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UNDERSTANDING AND ADDRESSING THE WATER FOOTPRINT IN THE TEXTILE SECTOR: A REVIEW

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Abstract:

Textile industry has a significant water footprint (WF), leading to various sustainability challenges. This article discusses key findings on the WF and outlines potential solutions. The industry's WF includes three types: green, blue, and grey. Textile manufacturing is water-intensive, with stages like pretreatment, dyeing, printing, and finishing. This can contribute to water scarcity in some regions. Water pollution is another critical challenge, as the industry generates considerable wastewater containing diverse pollutants which can harm ecosystems and pose risks to public health. Different treatments to reduce the pollutants in water are studied. We have grouped innovations into five major categories for water conservation efforts in the textile industry: To address these sustainability challenges, several solutions are proposed. Each category offers a pathway to reduce its environmental footprint through water conservation. The adoption of water-efficient technologies, such as low-water dyeing and wastewater recycling, can reduce water consumption. Stricter policies for pollution control, along with incentives for sustainable practices, can encourage industry-wide change. Collaboration among stakeholders, including industry, government, and environmental groups, is also crucial for promoting sustainability and reducing the industry's environmental impact. These approaches can help the textile industry move toward a more sustainable future. Further research needed is suggested.

Keywords:

Sustainability, water footprint, textile industry, wastewater, water-efficient technologies

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1. Introduction

The water footprint (WF) is an estimate of the amount of water adapted in the assembly and fabrication of goods. In the textile sector, the WF refers to the total capacity of water used to construct a textile material, from the cultivation of raw materials, such as cotton or wool, to the processing and finishing of the final product. It incorporates both direct water, such as the water used in textile processing, and indirect water practice, such as the water used to grow the raw materials [1]. Accordingly, there are three major components that are included in the WF: green, blue, and grey. The green WF denotes the utilization of rainwater that does not runoff. The blue WF signifies the consumption of surface and groundwater resources. Meanwhile, the grey WF serves as an indicator of water pollution, representing the volume of freshwater necessary to absorb the pollutants to reach specific natural background concentrations or prevailing ambient water quality standards [2–5]. The correlation among various WFs surrounded by a specified geological sphere is mentioned in Figure 1.

The textile industry stands out as among the most water-intensive sectors globally. The WF of textile goods can fluctuate based on several factors, such as the fiber type utilized, the manufacturing techniques employed, and the geographical area of production. The WF of textile products is increasingly recognized as an important sustainability issue in the textile industry. There is a significant amount of water that will be consumed in the textile industry, which can strain local water sources, especially in regions that are already facing water scarcity issues. There are several other risks associated with the use of water in textile manufacturing processes, including the possibility of contaminating the water and adversely affecting the ecosystems and communities nearby. It is widely known that textile wastewater contains a variety of chemicals, such as oil, grease, NaOH, Na_2SO_4, NH_3, H_2S, lead (Pb), heavy metals, as well as other harmful substances [6]. There are many typical characteristics of wastewater from the textile industry. These characteristics include high temperatures, a range of pH levels, high levels of biological oxygen demand (BOD), high levels of chemical oxygen demand (COD), high levels of total dissolved solids (TDS), heavy metals, and potent pigments [7–9]. The distinct attributes of wastewater generated at different stages throughout the textile manufacturing process are illustrated in Figure 2.

To address the WF of fibers, yarns, fabrics, and related products, the industry is exploring a range of strategies and initiatives. These embrace the practice of water-efficient technologies and practices,

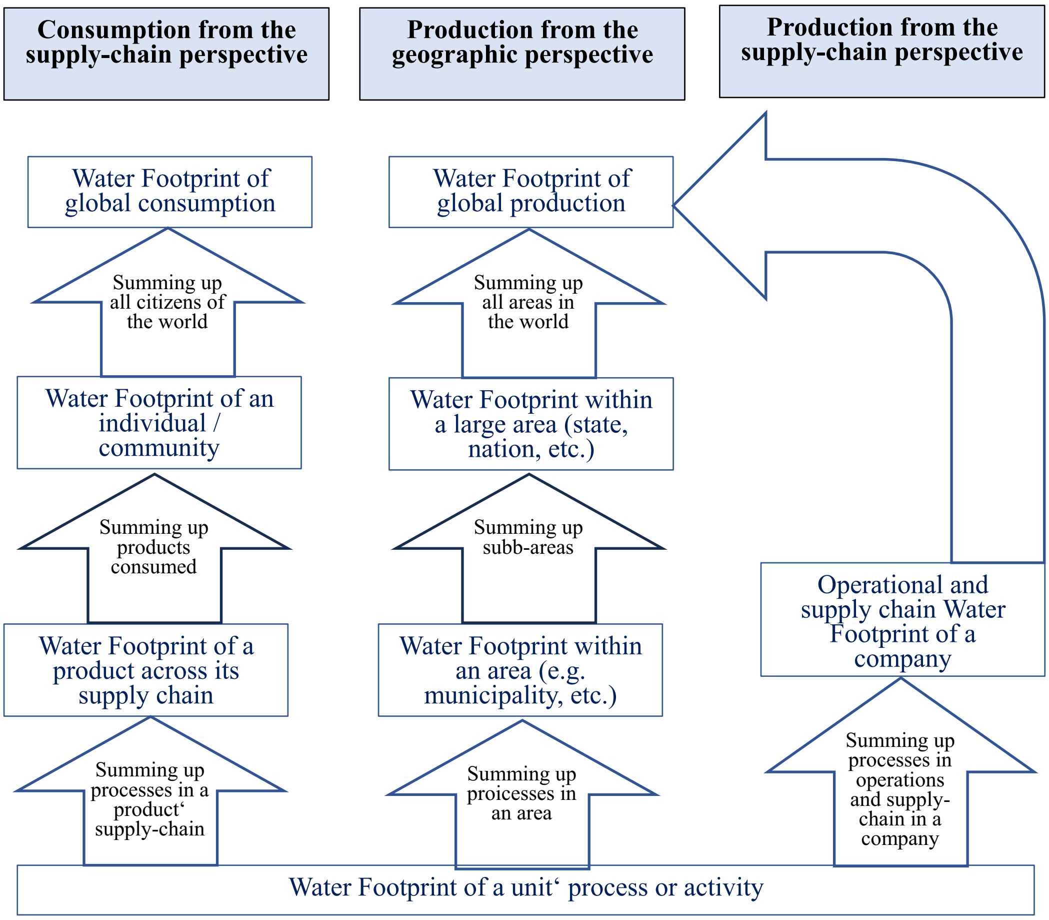


Figure 1. The correlation among various WFs surrounded by a specified geological sphere [4].

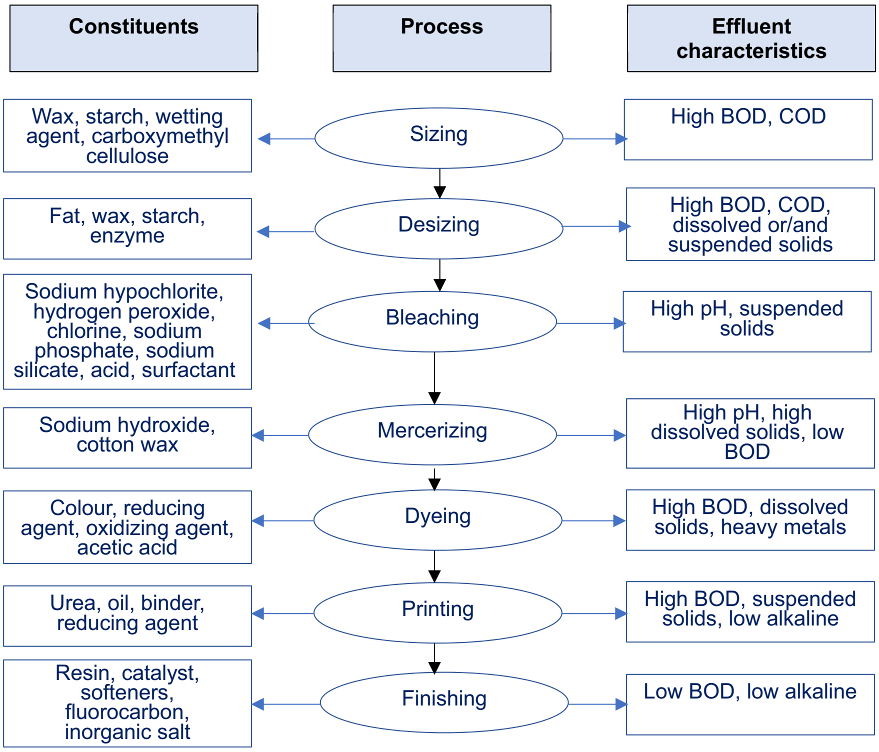


Figure 2. Textile processes and characteristics of pollutants generated during operations [10–12] (reproduced with permission [10]. Copyright ©2018, Elsevier).

such as low-water dyeing and wastewater treatment and reuse, as well as the sourcing of sustainable raw materials, such as organic or recycled fibers [13]. In addition, there is a growing focus on transparency and traceability in the industry, with initiatives such as the HI and the sustainable apparel coalition (SAC) promoting greater transparency and accountability in the supply chain.

The aim of this review article is to present summary data about the situation with WF in the textile industry by highlighting the significance of sustainable practices in the industry, water-saving and pollution-reducing technologies, wastewater management, WF measurement tools, and practices (Figure 3).

2. State of the art review

Textile wet processing industry accounts for a huge proportion of the consumption and pollution of fresh water. Increasing consumer awareness of the environmental issues, tightening environmental legislations on the effluents generated by textile industry, and water scarcity in different areas of the world have compelled textile industry to review, restructure, and reduce its water consumption and the associated effluent hazards. In this article, a critical review of the latest water conservation practices in the textile wet processing industry is presented. Water conservation efforts in different segments of the textile industry have been classified into five major categories. These include wastewater treatment and reuse, machine innovations, process innovations, chemical innovations, advanced water analysis, and water-saving tools. Waterless dyeing using supercritical carbon dioxide (SC-CO_2) and the use of low-liquor ratio machines in textile wet processing are two very promising approaches for water conservation. But waterless dyeing needs further working to dye natural fibers in a reliable way. The huge capital investment required for SC-CO_2 dyeing machines and conversion of conventional dye houses into low liquor ratio dye houses is also a major hindrance in the way of the wider acceptance of these techniques in the industry [18]. Waterless dyeing using SC-CO_2 is promising but requires further development for natural fibers and significant capital investment.

