Water footprint assessment of viscose staple fiber garments
Weiran Qian, Juxiang Zhu, Fangli Chen, Xiang Ji, Xiaopeng Wang and Laili Wang

ABSTRACT
The viscose fiber industry forms a large part of the textile industry and is a typical water consumption and wastewater discharge industry. As a tool to quantify environmental impacts in terms of water resources, the water footprint assessment (WFA) is a control method for the textile and apparel industry to measure water consumption and wastewater discharge. In this study, the water footprints of viscose staple fiber blouses and blended men’s suits were comprehensively evaluated based on the ISO 14046 standard and the life cycle assessment (LCA) polygon method. The WFA results from our study indicate that the production stage of viscose staple fiber garments has the most significant water resource environmental load. Specifically, the water footprint related to the production of viscose staple fiber for three types of clothing accounted for more than 50% of the total water footprint, with men’s 100% viscose staple fiber suits having the largest impact on water resources and the environment. Furthermore, our results indicate that the water alkaline footprint is primarily influenced by the viscose staple fiber production as well as the dyeing and finishing processes. NaOH and Na₂CO₃ are the main pollutants that caused the water alkaline footprint. In addition, the water ecotoxicity footprint was the major driving factor of water resource environmental load. Zn²⁺ is the main pollutant that caused the water ecotoxicity footprint.

Key words | environmental impact, life cycle assessment, viscose staple fiber, water degradation footprint, water scarcity footprint

HIGHLIGHTS
- Water environmental impacts of three typical types of viscose staple fiber garments were assessed.
- LCA polygon method was used for a comparative impact assessment.
- NaOH and Na₂CO₃ are the main pollutants that caused water alkaline footprint.
- Zn²⁺ is the main pollutant that caused water ecotoxicity footprint.

INTRODUCTION
According to data from the China Statistical Yearbook, in 2017, China’s per capita water supply was only...
discharge to the total national wastewater discharge (including industrial and domestic wastewater discharge) was 27%–47% (NBS 2017a, 2017b, 2017c). China’s environmental situation in terms of water resources is a cause for concern, with water consumption and wastewater discharge from industry being one of the main reasons. The textile and garment industry is a traditional pillar industry in China, and viscose, including both viscose staple fiber and viscose filament yarn, has become an important raw material for the production of textiles and garments. In 2017 and 2018, China’s viscose production was 3.70 and 3.97 million tons, respectively, with viscose staple fiber production accounting for approximately 95% thereof (Ji 2019). The market share of viscose staple fiber is larger than that of viscose filament, and China is the world’s largest consumer of viscose staple fiber, with the domestic consumption of viscose staple fiber increasing from 2.8 million tons in 2011 to 3.4 million tons in 2018 (CBG 2019). Viscose staple fiber is mainly used for the manufacturing of textiles and garments due to advantages in comfort and moisture absorption, and its proportion in the mid-to-high-end fabric market continues to increase. It is often used in two major garment categories, namely shirts and suits. According to statistics, approximately 65 tons of fresh water is used for the production of one ton of viscose staple fiber, and approximately 110 tons of fresh water is used for the dyeing and finishing of one ton of textiles. Alkali, carbon disulfide, sulfuric acid, and other chemicals used in the production process, in total approximately 3.3 tons/ton viscose staple fiber, remain in the wastewater and are discharged together with the wastewater (Yang 1989). Therefore, the viscose staple fiber industry and its associated textile and garment industries consume a large amount of water and are responsible for serious wastewater pollution, which has multiple environmental impacts on water resources.

