed-loop systems that minimize waste and maximize resource efficiency [97]. Investing in sustainable and renewable energy sources, such as solar or wind power, to power production processes with implementation of transparency and traceability measures to ensure the responsible sourcing of chemicals and dyes [96]. By adopting these and other best practices and standards, denim industry players can improve their ESG performance and meet growing demands for more sustainable and responsible practices.

7. Role of Chemical Dyes and Dying Technologies in Denim Industries, In Terms Of SBTI'S- A future roadmap

The Science Based Targets initiative (SBTi) is a collaboration between CDP, the United Nations Global Compact, World Resources Institute (WRI), and the World Wide Fund for Nature (WWF) that provides companies with a defined pathway to future-proof growth by specifying how much and how quickly they need to reduce their greenhouse gas emissions [106]. In order to align with the SBTi, companies need to set greenhouse gas (GHG) reduction targets that are consistent with the level of decarbonization required to keep global temperature increase below 2°C above pre-industrial levels [107]. While SBTI primarily focuses on GHG emissions, it indirectly influences other aspects of sustainability, including the use of chemical dyes in denim production.

Chemical dyes play a crucial role in achieving sustainability targets within the denim industry in the following ways:

1. Carbon Footprint Reduction: The selection and use of chemical dyes can contribute to the reduction of carbon emissions in denim production. By choosing dyes that require lower energy consumption during the dyeing process, the overall carbon footprint of denim manufacturing can be reduced. Additionally, the implementation of dyeing techniques that minimize water usage and wastewater treatment can further contribute to carbon emission reduction [108].
2. Eco-Friendly Dye Formulations: The development and utilization of eco-friendly dye formulations can help reduce the environmental impact of chemical dyes. Eco-friendly dyes are designed to minimize the use of hazardous chemicals and reduce water and energy consumption during the dyeing process. These dyes are formulated to be biodegradable, non-toxic, and have lower carbon footprints, making them more aligned with sustainability goals [109].
3. Waste Minimization: Chemical dyes that promote waste minimization strategies in denim industries can support SBTI objectives. By using dyes that have higher dye fixation rates, which ensure better color retention and reduce dye wastage, the industry can minimize the overall amount of dye used and the associated environmental impact [110].
4. Circular Economy Principles: Chemical dyes that adhere to circular economy principles can support the SBTI's sustainability agenda. Dyes that enable easier recycling and reusing of denim fabric, such as through more efficient dye removal techniques or the use of dye pigments that can be easily extracted during recycling processes, contribute to the circularity of denim production[111].
5. Environmental and Health Impact Mitigation: The choice of chemical dyes in denim industries can influence the environmental and health impacts of the dyeing process. By selecting dyes that have lower toxicity levels and reduced environmental risks, the industry can mitigate potential harm to workers, consumers, and ecosystems. Additionally, the adoption of environmentally friendly dyeing processes, such as low-temperature or waterless dyeing, can further enhance the sustainability of the denim industry [112].

By considering the role of chemical dyes in achieving SBTI's objectives, denim industries can make informed choices that align with sustainability goals and contribute to mitigating climate change. Implementing sustainable dyeing practices, optimizing dye selection, and adopting eco-friendly formulations can drive positive environmental and social impacts while meeting the demands of the fashion industry [113]. The targets or limits serve as benchmarks for denim manufacturers to strive for in order to improve the sustainability of their dyeing processes and minimize environmental impact.

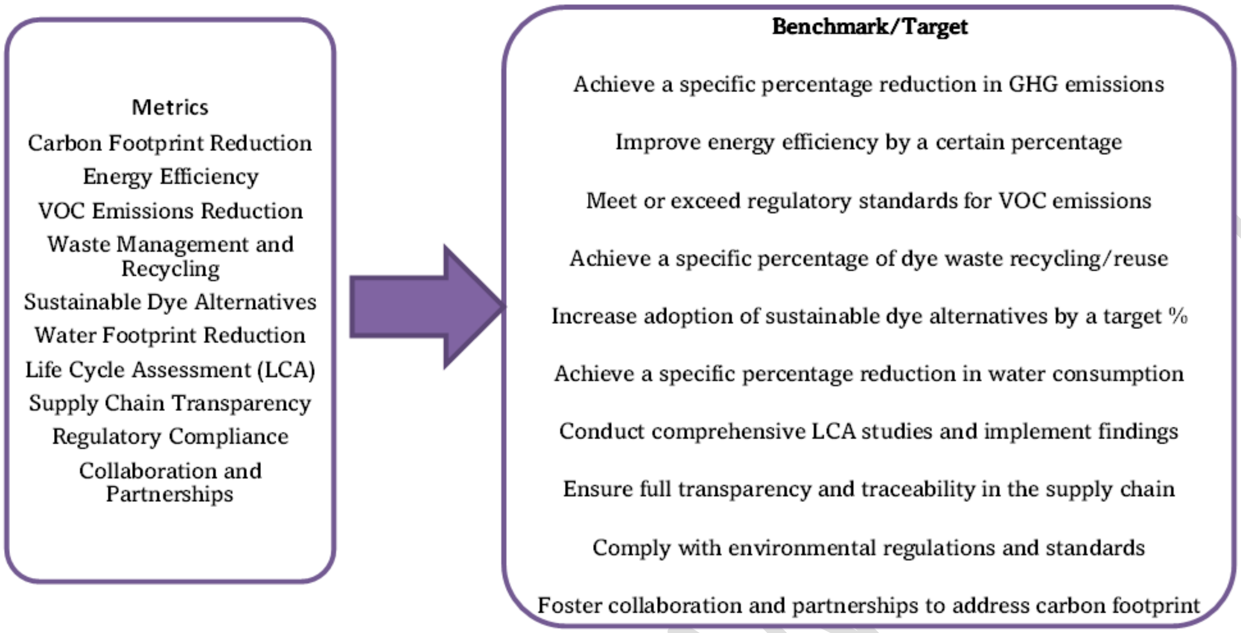


Figure 7: Highlights generalized metrics relating dyes and Science-Based Targets Initiatives (SBTIs) in the Denim Industry