2.1. Water consumption

Textile processing industries are among the top polluters, using up to 1 L of water per kg of dye processed, necessitating broadly applicable treatment technologies for the variable wastewater [19]. The textile industry, known for its significant consumption and pollution of freshwater resources, presents both environmental challenges and opportunities for sustainable management practices. Key literature reviews and systematic studies have examined the sector's WF, emphasizing the critical need for efficient water use, wastewater treatment, and pollution mitigation [20–23].

The total water consumption in textile processing depends on the type of fiber and machinery used, as well as the finishing effect required. The textile industry is one of the major consumers of water, using substantial amounts for pretreatment, dyeing, printing, and finishing [24]. On average, about 200 L of water is required to process 1 kg of textile material [9,25,26]. This encompasses various stages from dyeing, where dyes are dissolved in water, to the final washing. Notably, achieving complete dye absorption and preventing runoff can be challenging, contributing to water pollution [27]. A. Hossain focuses on the water consumption of the textile industries in Bangladesh. It highlights the high-water usage and the resultant production of wastewater containing contaminants like lead, mercury, and arsenic. The article reviews the quantity of water used in different textile processing stages, the characteristics of the effluent, and its environmental impact. Recommendations for reducing water usage in the textile industry are also provided [28].

Environmental performance evaluations of textile mills, including fiber production and subsequent dyeing, emphasize

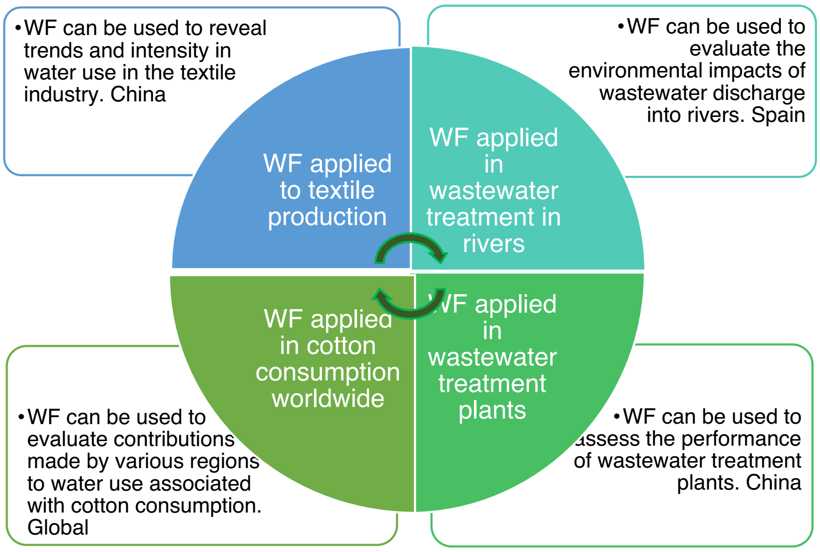


Figure 3. Different effective concepts of WF utilized in textile and wastewater treatment [1,14–17].

Table 1. Average ratio on water consumption from fibers

L/kg	Cotton	Viscose	Animal	Polyester
Production	10,000–15,000 [14]	60 [29]	2.5–50 [29,30]	70 [31]
Textile processing	100–125 [32]	65–169 [33–35]	100–200 [36]	70–136 [31,34]

the importance of assessing specific water and chemical consumptions. Innovations in cleaner production and wastewater recovery can significantly reduce water and chemical consumption [37].

Textile production, especially cotton, is a major contributor to water consumption [38]. Cotton, being a major component of the garments exported from countries like India, requires extensive water during processing [14,39]. This high-water requirement is also linked to the natural properties of cotton that necessitate various water-intensive treatments, and many studies have been conducted in order to estimate its water consumption [40]. Assessments of water consumption during the production of viscose staple fiber garments have highlighted the significant water resource environmental load at the production stage [38], it is said that 1 ton of viscose staple fiber consumes 65 tons of freshwater [33]. Something similar is observed with animal fibers, and it has been estimated that around 125 L is necessary to treat 1 kg of wool [41]. Synthetic fibers like polyester, which make up a significant portion of synthetic fibers used globally, also require considerable water, primarily during the dyeing process. However, the overall water consumption can vary depending on the specific processes and technology used [42]. Table 1 shows a summary of the request for water to obtain the fibers and for the textile process till the garment is in the market.

Several tools have been developed to compare the environmental impact of textiles. The most widely used are the Higg Materials Sustainability Index and the MADE-BY Fiber Benchmark. They use data from production to evaluate the environmental impacts of textiles differentiated by fiber type. The use phase is excluded from both tools. This article discusses whether there is evidence that the use of textiles differs systematically between different fiber types (Table 1) and examines the consequences of comparing the environmental impacts of clothing based on differences in the production of fibers alone without including differences in their use. The empirical material in this article is based on an analysis of rating tools and a literature review on clothing use. It shows that fiber content contributes to the way consumers take care of and use their clothing. When use is omitted, major environmental problems associated with this stage, such as spread of microplastics, are also excluded. This one-sided focus on material production impacts also excludes the importance of product lifespans, quality, and functionality. The consequence is that short-lived disposable products are equated with durable products. Comparing dissimilar garments will not help consumers to make choices that will reduce the environmental burden of clothing. We need an informed discussion on how to use all materials in the most environmentally sustainable way possible [43].

2.2. Wastewater treatment and reuse

The effluents from textile mills are noted for their high pollution and volumetric load. This calls for effective water management strategies within the industry to reduce the environmental impact and enhance the sustainability of textile processing [42]. Effective wastewater management in the textile industry not only focuses on meeting environmental standards but also aims at water reuse and recycling to reduce the consumption of freshwater resources. The process of wastewater treatment can be divided into primary, secondary, and tertiary ones. These treatment steps can be combined in various configurations depending on the specific requirements of the effluent produced by the textile processes. Figure 4 shows a summary of the general configuration.

2.2.1. Primary treatment

- Screening: Removes large solid particles.
- Sedimentation: Allows suspended solids to settle as sludge while the clear water moves to the next stage.
- Neutralization: Adjusts the pH of the wastewater to neutral, which is crucial before biological treatments.
- Coagulation and Mechanical Flocculation: Chemicals like alum or polymers are added to form flocs which can be settled or filtered out. Coagulation/flocculation methods, especially using pre-hydrolyzed coagulants like polyaluminum chloride and natural coagulants, are effective for color removal from textile wastewater and are recommended due to their eco-friendly nature [44]. Electrocoagulation can effectively remove color, turbidity, and COD from wastewater, making the treated water reusable in dyeing processes without affecting the quality of the dyed fabric [45].

2.2.2. Secondary treatment

- Aerobic treatment: Uses aerobic microorganisms to degrade organic pollutants in the presence of oxygen. Methods include activated sludge process, where air or oxygen is blown into the effluent, or aerated lagoons and oxidation ditches which provide long retention times with natural aeration.
- Anaerobic treatment: Uses microorganisms to degrade pollutants in the absence of oxygen. This is less common but effective for high-strength wastewaters.
- Trickling filtration: Wastewater is passed over a bed of stones or other material on which microbes are attached, and it trickles over these materials, allowing microbial communities to consume the organic matter.

Biological, physicochemical, and combined treatment processes have been explored for the removal of pollutants from textile wastewater. The implementation of an ecofriendly model of

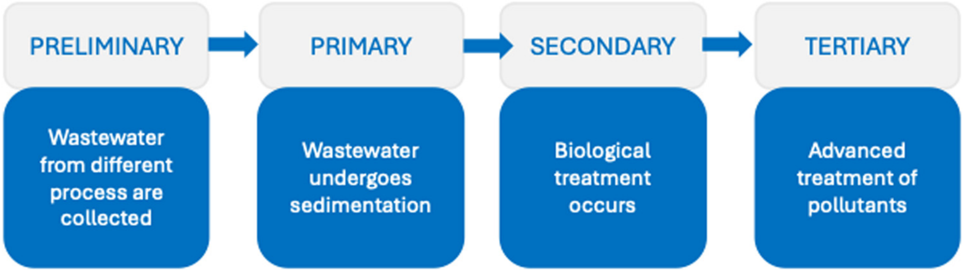


Figure 4. Scheme for wastewater treatment.

textile industry operations is emphasized to address environmental standards [46].

2.2.3. Tertiary treatment

- Membrane technologies: Such as ultrafiltration, which can remove remaining suspended particles and some dissolved contaminants.
- Adsorption: Often using activated carbon to remove remaining organics and color. Membrane technologies, such as ultrafiltration and nanofiltration, offer advantages in treating heterogeneous textile effluents, allowing for water reclamation and reuse. However, membrane fouling remains a significant challenge [47]. Ahmad presents a case study on advanced membrane treatment of treated water from a denim washing factory's effluent treatment plant (ETP). It analyzes the technical and economic aspects of water recycling and reuse in the textile industry, specifically focusing on a denim washing facility in Bangladesh. The study assesses the feasibility of implementing advanced treatment techniques like ultrafiltration and reverse osmosis for water reuse [48].
- Advanced oxidation processes (AOPs): Use chemicals or physical processes to generate strong oxidants like hydroxyl radicals in the water to break down complex organic pollutants.
- Ion exchange and electrolytic methods: Can be used to remove specific ionic compounds. Ozonation pretreatments combined with coagulation can be used to mitigate reverse osmosis fouling in reclamation of textile secondary effluent [49].
- Photocatalytic degradation: Uses UV light and a photocatalyst, such as titanium dioxide, to degrade organic pollutants. Utilizing photocatalytic degradation alongside adsorbents can effectively remove dyes and pollutants from wastewater. This integrated approach also incorporates membrane filtration to recover spent catalysts and discharge reusable clean water [21].
- Thermal evaporation: Involves evaporating water to leave behind the contaminants.

The differences between wastewater treatment in textile industries and urban sewer systems are addressed, as well as details on the specific pollutants treated by each method in textile wastewater details are provided in Table 2.

According to the pollutant employing the following targeted treatment methods, the textile industry can effectively manage and reduce the environmental impact of its wastewater, ensuring compliance with environmental regulations and protecting water resources.

2.2.4. Dyes and colorants

- Adsorption: Activated carbon or other adsorbents to remove colorants.
- AOPs: Using ozone, hydrogen peroxide, or UV light to degrade dye molecules.
- Membrane filtration: Ultrafiltration and nanofiltration to remove dye molecules.

2.2.5. Heavy metals

- Chemical precipitation: Adding chemicals (e.g., lime, sulfide) to form insoluble metal compounds that can be filtered out.
- Ion exchange: Removing metal ions from wastewater by exchanging them with less harmful ions.