Water footprint assessment (WFA) is an effective tool for analyzing the correlation between human activities or manufacturing of specific products and water shortages and pollution problems. It aims to quantify the water footprint of production processes, products, producers, or consumers and also evaluates the sustainability of water resources and the environment. The water footprint network (WFN) defines water footprint as a comprehensive evaluation indicator to measure the level of water resource utilization, including the blue, green, and gray water footprints (Hoekstra et al. 2011). The International Standard (ISO) 14046:2014 ‘Environmental management – water footprint – principles, requirements and guidelines’ classifies water footprints by various environmental impact categories, such as water scarcity and degradation footprints. Results from water footprint analyses according to ISO 14046 focus on identifying water environmental impact categories and quantifying the potential environmental impact on water resources. The water scarcity footprint accounts for regional differences in water shortage based on the blue water footprint, whereas the water degradation footprint quantifies the environmental impact of pollutants on water resources using pollutant types and emissions. The WFA method, developed by the WFN and International Standards Organization (ISO), is centered on water volume and potential environmental impact. Furthermore, Zonderland-Thomassen & Ledgard (2012) and Berger & Finkbeiner (2013) considered the impact-oriented WFA method more suitable for decision-making than the volume-oriented WFA method, as it better reflects the supply capacity of the water resources as well as the wastewater pollution tolerance capacity of the water environment (Huang et al. 2015).

The WFA method has been widely applied across various organizational, regional, service, and product levels, especially for agricultural products, such as cotton (Chico et al. 2013; Xuan et al. 2014), wheat (Ababaei & Etedali 2014; Xuan et al. 2014), corn (Ababaei & Etedali 2014; Xuan et al. 2014; Duan et al. 2016), rice (Cao et al. 2018), coffee, tea (Chapagain et al. 2006), tomatoes (Chapagain & Hoekstra 2007), sugarcane (Barbosa et al. 2017), mangos (Ridoutt et al. 2010), citrus (Munro et al. 2016), poultry (Gerbens-Leenes et al. 2015), pork (Gerbens-Leenes et al. 2015; Bai et al. 2018), and beef (Gerbens-Leenes et al. 2015; Harding et al. 2017). The WFA method is also used for industrial products, such as sugar-rich carbonated beverages (Ercin et al. 2011), dairy products (Bai et al. 2018b), coal (Ding et al. 2016), building materials (Gerbens-Leenes et al. 2018), cables (Bai et al. 2016), and chemical products (You et al. 2014). In the textile and garment industry, the WFA method has been used to evaluate viscose staple fiber (Zhu et al. 2019), cashmere knitwear (Sun et al. 2018), polyester dyed cloth (Zhong et al. 2016), polyester knitted coral fleece (Xu et al. 2015), cotton textile products (Yan et al. 2014), and jeans (Chico et al. 2015). In particular,
(2013) calculated the water footprint of various fabrics, with results indicating cotton denim fabric to have a greater blue and gray water footprint, but a smaller green water footprint than that of lyocell denim fabric. Wang et al. (2013) calculated the direct blue and gray water footprint of China’s textile industry from 2001 to 2010, with results indicating a rise in the direct blue water footprint and showing both the direct blue and grey water footprint of the textile industry to be larger than that of the clothing, footwear, and chemical fiber industries. Wang et al. (2012) conducted an industrial water footprint analysis on seven types of knitted cotton dyeing fabrics from yarn to finished fabric and found the dyeing stage to have the largest industrial water footprint. Results from a study by Yan et al. (2014) on the industrial water footprint of four different shades of cotton textiles indicate that the darker the color, the greater the industrial water footprint. Furthermore, He et al. (2017, 2018) analyzed and discussed the water degradation footprint of various textiles and garments and calculated the baseline water degradation footprint of functional units of silk products based on the silk industry’s water intake quota and wastewater pollutant discharge limits. Results from this study showed nitrogen and ammonia nitrogen to be responsible for water eutrophication with sulfide and total antimony to be responsible for water ecotoxicity (He et al. 2017, 2018). Recently, Linhares & Amorim (2017) evaluated the environmental impact caused by two dyed cotton fabrics (natural direct dyed and synthetic reactive dyed) with results showing the use of natural direct dyes to have less of an environmental impact than synthetic reactive dyes.

Water scarcity and degradation footprints are used as indicators to quantify water use in terms of total water resource supply capacity and wastewater discharge pollution in terms of the total pollution capacity of the water environment, respectively. Although the WFA is already used in the textile and clothing industry, it is not yet possible to fully quantify all the environmental impacts caused by the production of textiles and garments. In particular, there is no report on the environmental impacts of alkaline wastewater from viscose fiber production. In addition, water scarcity and degradation footprints can be quantified and evaluated from either a water consumption (volume) or a water pollution perspective (environmental impacts). Notably, the different evaluation methods for volume and quality do not reflect the overall environmental load in terms of water resources, making it difficult to horizontally compare and evaluate across products and processes.