The role of chemical dyes in denim industries with respect to SBTi's can be evaluated using a metrics diagram. This diagram can be used to compare the environmental impact of different dyes and their impact on the SBTi's [114,115]. The metrics diagram may include factors such as the amount of water used in dyeing processes, the amount of energy required, the amount of waste generated, and the amount of emissions produced as well as include a comparison of different types of dyes, such as natural dyes versus synthetic dyes [116]. These benchmarks may include targets for reducing water usage, energy consumption, waste generation, and emissions. For example, a benchmark for water usage may be to reduce the amount of water used in dyeing processes by 50% by the year 2030. A benchmark for energy consumption may be to reduce energy usage by 20% by the year 2025 [117,118]. These benchmarks can help to guide the industry towards more sustainable practices and align with the SBTi's.

Research has shown that the denim industry is one of the most water-intensive industries in the world, with dyeing processes being a significant contributor to water usage[119,120,121]. One study found that up to 75% of the water used in denim production is used in dyeing processes [122]. Another study found that synthetic indigo dyeing processes are particularly water-intensive, requiring up to 60 liters of water per kilogram of fabric [123]. In terms of energy usage, synthetic indigo dyeing processes have been found to require more energy than natural indigo dyeing processes [124,125,126]. Overall, the role of chemical dyes in denim industries with respect to SBTi's is an important area of focus for the industry. The use of sustainable and environmentally friendly dyeing processes can help to reduce the environmental impact of denim production and contribute to the industry's efforts to align with the SBTi's.

8. Conclusions:

The textile industry, including the denim sector, faces environmental challenges due to the use of synthetic dyes. To address these issues and promote sustainability, adopting sustainable dyeing practices is crucial. Sustainable dyes, such as natural and low-impact dyes, offer eco-friendly alternatives that reduce the industry's environmental impact. These dyes are derived from renewable sources, minimizing carbon emissions and conserving resources through energy and water savings. Collaboration among stakeholders is essential for achieving sustainability goals. Manufacturers, suppliers, and consumers must work together to drive the adoption of sustainable dyeing practices. Consumer awareness plays a key role in creating demand for eco-friendly products and incentivizing the industry to prioritize sustainability. Integrating Life Cycle Assessment (LCA) into industry practices provides a comprehensive understanding of the environmental impacts associated with different dye types and processes, guiding decision-making towards sustainable options.

Environmental, Social, and Governance (ESG) factors are important considerations in sustainable denim dyeing. Environmental aspects involve reducing water and energy consumption and adopting low-impact dye formulations. Social aspects focus on worker safety, fair labor practices, and ethical sourcing. Governance considerations include complying with regulations, implementing responsible waste management, and sustainable supply chain practices. By incorporating ESG principles, the denim industry can align its operations with sustainability, promote transparency, and meet societal expectations. Validating sustainability claims and enhancing consumer trust requires recognized sustainability standards, independent certifications, and third-party audits. Certifications like GOTS and Oeko-Tex ensure adherence to sustainable dyeing practices, increasing transparency and credibility. Chemical dyes also play a role in achieving sustainability targets by using eco-friendly formulations, minimizing waste, and supporting circular economy principles. Careful selection and use of chemical dyes enable informed choices aligned with sustainability goals.

Implementing sustainable and environmentally friendly dyeing processes is crucial for reducing the denim industry's environmental footprint. Water-intensive dyeing processes contribute to high water usage, making water conservation a priority. Sustainable techniques like water recycling and closed-loop systems significantly reduce water consumption and wastewater discharge. Energy-efficient practices, such as utilizing renewable energy sources, further minimize the industry's environmental impact. Comprehensive integration of sustainability principles throughout the denim industry's supply chain is essential. Stakeholder engagement and collaboration facilitate the sharing of best practices, innovation, and the development of sustainable dyeing technologies. Consideration of worker well-being, responsible waste disposal, and ethical sourcing ensures social and ethical aspects are integrated into sustainability efforts. Adhering to regulations, implementing sustainable supply chain management practices, and responsible governance are crucial for a holistic approach to sustainability. Measuring and evaluating sustainability performance require the use of metrics, calculations, and specific guidelines. Metrics assess factors like water usage, energy consumption, waste generation, and emissions, providing a quantitative understanding of the industry's environmental impact. Continuously monitoring and reporting these metrics allows the denim industry to track progress, identify areas for improvement, and set ambitious sustainability targets.

In conclusion, sustainable dyeing practices are vital for the denim industry to reduce its environmental impact, enhance product sustainability, and align with circular economy principles. By adopting sustainable dyes and dyeing processes, the industry can minimize resource consumption, waste generation, and emissions. Collaboration among stakeholders, consumer awareness, and the integration of LCA and ESG principles are crucial in driving the adoption of sustainable dyeing practices. Embracing sustainability and making responsible choices can pave the way towards a more sustainable future, meeting the demands of conscious consumers and safeguarding the environment for generations to come.

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