2.2.6. Organic compounds and surfactants

- Biological treatment: Aerobic and anaerobic processes to break down organic compounds.
- Chemical oxidation: Using chemicals like chlorine or ozone to oxidize and break down organic contaminants.

2.2.7. High COD and BOD

- Aerobic treatment: Activated sludge, aerated lagoons, or oxidation ditches to reduce BOD levels.
- Anaerobic treatment: Anaerobic digesters to treat high-strength wastewater.

2.2.8. Specific chemicals (e.g., formaldehyde, azo dyes)

- Specialized biological treatment: Using specific strains of microorganisms that can degrade particular chemicals.
- Physical–chemical methods: Techniques like coagulation, flocculation, and sedimentation to remove specific chemicals.

2.3. Emerging technologies for water efficient use

- Cutting-edge technologies for energy, water efficiency, and pollution reduction in the textile industry are crucial to address the expected increase in textile consumption, energy use, and pollutant emissions [50]. Various emerging technologies are aimed at making the textile industry more energy-efficient,

Table 2. Wastewater treatment in textile industries versus urban sewer system

	Types of pollutants	Focus	Treatment processes
Urban Sewer system	General domestic wastewater components, such as organic waste, nutrients (nitrogen and phosphorus), and pathogens	Emphasis is on reducing organic matter, nutrients, and pathogens to safe levels for discharge or reuse	Primary Treatment: Involves screening and sedimentation to remove solids and large particles
	Chemical contaminants from household products		Secondary Treatment: Typically includes biological treatment (activated sludge process, trickling filters) to reduce BOD and COD levels
	Lower concentrations of heavy metals and specific industrial chemicals		Tertiary treatment: Focuses on nutrient removal (nitrogen and phosphorus) and additional disinfection to ensure the treated water meets health standards
Textile industry	High levels of dyes and colorants	The primary focus is on removing specific pollutants related to textile processing, such as colorants and specific chemicals, and managing the high organic and inorganic loads	Primary treatment: Typically involves screening, sedimentation, and neutralization to remove large particles and adjust pH
	Heavy metals such as lead, mercury, and chromium		Secondary treatment: Often includes biological treatment processes to degrade organic matter. Aerobic treatment is commonly used, sometimes accompanied by anaerobic processes
	Organic compounds and surfactants		Tertiary treatment: Advanced treatment methods are employed to remove color, heavy metals, and remaining organic matter. Techniques include adsorption, chemical oxidation (e.g., ozonation), membrane filtration, and AOPs
	High COD and BOD.		
	Specific chemicals used in textile processing, such as formaldehyde and azo dyes		

water-efficient, and less polluting. These include improved water recycling systems, advanced filtration techniques, and low-water dyeing processes that aim to minimize the volumetric and pollution load of wastewater [51]. Advanced water management systems are crucial for reducing the overall water consumption in textile processing. These systems focus on recycling and reusing wastewater, utilizing advanced treatment technologies that can handle the diverse and high-load effluents typical in the textile industry [19].

- Additive manufacturing, particularly 3D printing, is revolutionizing textile production by minimizing waste and reducing the use of water and raw materials. This technology allows for the precise application of materials, significantly lowering the environmental impact compared to traditional manufacturing methods. Materials like thermoplastic polyurethane and polyethylene are found to be most effective with fused deposition modeling and stereolithography techniques, supporting sustainable production practices [52].

- Biotechnology in general and concisely the use of enzymes in various stages of textile manufacturing such as desizing, scouring, bleaching, dyeing, and finishing are gaining popularity due to their non-toxic and ecofriendly nature. Enzymes can significantly reduce the need for harsh chemicals, thereby reducing water pollution and enhancing the recyclability of water [53,54]. They can be used to replace chemicals [55,56] or in wastewater treatments [57,58].

These technologies not only aim to reduce the environmental footprint of textile production but also align with global sustainability goals by conserving water and reducing pollution levels. Illustrative examples of best sustainable practices will be detailed in the forthcoming sections.

2.4. Areas where further research is needed

Identifying gaps for further research in the area of textile industry water use involves examining the limitations of current technologies and the challenges that remain unresolved. Here are some potential gaps and areas needing more research:

- Economic feasibility of waterless dyeing technologies: While waterless dyeing using SC-CO_2 is a promising technology, it is capital-intensive and its economic viability for widespread adoption in the textile industry needs further study. In this process, no additional chemicals (salt, etc.) are requested, and it shows better penetration and uniformity, CO_2 can be reused, and there is no need to dry. However, the range of dyes that can be effectively used with SC-CO_2 is currently limited.

- Natural fiber dyeing: Current advancements in waterless dyeing need to be extended to reliably dye natural fibers, which have different properties compared to synthetic ones.
- Membrane technology scaling: Membrane-based treatments show promise but scaling them from pilot to full-scale industrial applications, while maintaining efficiency and managing fouling, needs more research.
- Integrated treatment systems: Designing integrated systems that combine various water treatment methods (physical, chemical, and biological) for optimal performance and cost-effectiveness is an area ripe for development.
- Recycling and reuse of treated wastewater: The feasibility of reusing treated wastewater in primary textile processing operations needs more research to ensure water quality and process suitability.
- Eco-friendly chemical use: Further research is required to identify and develop new chemicals for use in textile processing that are less harmful to the environment and easier to treat in effluents.
- Resource recovery from wastewater: Techniques for recovering resources (like water, chemicals, and energy) from textile wastewater are underdeveloped. Research into methods for resource recovery can make the industry more sustainable.
- Environmental impact assessments: Long-term studies on the environmental impacts of both traditional and emerging textile wastewater treatment technologies are needed to understand their ecological footprint better.
- Adoption barriers for sustainable practices: Identifying economic, regulatory, and technical barriers to the adoption of sustainable water use practices in the textile industry could help in developing targeted strategies for overcoming these hurdles.
- Techno-economic evaluations: Comprehensive techno-economic analyses of emerging wastewater treatment technologies would help in understanding their cost–benefit ratio and pave the way for commercialization.

Research in these areas can lead to the development of more sustainable, cost-effective, and environmentally friendly practices within the textile industry.

The textile sector must continue to evolve, adopting sustainable practices that reduce its WF while meeting growing global demands. Effective water conservation, innovative treatment technologies, and pollution control are essential to mitigating the environmental impacts of this industry.

3. WF in textile production

There is no doubt that the textile industry is responsible for a significant portion of the internal WF associated with textile products. The dyeing of yarns and fabrics as well as the finishing of fabrics are processes where significant amounts of water are used. As it pertains to textile operations, water usage can be classified into two types: bluewater, which is used for consumptive purposes and is drawn from groundwater or surface water sources, and greywater, which is used for dumping pollutants into the water supply.

As a result of yarn dyeing, effluent water is generated during the dyeing process. This water is calculated by multiplying the total amount of yarn dyed in a year by the water KPI. In the same way, the effluent water from the dyeing of fabrics follows the same calculation method as the effluent water from yarn dyeing. Water KPI for yarn, knit, and woven fabric dyeing is considered to be 80, 120 and 140 L/kg respectively. All these values have been derived from local industries involved with yarn, knit, and woven fabric dyeing. During the process of washing fabrics, approximately one-third of the amount of water that has been used for dyeing fabrics is needed. The blue WF can be calculated using equation (1) [59]:

$$\text{Blue WF} = \text{BWE} + \text{BWI} + \text{LRF}, \tag{1}$$

where BWE is the bluewater evaporation; BWI is the bluewater incorporation; LRF is the lost return flow.

The concept of lost return flow is used to describe the part of the return flow which cannot be utilized throughout the same catchment area during the same withdrawal period as the previous withdrawal period. The formula used to determine the grey WF can be found in equation (2) [59].

$$\text{Grey WF} = \frac{L}{C_{\max} - C_{\text{nat}}} = \frac{\text{Effl} \times C_{\text{effl}} - \text{Abstr} \times C_{\text{act}}}{C_{\max} - C_{\text{nat}}}, \tag{2}$$

where Effl is the effluent volume, Abstr is the water volume of the abstraction, C_{effl} is the pollutant concentration in the effluent, and C_{act} is the actual intake water concentration.

GWF is calculated based on the BOD since it has been established that the GWF associated with BOD is approximately three times greater than that associated with COD. In terms of water quality standards, it is important to note that the COD standard is four times higher than the BOD standard. There is additionally a standard for the natural concentration of COD in the receiving water body that is three times higher than the standard for BOD for the receiving water body (Hossain et al. [10]). The result of this is a higher denominator (when compared to when BOD alone is considered), which, in turn, results in a smaller footprint for greywater.

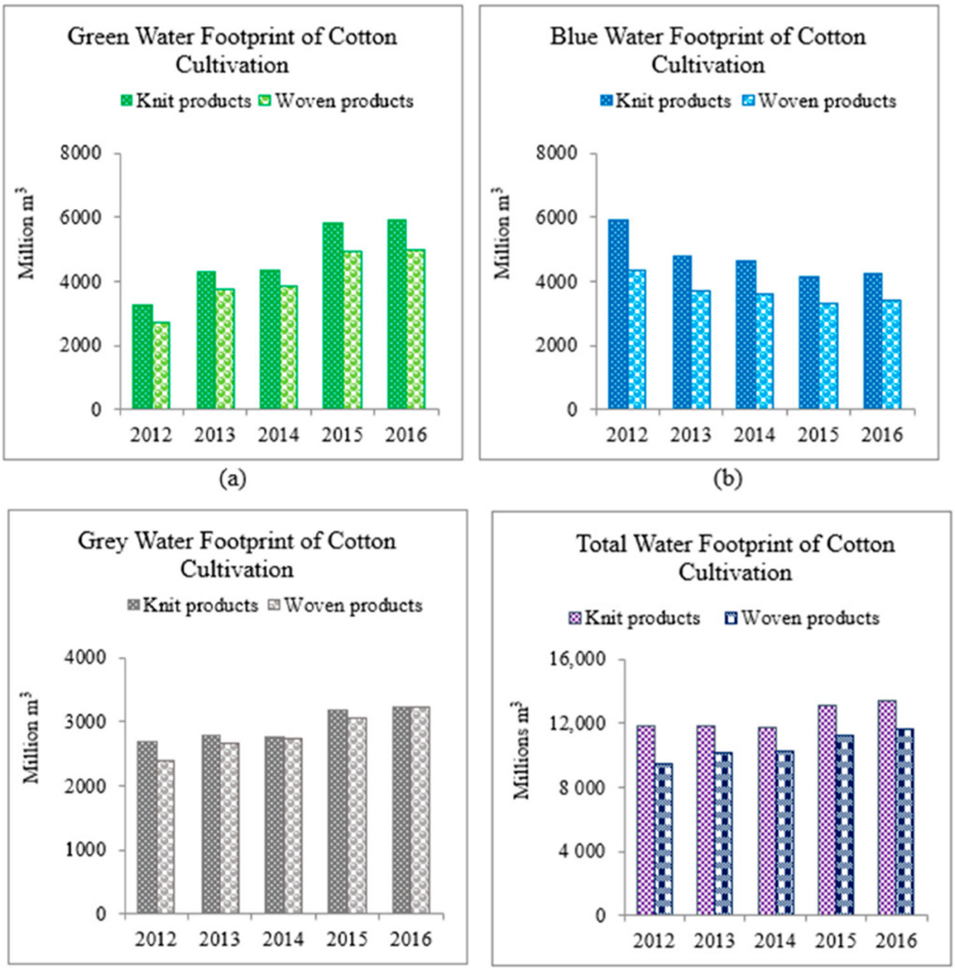
The GWF in the textile industry is calculated by taking into account the BOD values for both knit and woven textile industries, with respective values of 450 and 550 ppm, which are used to calculate the GWF [49]. During the process of determining the grey WF of an industry, the pollution load from the outlet of the industry's ETP is considered.

3.1. Raw materials' WF

To illustrate raw materials' WF, Bangladesh can be taken as an example, since the textile industry in this country makes up a particularly significant part of the GDP [60,61]. As the demand for ready-made garments (RMG) and other value-added goods continues to rise in both local and international markets, Bangladesh must rely on massive annual cotton imports. As a result, most of the WF associated with cotton farming originates in the nations from which Bangladesh imports raw materials for RMG products [62].

Approximately half of the raw cotton that Bangladesh imported in 2016 came from India, in total 6.3 million bales or 1,371,665 metric tons [63]. Domestic production accounts for about 0.13 million bales which is about 2% of the country's total demand. Imports of cotton yarn and fabric totaled about 263,071 and 294,335 ton in 2016 [65].

Figure 5 shows the total green, blue, and grey WFs of growing cotton for woven and knitted goods from 2012 to 2016. Cotton for knitting production uses more water than cotton for weaving. Domestic spinning mills supply 60% of raw materials for knitwear while foreign cotton brands supply 40%. Regional yarn manufacturing industry utilizes imported cotton mostly to make yarn. About 80% of raw cotton imported worldwide comes from three countries like India, Uzbekistan, and Africa. These countries require more green and bluewater for cotton manufacture than China, which mostly imports cotton yarn and fabric. The green WF for woven and knitted goods was slowly growing, while the blue WF was shrinking in the analyzed period (Figure 5a and b). The GrWF for cotton production in RMG products was 5.98 billion m^3 in 2012 and 10.21 billion m^3 in 2016, while the BWF was 7.65 billion m^3. Unprocessed cotton is mostly sourced from India, where rainfed cultivation accounts for 65% of cotton production. Uzbekistan imports less raw cotton despite growing nearly all cotton in irrigated conditions. For woven and knitted goods, the GrWF has grown while the blue WF has shrunk over time. There are opportunities to reduce the global textile use's WF when compared to other raw materials used in textiles. The



(a) (b)

(c) (d)

Figure 5. WF of cotton cultivation for different fabric structural materials: (a) GrWF, (b) BWF, (c) GWF, and (d) TWF [64].

Table 3. Global average WF (L/kg) for different fibers [66]

Fiber name	Global average WF (L/kg)			
	Green	Blue	Grey	Total
Cotton	5,163	2,955	996	9,114
Hemp	2,026	0	693	2,713
Flax	28,866	482	436	3,783
Jute	2,356	33	217	2,606
Ramie	3,712	201	595	4,508

average WFs of various cellulose-based raw materials used for textiles worldwide are listed in Table 3.

3.2. WF in wet processing

Various wet processes are used in the manufacturing of yarns and textile fabrics. Table 4 shows the blue WF required in different yarns and fabrics processing units. The presented data demonstrate that dyeing uses the most significant amount of water compared to other wet processes used in manufacturing. Desizing and bleaching processes use 2.5–25 L/kg water per 1 kg of fabric. About 20–45 L/kg water is used in scouring, while in mercerization, 17–32 L/kg fabric is used. Water usage for dyeing ranges from 10 to 300 L/kg of product. The range is larger due to varying water requirements based on the dyeing chemical and machinery used.

In Table 5, the water requirements for dyeing, depending on the equipment used, are presented.

Water consumption for dyeing woven fabric ranges from 130 to 150 L/kg. While for knitted fabric dyeing, the process requires 110–130 L/kg of water. It is noted that the woven fabrics have a much higher WF than the knitted fabrics because of the additional pretreatments that are carried out in the wet processing unit to make the fabrics suitable. High water consumption in the dyeing process results in higher greywater effluent from individual processes.

3.3. WF in textile finishing

The WF in the textile finishing is the total volume of water consumed and polluted during the textile finishing. Excessive water use and wastewater discharge harm the environment. Textile finishing requires a lot of water to enhance the properties of the finished fabric, such as softness or water repellency and dyeing processes such as topping, color addition, rinsing, washing off excess dyes or chemicals, etc. [68]. The water used in these processes becomes polluted with fixatives, finishing agents, dyes, and many more, making it unusable unless properly treated [69]. WF in textile finishing can harm the environment in several ways. In areas with scarce water, high consumption worsens the problem even more. Wastewater containing heavy metals, synthetic dyes, and other chemicals pollutes waterways and harms biodiversity, endangering aquatic ecosystems. Table 6 demonstrates the maximum to minimum pollution loads from the textile wet finishing plant.

Table 4. Required bluewater in wet processing of yarns and textile fabrics [67]

Process name	Water required (L/kg)		
	Minimum	Average	Maximum
Desizing	2.5	11.75	21
Scouring	20	32.5	45
Bleaching	2.5	13.75	25
Mercerizing	17	24.5	32
Dyeing	10	155	300

Table 5. Main dyeing machine types and their liquor ratio for dyeing operation [67]

Machine type	Material-to-liquor ratio (M:L)
Jet	1:7–1:15
Jig	1:5
Beam	1:10
Continuous	1:1
Beck	1:17

3.4. Impacts on environment

The volume and composition of textile wastewater make it a major environmental threat. This wastewater poses a significant threat to aquatic ecosystems due to the wide variety of chemicals such as dyes, heavy metals, surfactants, etc. [70]. Chemical contaminants create damage to ecosystems by poisoning underground water supplies and cutting down on the diversity of species [71]. In addition, eutrophication is facilitated by the nutrients found in textile wastewater, which in turn promotes the growth of algae and reduces oxygen levels in bodies of water [72]. The subsequent loss of aquatic life and accelerated ecological deterioration are direct results of this. In areas where water is already scarce, the massive amounts of water required for textile production only make the problem even worse. Agricultural productivity and food safety are both compromised when wastewater from textiles is not properly disposed. Table 7 represents the ecological consequences of wastewater generated by the textile industry.

Table 6. Maximum to minimum pollution loads from the textile wet finishing plant

Parameter	Pollutant load		
	Maximum	Average	Minimum
Inorganic load (kg day^{-1})	15,356	964	5
Organic load (kg COD day^{-1})	7,793	1,766	100

Table 7. Ecological consequences of wastewater generated by the textile industry [33]

Environmental impact	Type of pollutant	Characteristic factors, kg/m^3 of pollutant per kg of material
Eutrophication	COD	0.022 kg/kg
	BOD	0.11 kg/kg
	NH_3N	3.64 kg/kg
Acidification	H_2SO_4	0.65 kg/kg
	Chloride	0.88 kg/kg
Alkalization	NaOH	0.425 kg/kg
	NA_2CO_3	0.321 kg/kg
Ecotoxicity	Zn^{2+}	0.38 m^3/mg
	CS_2	0.18 m^3/mg

3.5. Regional variations in water use within the textile sector

Various factors, such as geography, climate, water availability, regulatory frameworks, and industrial practices, contribute to regional variations in water use and WF within the textile sector. Some regions use a disproportionate amount of water for textile production due to these variations, while other regions use a much more uniform amount. Some regions that face the most serious problems related to the WF in the textile industry are discussed below.

3.5.1. Bangladesh

Yarn and fabric manufacturing, their pretreatment, dyeing and finishing, and making finished products are the main steps in the textile and garment manufacturing process in Bangladesh. An estimated 1,700 wet processing units (WPF) in Bangladesh were devoted to the washing, dyeing, and finishing (WDF) process of textiles [73]. The WDF textile units are responsible for the industry's highest freshwater abstraction rates, the largest volumes of wastewater generation and discharge. The highest chemical use and the highest energy consumption for water heating and steam generation make them the most environmentally damaging units in the sector [74]. Bangladeshi textile units use 250–300 L of water per kilogram of fabric, enough to supply two people with water daily. Dhaka and its surrounding areas have 70% of the WDF textile units, while Mymensingh and Chittagong have the rest. Over 95% of WDF textile units are near water in Chittagong and Dhaka due to convenient access to services, infrastructure, and markets and the potential for daily direct discharges of large volumes of wastewater to nearby bodies of water [73]. Except for a few WDF units in the six export processing zones, most textile units are in informal, diverse, and under-serviced industrial clusters. These clusters often contain residential homes and small and medium factories from various industries. Thus, WDF textile units often have a localized impact on the environment in terms of water contamination, groundwater overexploitation, and energy strain [75].

3.5.2. India

Textile industry is one of the extremely significant manufacturing companies in India, accounting for around 2% of GDP and approx. 35 million workers in the Indian economy. India demonstrated the topmost progress as the world's third biggest textiles and clothing exporter (after China and EU28) with 23% growth in 2013 (World Trade Organisation's Statistics, 2014). However, the textile industry is also a significant water polluter and one of the most water-intensive industries in India; therefore, India has been detected as an extremely water-scarce territory. Water pollution and scarcity in the textile industry are linked to wet processing, as highlighted by the Centre for Science and Environment study. In the study, it was found that the Indian textile industry consumes approximately 200–250 m^3 of water per ton of cotton cloth, a marked difference from the global average of less than 100 m^3 per ton, which is used by the global industry. In addition, it is estimated that over 70% of water consumed by rural communities in India does not meet WHO standards, which causes 80% of rural illnesses and 20% of deaths among children under the age of five. There are also reports that only 31% of sewage is treated before it is discharged into 18 of the country's major rivers, with the rest being discharged into surface waters [76].

3.5.3. China

China is a major global producer of textiles, and due to the rapid growth of the industry, it leads to a high volume of water utilization and consequently pollution. The Chinese textile materials manufacturing industry is well-known for its massive water consumption due to the wide range of textiles it produces, from yarns to fabrics and garments, and other accessories [17]. The WF of China's textile industry has been a topic of concern due to the industry's significant water consumption and pollution. Recent studies have shown that the WF intensity of China's textile industry has decreased [77]. This improvement is largely due to government administrative control and actions taken by producers to save freshwater and treat wastewater. Despite these efforts, the industry still faces challenges due to the large volumes of consumed and polluted water [78]. Water scarcity, particularly in the northern regions of China, remains a significant challenge [79,80]. Despite China ranking fourth in global freshwater reserves, it has the second-lowest per capita water supply of any country in the world [80]. This scarcity is exacerbated by the geographic and temporal mismatch between water availability and demand.

3.5.4. Ethiopia

In Ethiopia, the industrial sector has the lowest water consumption rate compared to other sectors. As per the UNEP Ethiopia country profile report, in 2002, only 0.4% of the total water use was accounted for by industrial uses [81]. The textile and garment industry's recent expansion suggests that this figure could be substantially higher today. Perhaps, the low water consumption in industry is a result of the country's lack of developed large-scale manufacturing facilities. At the moment, the majority of Ethiopia's textile industries are on a smaller or medium scale [82].

4. Environmental impacts

The textile industry is a key manufacturing sector in developing countries. Textile industries are among the most chemically intensive and water-intensive sectors globally, as well as the largest consumers and primary polluters of potable water [55]. The use of water varies between 200 and 400 L per kilogram of completed product and generates a high amount of wastewater, based on the process and fiber type utilized [83]. This results in an average pollution of 100 kg COD per ton of fabric [55]. Furthermore, wet processing involves the use of various chemicals, dyes, auxiliary chemicals, and sizing materials, resulting in the production of polluted wastewater [84]. Elevated quantities of textile effluent have the potential to induce modifications in the physical, chemical, and biological attributes of the aquatic ecosystem, thereby posing risks to public health, livestock, wildlife, fish, and other forms of biodiversity. Wastewater resulting from the wet processing must therefore be treated extensively prior to discharge into the environment.

The textile industry is composed of a multitude of chemical and mechanical processes, each of which has a unique environmental impact. Textile manufacturing has the potential to produce both inorganic and organic wastes that become contaminated with effluent from production processes [85]. As a result, the receiving water bodies may experience alterations in both chemical and biological parameters. The primary environmental concerns linked to the textile industry encompass water consumption, treatment processes, and the disposal of effluent [86]. The most significant sustainability challenge confronting the textile industry is water scarcity [87]. The environmental exposure such as duration and concentration and polluting potential such as hazard attributes and toxicity determine the environmental risk [88]. Reducing emissions through the various environmental pathways can therefore mitigate environmental risk [89].

The primary concern regarding effluent from the textile industry pertains to the utilization of dyes for coloring purposes [90]. These substances are inherently toxic and may lead to intestinal cancer, developmental issues in the fetal brain, as well as allergic reactions such as contact dermatitis, respiratory conditions, skin irritation, and irritation of the mucous membranes and upper respiratory system [90,91]. These colored allergens are capable of undergoing chemical and biological assimilations, inducing eutrophication, consuming dissolved oxygen, impeding re-oxygenation and accelerating genotoxicity and microtoxicity [92]. Dyes contain heavy metals, surfactants, oxidizing and reducing agents, several salts, and enzymes [93]. Inefficiencies in the dyeing process result in the release of a significant quantity of dyestuffs, which are subsequently lost directly into the effluent and subsequently discharged into the environment, resulting in a gradual deterioration of both surface water and groundwater quality [94]. During the textile manufacturing process, antimicrobial agents that are resistant to biological degradation are commonly employed, resulting in an effluent that is also resistant to biodegradation [95,96]. The azo dyes can induce toxicity through either the direct action of the agent or the aryl amine derivatives produced during the reductive biotransformation of the azo bond [97]. Azo dyes that are ingested into the body may undergo metabolism by intestinal microorganisms utilizing azoreductases, which convert them to aromatic amines [98,99]. Enzymes present in the liver of mammals, among others, have the capability to facilitate the nitroreduction of the nitro group and the reductive cleavage of the azo bond [100]. In this process, *N*-hydroxylamines can be produced and they have the potential to induce DNA damage [101]. Furthermore, dyes have frequently contained heavy metals that are toxic in particular concentrations, such as nickel, cobalt, copper, and chromium [102,103].

Furthermore, several other toxic compounds can be found in textile wastewater, such as chlorinated phenols, sulfur, brominated flame retardants, formaldehyde, naphthol, nitrates, soaps, acetic acid, and many other auxiliary chemicals [103]. The pH and temperature of the mill effluent are extremely high, both of which are very detrimental to the deterioration of the quality of the natural environment [85]. Additionally, the accumulation of dyes disrupts the ecosystem of the receiving water body, by obstructing sunlight penetration and the photosynthesis process [104]. The discharge of this effluent into the fields causes a blockage of the soil's pores, which subsequently leads to a decline in soil productivity, as the soil becomes more rigid, impeding the ability of plant roots to penetrate and grow [105].

The pipes transporting sewage develop corrosion and incrustation due to the flow of wastewater through the drains [90]. The discharge of wastewater into rivers and sewers compromises the potable water quality from a hygienic point of view, rendering it unfit for human consumption. Additionally, wastewater causes drain leakage, which raises the cost of drain maintenance. The color in water bodies is mainly regarded as an aesthetic problem rather than an eco-toxic hazard, however can be a problem due to the blocking of sunlight penetration. People normally tolerate the blue and green color of rivers and lakes but for example, a color such as purple or red tends to elicit the most concern [106].

Additional environmental concerns of equivalent significance include air pollution, particularly volatile organic compounds, and excessive commotion or odor [90]. Wastewater treatment facilities, printing, dyeing, fabric preparation, finishing, and drying processes are additional significant sources of air emissions in the textile industry. Drying furnaces and high-temperature drying/curing of mineral oils, both emit hydrocarbons [89]. In addition to formaldehyde, acids, and softeners, these procedures may release additional volatile compounds [106].

5. Sustainability practices in textile industry

The textile industry occupies a central position in the global economy, driving fashion trends and meeting the growing demand for clothing and textiles. However, it hides a major problem that is often overlooked: its staggering water consumption.

Ranked among the top ten most water-intensive industries, the textile industry relies heavily on water throughout its entire production cycle. This journey begins with the cultivation of natural fibers, where water is vital for agricultural production. It extends through processes such as cleaning and preparing fibers for spinning and weaving and culminates in wet chemical processes such as sizing, scouring, bleaching, dyeing, finishing, and washing.

Each of these stages contributes to the industry's significant WF, posing challenges for sustainability and environmental conservation. As consumer awareness increases, addressing water use in textile manufacturing becomes increasingly critical to the long-term viability of the industry and mitigation of ecological impact [78].

Efficient wastewater management, chemical process optimization techniques, and emerging technologies are playing a key role in reducing water consumption, improving treatment efficiency and promoting environmental sustainability [74].

The following is a review of wastewater management, alternative chemical process techniques, and the advancement of the latest emerging technologies, providing insights into how the textile industry can transition to more efficient and environmentally responsible practices.

5.1. Wastewater management

Wastewater management is a critical aspect of sustainability in the textile industry. Proper treatment and management of wastewater can help minimize the environmental impact of textile manufacturing processes, ensure compliance with regulatory requirements, and protect local water resources. Textile manufacturers must implement wastewater management practices such as treatment processes, wastewater reuse, monitoring, and reporting, sustainable chemical management, and employee training and education to operate sustainably and responsibly. The various aspects of wastewater management in the textile industry are discussed below.

5.1.1. Treatment processes

Wastewater from textile manufacturing processes must be treated before it can be safely discharged into the environment. Treatment processes can range from simple physical treatments, such as sedimentation and filtration, to more complex biological and chemical treatments. The choice of treatment process will depend on the type of pollutants present in the wastewater and the regulatory requirements of the local environment agency [8,96].

It is crucial to adhere to specific water quality standards to ensure the treated wastewater is safe for discharge into the environment. These standards can vary depending on the local regulations and the receiving water body's sensitivity.

Some European Union Regulations are cited as follows.

Wastewater Treatment Directive (WTD): The EU's WTD sets minimum requirements for the treatment of urban wastewater, which textile manufacturers must comply with if their wastewater is discharged into municipal treatment plants. This directive aims to mitigate the environmental impact of urban wastewater discharges by promoting cost-effective treatment measures that protect water quality in rivers, lakes, groundwater, and seas.

Water Framework Directive (WFD): This directive aims to protect and sustainably use water resources in the EU. It requires member states to implement river basin management plans and achieve good ecological and chemical status for all water bodies.

REACH regulation: This regulation focuses on the Registration, Evaluation, Authorization, and Restriction of Chemicals. It requires textile manufacturers to manage and report the chemicals used in their processes, ensuring they do not harm human health or the environment.

Water Quality Standards

The Water Quality Standards generally include parameters such as:

- COD reflects the number of organic pollutants in the wastewater.
- BOD indicates the organic matter level that can be biologically degraded.
- Total suspended solids: The solids suspended in wastewater that can settle out.
- pH levels: The acidity or alkalinity of the water, which should be neutralized before discharge.
- Heavy metals and toxic compounds: Specific limits for heavy metals like lead, mercury, chromium, and other hazardous substances.

These parameters must be controlled to acceptable levels before the treated wastewater can be discharged, ensuring it does not adversely affect the receiving water bodies or the environment. Compliance with these standards is critical for the sustainability and legal operation of textile manufacturing facilities.

For more specific guidelines and limits, it is advisable to consult local environmental protection agencies or regulatory bodies, as standards may vary by region and the nature of the receiving water body.

5.1.2. Segregated wastewater flows

In the textile industry, the utilization of split or segregated wastewater streams offers significant benefits. These streams result from the diverse wet processes involved, producing complex mixtures of dyes and chemicals in the effluent.

Segregating these wastewater streams simplifies their treatment and facilitates reuse, offering cost-effective solutions. Known as “split flow treatment,” this approach surpasses mixed flow treatment methods in several aspects. It enables higher water recovery rates, increased recycling rates, and enhanced water quality, all achievable with smaller investments [18].

5.1.3. Reuse of wastewater

In addition to treating wastewater, textile manufacturers can also implement wastewater reuse systems. Wastewater reuse involves treating the wastewater to a quality level that is suitable for reuse in non-potable applications, such as cleaning, irrigation, or cooling. Reusing wastewater can help textile manufacturers reduce their water consumption and minimize their impact on local water resources [107].

5.1.4. Monitoring and reporting

Textile manufacturers must monitor and report their wastewater discharges to comply with regulatory requirements. Monitoring involves regularly testing the quality of the wastewater to ensure that it meets regulatory standards. Reporting involves submitting regular reports to the local environment agency detailing the volume and quality of wastewater discharged [108].

5.1.5. Sustainable chemical management

Chemicals used in textile manufacturing processes can be major pollutants in wastewater. To minimize the environmental impact of these chemicals, textile manufacturers can implement sustainable chemical management practices. These practices include reducing the use of hazardous chemicals, implementing safer chemical alternatives, and properly managing chemical waste.

5.1.6. Employee training and education

Proper wastewater management requires the participation of all employees involved in the manufacturing process. Textile manufacturers can provide employee training and education to ensure that all employees understand the importance of proper wastewater management and the impact of their actions on the environment.

5.2. Chemical process optimization techniques to save water in the textile industry

In textile chemical processing, there are several water-saving technologies and process optimization techniques. The following are some of the examples used.

5.2.1. Pad-batch countercurrent washing

A backwashing strategy in textile processing consists of introducing fresh water in the last wash of a series of washes. The wastewater flows in reverse, from the last wash to the previous ones, with the cleaner water being used to wash the cleaner product and the dirtier water being used for the more contaminated product. This method allows substantial water savings [2,109,110].

5.2.2. Reuse of final rinse water from dyeing for dye bath makeup

In batch dyeing processes, the final rinse water from dyeing, which is relatively clean, can be effectively reused. This water can either be used directly for further rinsing or to prepare subsequent dye baths. This method is commonly employed in industries such as fabric and carpet manufacturing [111].

5.2.3. Repurposing scouring rinse water for desizing processes

Mercerizing and bleach-wash water, rich in caustic and bleach compounds, can be effectively repurposed in scouring or desizing processes. The chemicals present in these wastewaters, including caustic soda, can degrade many sizing compounds, making them suitable for scouring. Additionally, since scouring cotton typically requires caustic soda, the reuse of caustic-rich wastewater from mercerization and bleaching offers added advantages in terms of resource efficiency and cost-effectiveness [110].

5.3. Emerging water-saving wet processing technologies

Emerging water-saving wet processing technologies are continuously evolving to address the textile industry’s water consumption challenges. These technologies aim to reduce water usage while maintaining or improving process efficiency and product quality. Some of the notable innovations include:

5.3.1. Enzymatic treatment of textile products

In wet textile processing, enzymes play an important role, especially in the treatment of natural fibers. Various enzymes are used for different purposes, such as desizing (e.g., amylase), bioscouring (e.g., pectinase), biobleaching (e.g., cellulase), and denim biobleaching (e.g., laccase). Enzymatic scouring, which involves the use of enzymes in combination with surfactants as wetting and emulsifying agents, together with complexing agents, presents an environmentally friendly alternative to traditional alkaline scouring methods. This process consumes fewer auxiliaries and chemicals, while offering better results than conventional methods [112].

Enzymatic bleaching of textiles, especially denim, with laccase, reduces water consumption and processing temperature, which increases its efficiency and environmental friendliness compared to other methods. In addition, current research and development is focused on enzymes for wool scouring, cotton scouring, cotton bleaching, linen softening, and silk degumming, indicating the growing potential of enzymatic treatments in textile processing.

In general, enzymatic processes offer advantages such as lower water consumption and lower processing temperature, making them more sustainable and environmentally friendly than conventional methods [113].

5.3.2. Ultrasonic treatments

Ultrasonic treatments produce mechanical vibrations that are transmitted as longitudinal waves through the fluid and significantly accelerate the washing processes after dyeing cotton, nylon, and polyamide. Benefits include shorter cycle times, lower process temperatures leading to energy savings, a 20–30% reduction in effluent load by reducing dye and chemical consumption, water savings of around 20%, and increased productivity due to shorter cycle times [18].

5.3.3. Ozone bleaching

Ozone bleaching offers a solution to the environmental problems posed by conventional cotton bleaching methods, which consume large amounts of water and chemicals. Ozone reduces wastewater discharge during cotton preparation, energy savings due to ambient temperature operation, a 50% reduction in CO_2 emissions, and increased productivity due to reduced cycle times [114].

5.3.4. Electrochemical dyeing

Electrochemical dyeing presents an effective alternative to traditional methods. Direct electrolysis reduces the dyes on the cathode surface, while indirect electrochemical dyeing relies on conventional reducing agents such as Fe^{2+}/Fe^{3+}. Benefits include reduced water and chemical consumption through recycling, minimal impact on aquatic life, and reduced wastewater discharges [115].

5.3.5. Digital dyeing and printing

Digital dyeing and printing technologies allow for precise application of dyes and pigments directly onto fabrics, minimizing the need for excessive water in traditional dyeing processes [116]. Digital inkjet printing has been shown to reduce dye residues in effluent by approximately 45% [117].

5.3.6. Nanotechnology

Nanotechnology-based treatments can modify fabric surfaces to enhance water repellency, reducing the need for water during washing and finishing processes [118].

5.3.7. Supercritical fluid dyeing

Supercritical fluid dyeing uses carbon dioxide in a supercritical state as a solvent for dyes, eliminating the need for large volumes of water and chemical additives typically used in conventional dyeing processes [119].

5.3.8. Biodegradable finishes

Development of biodegradable finishing agents reduces the need for extensive washing to remove chemical residues, thus conserving water resources [120].

Efficient wastewater management and emerging technologies offer promising solutions to the textile industry’s water-saving challenges, contributing to sustainability and environmental conservation efforts. Continued research and development in this area will further drive innovation and the adoption of water-efficient practices in the textile wet process.

6. Challenges and barriers

6.1. Challenges in textile wet processing

The primary challenges and barriers regarding the sustainability of textile wet processing are the consumption of water, energy, chemicals, and the discharge of unexhausted chemicals and wastewater [121]. The general wet process of textile can be described as follows:

Raw Fabric → Pretreatment → Dyeing/Printing → Fixation → Washing → Finishing → Quality Control → Finished Product.

In the following subsections, the sustainability implications of current procedures utilized in a variety of wet processing practices are analyzed.

6.1.1. Preparatory processing

In general, preparatory processing, especially of natural fibers, consumes large quantities of water and generates effluent with considerable BOD and COD values [32]. For example, cotton preparatory operations account for about 38% of overall water use in cotton processing [121].

6.1.1.1. Desizing or removal of size

The method utilized for desizing depends on the nature of the size being applied. There are two categories of sizing materials: (a) native and degraded starch and starch derivatives, (b) cellulose derivatives like carboxymethylcellulose, protein sizes and synthetic sizes (e.g., polyvinyl alcohol [PVA], polyacrylates, and polystyrene-maleic acid copolymers) [121,122]. Desizing is a critical pretreatment method in the wet processing of cotton fabrics [123]. Cotton can be considered the most important natural fiber and accounts for nearly 80% of natural total global fiber production by weight [124].

Cotton fibers are typically sized with sizing agents derived from starch due to their cost-effectiveness and ability to produce satisfactory weaving results [125]. The elimination of these sizing substances can be achieved through hydrolysis utilizing diluted acids or enzymes, such as amylases [126]. Additionally, hot caustic soda or detergent can be used to remove these sizing substances, albeit with a lower degree of effectiveness. Despite the relatively low water demand of the desizing process, the BOD of the effluent is significantly increased by starch hydrolysis products; thus, the desizing process is the primary contributor to BOD in cotton processing [127]. Approximately 50% of all water pollution is caused due to the desizing process that produces wastewater with a high BOD [128]. Synthetic sizing materials, such as PVA, although more expensive may be easily removed with hot water and recovered using ultrafiltration processes that can reduce the cost but also decrease pollution [129].

6.1.1.2. Scouring and bleaching

The scouring process wastewater is characterized by high COD, BOD, TDS, and alkalinity. During the scouring process, impurities like waxes, oils, lubricants, pectin, and proteins from textile fabrics are removed [130]. Also, wetting agents, sequestering agents, and emulsifiers are also added to improve the process efficiency. Silk scouring or degumming removes sericin, a sticky substance made of fibroin protein, from the fibers under gentle circumstances using soap or surfactants [131]. Another option is the protease enzymes, which can also be used in order to remove sericin by hydrolysis [132]. The use of synthetic fibers, both man-made and regenerated, is considered more sustainable because they are free of impurities and require only mild cleaning with surfactants to remove dust and spin finishes. Sericin and other materials can be recovered from processing water so as to reduce the BOD and they can be further utilized in other applications [132]. Scoured textile materials contain natural or added colorants that are broken down during bleaching using oxidative or reductive agents, resulting in a pure white appearance. The use of chlorine-based bleaching chemicals, including hypochlorite, has been restricted due to the production of adsorbable organohalides [133]. The use of hydrogen peroxide is harmless, as its degradation products are oxygen and water, however, requires a significant volume of water, high temperatures, stabilizers both inorganic and organic, and neutralizing agents. A more sustainable method involves using a specialized enzyme-based process focused only on the colored substances [134].

Scouring and bleaching also include the use of surfactants such as alkyl phenol ethoxylates (APEOs). APEOs alter hormones and are hazardous to aquatic species; they are non-biodegradable and persistent, causing issues with wastewater treatment [84,121].

6.1.2. Dyeing and printing

Most commercial textile dyes are synthetic, derived from aromatic compounds in coal tar, and show little biodegradability [10]. The main environmental concern in dyeing is the dye present in wastewater due to low fixation. Dye fixation depends on the dye chemistry and application. Unfixed dyes produce intensely colored effluent, which harms aquatic ecosystems, color reduces the photosynthetic ability of aquatic plants by limiting light availability, and the breakdown of dyes can result in carcinogenic, mutagenic, or toxic byproducts [89,95,102].

Printing uses thick pastes to apply dye and pigments, resulting in lower effluent volume. However, the use of volatile organic compounds (VOCs) in printing pastes raises concerns regarding the emission of VOCs into the environment (Aydemir and Ozsoy, 2020). Unfixed dyes and pigments are released as effluent during the washing process [108]. Cleaning printing screens and equipment uses water and organic solvents, releasing chemicals from printing pastes into the environment [9]. Dispersing agents and auxiliaries in printing pastes may contain formaldehyde from fixers/binders and other toxic compounds, making them unsuitable for the environment [9]. Plastisol printing pastes may contain hazardous substances such as PVC and phthalates [134].

6.1.3. Finishing processing

Textiles finishing utilize harmful chemicals, catalysts, and auxiliaries that pose a health risk to both users and workers in processing units [9]. The unfixed chemicals get discharged into wastewater and contaminate the ecosystem affecting human health [135]. During finishing processing, harmful chemicals such as formaldehyde are frequently utilized, including dye-fixing agents, softeners, and cross-linking resins. Formaldehyde released by these textiles can cause eye irritation, skin rashes, allergic reactions, and cancer [97,103].

Polymeric finishes containing perfluoroalkyl chains with eight or more fluorinated carbons provide long-lasting water, oil, and stain repellency in textiles. Long-chain fluorinated polymers frequently contain residual raw materials and trace amounts of long-chain perfluoroalkyl acids (PFAAs) as impurities. Residual raw materials and products can degrade into long-chain PFAAs. Long-chain PFAAs, like PFOA and PFOS, have been found in the environment, wildlife, and humans due to their widespread use and low biodegradability [121].

Other chemicals that can be found in the finishing wastewater are antimicrobial agents for health and hygiene purposes and to prevent odor formation due to bacterial action on perspiration [46,91]. Triclosan, a prominent synthetic antibacterial agent, is presently prohibited due to its degradation to polychlorinated dioxin that is harmful [136]. Many coatings used to add flame-retardant characteristics to fabrics are hazardous. Despite being highly harmful to humans, brominated flame retardants like polybrominated diphenyl ethers are nevertheless widely used for textile finishing. These chemicals are comparable to polychlorinated biphenyls, which are banned in many countries [103].

6.2. Sustainable strategies

The treatment of textile wastewater to make it safe for disposal in an environmentally friendly manner is difficult and expensive and various attempts have been made to reduce the input requirements in textile processing, which can reduce pollutant load as well as the quantity of effluent generated, thereby improving the sustainability of the textile industry [121]. Some of these approaches are (a) The use of biomaterials and renewable energy such as bioprocessing using enzymes, the use of natural dyes, the use of bioagents for finishing, functional finishing, UV-protective finishing, aroma finishing [133,137]; process improvement and optimization, such as combining two or more processes in a single step, replacement of biodegradable products, digital printing; (c) developments in textile chemicals, dyes, and auxiliaries such as bi- and multifunctional reactive dyes [121]; (d) development in textile machineries such as continuous bleaching and dyeing and vacuum application of dyes, e-control dyeing process introduced by Monforts, high-speed stenters with self-lubricating chains [138]; (e) developments in recycling and reuse of process inputs, such as chemicals, water recovery and reuse [139]; (f) use of waterless technologies for pollution-free textile processing, such as the use of supercritical fluids as processing medium, use of plasma [140]; and (g) the use of ecostandards and environmental regulations in promoting sustainability [103].

6.3. Economic, regulatory, and social barriers

Economic, regulatory, and social considerations are essential for the long-term viability of sustainable textile processing [14]. Textile processing must be economically competitive while also taking into account regulatory and social considerations. Textile value chain stakeholders, including fiber growers, spinners, chemical suppliers, processors, garment makers, transporters, retailers, and consumers, share responsibility for ensuring sustainable textile manufacturing [141].

In the chemical processing sector, voluntary eco-labeling for textiles considers the entire product, including its production process, to ensure minimal environmental impact [103]. They prioritize consumer safety and worker safety during manufacturing, ensuring fair wages and promoting sustainable textile production [120]. Adopting low-impact sustainable textile manufacturing processes is crucial to protect water resources in developing and undeveloped countries, affecting the well-being and livelihoods of communities that rely on them [142]. Textile industries in these countries often prioritize quick profits above sustainable chemical processing and lack the necessary resources to apply low-impact technology.

Adopting sustainable technologies may entail investment and higher initial expenses, but reductions in energy, chemicals, and process water use will result in lower long-term expenditures [143]. When considering environmental harm and restoration costs, these options become even more appealing [142]. To protect the environment, governments and policy-makers must establish and enforce stronger restrictions. Processors should be encouraged to embrace low-impact technologies through incentives and support. Big brands and consumers have an ethical obligation to avoid environmental damage and support sustainable textile production, including paying extra if necessary [132,141].

To achieve sustainability, all sector stakeholders must collaborate and participate. Chemical makers, machinery manufacturers, and academics should focus on developing low-cost, low-environmental-impact solutions to reduce the negative social and economic impacts of wet textile processing [143].

7. Policy and regulatory landscape

In the European Union (EU), there are several regulations and legislation in place to address the issue of WF in the textile sector. These regulations aim to promote sustainable water use and reduce the environmental impact of textile production. Some of the key regulations and legislation are as follows.

7.1. REACH

Registration, Evaluation, Authorization and restriction of Chemicals (REACH) was enacted in 2007 by the European Parliament and the Council [144,145]. REACH is the main adaptation in the EU suggested to estimate chemical threat, whereas defending human health and the surroundings. REACH requires textile manufacturers to register chemicals; they use in their production processes and assess their prospective impact on human health and the environment [146–148]. Many new approaches to chemical management were introduced by the Council and the European Parliament in December 2006 with the adoption of Regulation 1907/2006 concerning REACH. One of these changes was that the responsibility for finding and fixing problems with products was shifted to the producers, importers, and consumers [137]. The urgency of the need to swiftly regulate harmful substances was acknowledged at the UNCED in Rio de Janeiro, Brazil, which provided the impetus for the REACH law [149]. The result was a consensus on a course of action for “sustainable development” in the realm of environmental policy. In order to better manage harmful chemicals and achieve sustainable chemical use on a global scale, UNCED’s Agenda 21 outlined the necessity for enhanced international collaboration in six critical areas in Chapter 19. Many of the EU’s chemicals management policies were harmonized with UNCED objectives in the 5th Environment Action Programme (1992–1999, “Towards sustainability”) [150]. When considering chemicals with the potential to cause serious adverse effects, REACH also takes the precautionary principle into consideration [151,152]. Thus, before a substance can be sold, its potential hazards must be assessed. REACH requires companies to prove their chemicals are safe, shifting compliance from regulators to industry [112].

7.2. WTD

The WTD is an EU directive that sets out minimum requirements for the treatment of urban wastewater. This directive applies to textile manufacturers that discharge wastewater into municipal wastewater treatment plants. On October 25, 2022, the EC unveiled a proposal for the new Urban Waste Water Treatment Directive (UWWTD). A thorough REFIT assessment of the UWWTD dating back to 1991 demonstrated its substantial success in mitigating the negative impacts of urban wastewater discharges on the environment [153]. The proposal prioritizes enhancing the quality of rivers, lakes, groundwater, and seas by implementing cost-effective wastewater treatment measures. It addresses critical aspects such as the interconnection between energy and water, nutrient reclamation, and the inclusion of new mandates for microplastics/microfibers and other micropollutants, aligning with the Circular Economy Action Plan. By 2040, the sector is expected to achieve energy neutrality. Furthermore, the proposal seeks to establish new standards and thresholds, expand producer responsibility, enhance digitalized monitoring and pollution tracking, and foster collaboration between health and wastewater regulatory bodies. These advancements aim to promote improved health and environmental protection in accordance with the goals of the European Green Deal [154].

7.3. WFD

Globally, integrated pollution control, ecosystem-based approaches that integrate the natural and social sciences and holistic environmental management, all emerged in the 1990s [155]. Following the adoption of environmental quality objectives and standards by numerous European countries, this resulted in the proposal for an EU Directive on the Environmental Quality Standards for Water (EQSW) [156]. The WFD is an EU directive that aims to establish a framework for the protection and sustainable use of water resources in the EU countries. The directive requires member states to elaborate river water controlling plans and examine procedures to succeed appropriate ecological and chemical significance of water reservoirs. Textile manufacturers are required to comply with the water quality standards set by the directive [157,158]. Concerns about water status gave rise to the policies, which matched powerful economic interests against the more undefined public interest. The most common policy responses to this problem have been an establishment of water quality standards, an introduction of discharge controls, and a reduction of the effects of human activities on the quality of surface water [159].

7.4. SAC

The SAC is a non-profit organization that aims to promote sustainable textile production. The coalition has developed the Higg Index, a suite of tools that enables textile manufacturers to measure and improve their environmental and social performance [160]. Adopting an integrated standard for measuring sustainability performance is central to the mission of the SAC to lead the apparel industry toward a more sustainable future. The SAI is a standardized tool that the SAC developed to help apparel industrial businesses track the social and environmental impacts of their products from the design stage and all the way up to recycling [150]. Leaders in the apparel industries were concerned about the effects of heavy pollution of their industries on the environment, and they worked together to establish the SAC, i.e., an organization that strives for eco-friendliness and sustainability in the hopes of a better future [159,161].

7.5. Blue angel certification

The Blue Angel certification is the oldest eco-label in the world, established in 1978. The Blue Angel eco-label, currently owned by the German federal Ministry for the environment, is conferred by an autonomous, unbiased, and esteemed organization known as the Environmental Label Jury. Criteria for this label are formulated based on scientific principles and are regularly revised to incorporate the latest research [162,163]. It aims to promote environmentally friendly products and services. Textile manufacturers can obtain the Blue Angel Certification for their products if they meet certain environmental criteria, including water consumption and wastewater treatment standards [164].

Overall, the regulations and legislation in the EU aim to promote sustainable water use and reduce the environmental impact of textile production. Compliance with these regulations is essential for textile manufacturers to operate sustainably and minimize their WF.

7.6. Recommended policy improvements

For environmental sustainability, it is critical that policies be improved so that the textile industry can reduce its WF. Governments must strictly regulate water use and pollution control, and financial incentives should be offered to encourage the adoption of water-saving technologies. Companies should be held responsible for their water usage and pollution level through the implementation of transparency and reporting requirements.

7.6.1. Water efficiency standards

The textile production processes should adhere to strict water efficiency standards. For example, this may include regulations for the implementation of water-saving technologies such as closed-loop systems, recycling, and the reutilization of water in the production process.

7.6.2. Pollution control regulations

Though international regulations are set by the respective authorities and buyers to manufacturers in the booking sheets and agreements, they can be strongly regulated by buyers and other accountable organizations throughout the year. Every shipment including every batch can be regulated through regular monitoring to secure and control the pollution through wastewater.

7.6.3. Water pricing strategy

It is important that the pricing strategy for water take into account the actual cost of water that is used in the production of textiles. The promotion of the use of recycled or reclaimed water, including the increase of water tariffs for industries that have high water consumption rates, and the provision of incentives for the implementation of water conservation measures are all examples of this approach.

7.6.4. Investment in research and development

Research and development efforts should be supported financially so that new technologies and processes can be created to reduce the textile industry’s impact on water consumption. This can involve exploring new fibers with lower water requirements for production or investing in dyeing and finishing methods and technologies that use less water.

7.6.5. Incentives and award for sustainable practices

Companies in the textile industry can be incentivized to reduce their WF and adopt sustainable practices by offering them tax breaks, grants and subsidies. This can encourage more widespread adoption of water-saving technologies by helping to offset their initial costs.

8. Tools for WF evaluation

A number of WF tools have been developed to help academics and textile sector professionals assess and address WFs of textiles. We reviewed academic and grey literature on such tools, using search terms that included “textile,” “fashion,” or “apparel” in combination with “water” and “tool” or “application.” Only non-proprietary tools that have been developed specifically with water resources use in mind and which target the textiles sector are included.

Chen et al. [165] developed a process-level water conservation and pollution control performance evaluation tool for the textiles industry with a focus on technological innovation. Targeting mostly textile manufacturers, they employ reduction in water use, water consumption, and water assimilation as evaluation indicators, specifying the process level. The tool does not come with an online interface and relies on local user input for data.

Haque et al. [74] developed an industrial water management tool called SIWP, which attributes total daily water input at the plant level to various processes of a wet processing facility of the textile industry. The tool reports the blue and grey WF at the process level, as well as groundwater savings potential. Its specific development for a Bangladeshi industrial complex, however, complicates its generic use in other contexts. Although a screenshot of a tool interface is shown in the article, there seems to be no online application of the tool.

Li et al. [166] developed a process-level WF assessment tool for textile production based on Life Cycle Assessment and modularity principles. The LCA origins imply that their WF definitions are not directly aligned with the global WF Assessment standard [59]. Modularity suggests defining basic process units that cannot be subdivided, for which the WF assessment is done. So-called WF units can then be recomposed into various configurations of the textiles value chain. Their tool reports the blue WF, water scarcity footprint, and water degradation footprints at process level, including pre-treatment, dyeing, printing, and finishing. Moreover, each of these processes is further subdivided into multiple ways in which the process can be implemented. Although the design of the tool is intricate and allows scaling, its underlying WF values are tailored to the specific test cases in China, potentially reducing its more generic applicability.

The InoCottonGROW project developed a multi-scale, region-specific textile WF calculator to support decision-making in the textile industry and local policy [166]. This actual web application allows evaluation of water use, water consumption, wastewater discharge, grey WF, water scarcity footprint, human toxicity, and eutrophication associated with textile production at national. The tool does not specify evaluation indicators by process step. If the user does not provide particular values, e.g., due to a lack of data, default values will be applied.

UNIDO and DNV-GL developed the web-based Water Calculation Tool for the Textile Wet Processing Sector [167]. This detailed online tool allows evaluation of (blue) water use and various pollution-related metrics based on process-level entries. Confusingly, the terms water use and water consumption seem to be used interchangeably. Moreover, the tool fully relies on user input, which at the high level of detail requested by the tool will be hard for many users to submit. The resulting report compares user water consumption with regionally available indicators of best practice.

The REWAFT project developed a web-based tool to assess the WF of textiles [168]. This easy-to-use tool allows assessment of water use, blue WFs, and grey WFs of various fiber types at the process level. If process-level data are not available, users can opt to have evaluation indicators reported at the plant level as well. Results are compared to benchmark values to assess users’ resource use efficiency.

Tools are summarized and characterized in Table 8 by their main audience; the availability of an online interface; what part of the textile value chain they cover; what fabrics they include what evaluation indicators they use; and what data sources they use.

9. Future directions and recommendations

The business models of enterprises in the global fashion industry produce highly negative outcomes for the environment. High water usage, pollution from chemical treatments used in dyeing and preparation, and the disposal of large amounts of unsold stock through incineration or landfill deposits combine to make clothing one of the highest impact industries on the planet. This article uses the sustainable logics of narrowing, slowing, and closing the loop of resources used during the production, design, manufacture, and distribution of fashion garments to analyze emerging business models that seek to reduce the environmental impact of the fashion system. Taking the business model conceptualization of an enterprise as a system designed to create value for the customer and capture value for the firm, we add a consideration of environmental value and derive propositions that test the possibility that emerging sustainable business models in fashion will replace the dominant, unsustainable model. The article argues that lack of scalability and incompatibility with fashion customers' value propositions plus obstacles to supply chain changes militate against the prospect of the currently designed sustainable business models becoming the standard model of the fashion industry [169].

The textile industry’s constant changes pose significant environmental, social, and governance concerns, in addition to economic ones [142]. As consumer demand for eco-friendly and socially responsible fashion products grows, leading textile retailers are transforming their supply chains to become more sustainable [143,168]. The transition to sustainability involves using organic raw materials, developing sustainable manufacturing techniques, educating consumers about responsible laundry practices, and employing textile waste treatment, recycling, and remanufacturing techniques [139,170]. The scientific and corporate community sees WF assessment and stewardship in textile supply chains as crucial for achieving environmental and economic sustainability.

Table 8. Overview of existing WF tools for the textiles industry

Tool	Main audience	Value chain coverage	Fiber types	Evaluation indicators	Data needs	Application region	URL if available
[171]	Textile manufacturers	Process level: – Pre-setting – Printing – Aging – Washing (for printing fabric) – Softing (for printing fabric) – Dyeing – Washing (for dyeing fabric) – Softing (for dyeing fabric) – Setting	Agnostic, but tested for polyester flannel	Reduction in water withdrawal	User input	China	N/A
				Reduction in consumption			
				Assimilation			
[74]	Academics	Process level: – Dyeing – Printing – Washing – Finishing – Utility	Agnostic, but the test facility produces and processes various fiber types	BlueWF	User input	Bangladesh	N/A
				GreyWF			
				Groundwater saving			
[165]	Academics	Process level: – Pre-treatment – Dyeing – Printing – Finishing – (all with further subdivisions)	Cotton	BlueWF	Unclear	China	N/A
				(Blue) water scarcity footprint			
				(Grey) water degradation footprint			
[166]	Policy-makers	Cotton production in sourcing region and (unspecified) textiles production	Cotton	Water use	User input or default	Global, but most detailed for Pakistan.	InoCottonGROW https://wf-tools.see.tu-berlin.de/wf-tools/inoCotton/#/textile
				Water consumption			
				Wastewater discharge			
				GreyWF			
				Water scarcity footprint			
				Human toxicity			
				Eutrophication			

(Continued)

Table 8: *Continued*

Tool	Main audience	Value chain coverage	Fiber types	Evaluation indicators	Data needs	Application region	URL if available
[172]	Small and medium enterprises in developing countries	Process level: – Desizing – Scouring – Bleaching – Mercerizing – Dyeing – Printing – Finishing	Cotton Wool Flax Silk	Water use	User input	Global	https://watercalculator.dnv.com/
[167]	Professionals and educators in the textiles sector	Process level: – Desizing – Scouring – Bleaching – Mercerizing – Dyeing – Printing – Finishing	Cellulosic Protein Synthetic	Water use BlueWF GreyWF Water use efficiency	User input or default	Global	https://calculator.textilewaterfootprint.eu/

Emerging trends in the textile industry such as circular economy, 3D printing, and others create new research possibilities to effectively handle associated risks and problems [163,173]. Sustainability is a crucial motivator for entrepreneurs, creating new potential for fashion firms [173]. Also, promising technologies like plasma and supercritical CO_2 processing require more research to become competitive alternatives [151]. Efforts are needed to develop biodegradable dyes, chemicals, and auxiliaries, as well as enzyme-assisted processing, to benefit the environment.

Transforming popular trends into sustainable fashion presents significant obstacles [142]. Water appropriation and flows in the textile industry should be analyzed from a life cycle perspective. However, due to data constraints and the sourcing of fabric materials from multiple countries, reporting the associated impacts is challenging [164]. Water-friendly materials and production processes are not often considered a strategic priority in the textile industry [173]. Consumer education on garment longevity, water-friendly washing practices, and end-of-life options is limited due to cost and capacity restrictions [174,175].

Industry and scholars must develop sustainable choices with little environmental impact. Adoption of best practices for sustainable textile wet processing has been limited due to decentralized operations in third countries [141]. These units lack the means to implement modern facilities and processes. Governments should boost sustainable textile production, stricter regulations and proper execution are necessary to protect the environment and people's livelihoods, and also provide financial support alongside investors to modernize and reduce the sector's WF [103,163].

Non-profit and trade groups should also collaborate with all stakeholders to lessen the environmental and social implications of textile production globally [141]. The sector must set a target of zero hazardous chemical discharge and also minimize water use. Urgent action is required to prevent hazardous compounds from contaminating water sources and causing harm to humans and animals. Toxic pollution must be addressed globally to prevent water pollution and climate change, which endanger human life. Consumers, brands, and retailers must prioritize environmental sustainability and be willing to pay more for products that benefit both people and the planet [142].

10. Conclusion

The textile industry significantly impacts global water resources, consuming vast amounts of water for processes such as dyeing, washing, and finishing. This high water usage, combined with the release of polluted effluents, poses severe risks to both environmental and human health, particularly in water-scarce regions. The industry's WF, comprising green, blue, and grey water, highlights the need for more sustainable practices.

Definitive findings emphasize the critical importance of reducing water consumption and pollution. Effective measures include adopting water-efficient technologies, such as waterless dyeing and wastewater recycling, and adhering to stricter regulatory standards. Moreover, the sourcing of sustainable raw materials and transparency in supply chain practices are essential for minimizing environmental impact.

The industry's shift towards sustainability is promising, evidenced by innovations in production processes and growing awareness among stakeholders. Collaboration between governments, industry leaders, and environmental organizations is crucial to drive further advancements and ensure compliance with international standards.

Future efforts must prioritize continuous research and development in sustainable technologies, alongside regulatory frameworks that support environmental protection. This comprehensive approach is essential for reducing the textile industry's water footprint and promoting long-term sustainability.

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