Within this context, our study aims to (a) calculate the water footprints of typical viscose garment products from fiber production through to clothing consumption, and (b) conduct a comprehensive assessment and comparison of products and processes using the life cycle assessment (LCA) polygon method.

### METHODS AND DATA COLLECTION

For our study, the WFA method was used based on the ISO 14046 standard and the comprehensive LCA polygon evaluation method. The water alkaline footprint was used to quantify the water alkalization impact caused by pollutants in wastewater discharge, thereby improving the WFA method. Furthermore, we quantified the environmental impact of viscose staple fiber blouses and blended men’s suits on water resources; specifications of the blouses (size: 160/84A for the national garment size series standard in China) and men’s suits (size: 170/92A for the national garment size series standard in China) are presented in Table 1. The functional unit of the water footprint calculations was set to 1,000 pieces of viscose staple fiber

<table>
<thead>
<tr>
<th>Garment type</th>
<th>Fabric composition</th>
<th>Lining composition</th>
<th>Measurements of the garment (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blouse</td>
<td>100% viscose staple fiber</td>
<td>/</td>
<td>Length 60</td>
</tr>
<tr>
<td>Men’s suits (a)</td>
<td>100% viscose staple fiber</td>
<td>65/35 viscose staple fiber/polyester</td>
<td>76</td>
</tr>
<tr>
<td>Men’s suits (b)</td>
<td>55/45 viscose staple fiber/nylon</td>
<td>55/45 viscose staple fiber/polyester</td>
<td>76</td>
</tr>
</tbody>
</table>
garments and the calculation of all related inputs (e.g., water and chemicals) as well as outputs (e.g., wastewater discharge) was based on this unit.

System boundary description

The total life cycle of the viscose staple fiber blouses and blended men’s suits included the following seven parts: cotton linters, viscose production, fabric production, dyeing and finishing, garment production, consumer care, and recycling (Figure 1).

In this study, the system boundary of viscose staple fiber apparel included water usage and wastewater discharge from the production and processing of fibers, fabrics, and linings, as well as from the production and use of apparel products, but excluded consumption and emissions related to employees, transportation, as well as the maintenance and cleaning of machinery and equipment. As the amount of auxiliary materials (non-woven lining, buttons, etc.) was negligible, the processes related to their production were not included in our calculations. A summary of the system boundary is shown in Figure 2.

Framework for water footprint assessments

The WFA framework of the ISO 14046 standard includes the following guidelines: (a) determine the objectives and scope of the assessment, which should be consistent; (b) analyze the water footprint list, which should include the input and output of each process unit in the research system; (c) assess the impact of the water footprint, taking into account any potential environmental impacts caused by changes in water quantity and quality in the system, such as the water scarcity footprint and water degradation footprint; and (d) interpret the results in terms of the water footprint list and environmental sustainability (Bai et al. 2015).

Water scarcity footprint

The water scarcity footprint ($WF_{SC}$) is used to quantify the potential impact of the amount of water used on the local water supply capacity. In this study, we used water stress...
index (WSI) factors proposed by Pfister et al. (2009) and used the following equation to calculate the WFSC:

$$WF_{SC} = \sum_{j} \frac{WSI_j}{WSI_{global,av}} \times Q_j$$  (1)

where $WF_{SC}$ (m$^3$ H$_2$O eq) is the water scarcity footprint, $Q_j$ (m$^3$) is the freshwater consumption per unit product in position $j$, $WSI_{global,av}$ is the average global WSI of 0.602 (Boulay et al. 2012), and $WSI_j$ is the WSI value corresponding to $Q_j$, which is 0.478 (He et al. 2018).

Water degradation footprint

The water degradation footprint ($WF_{DE}$) is used as an indicator to evaluate the potential impact of wastewater pollutant discharge on the water environment and includes sub-indicators such as water eutrophication, acidification, and ecotoxicity footprints (Heijungs et al. 1992; Goedkoop et al. 2009).

Water eutrophication footprint

The water eutrophication footprint ($WF_{EU}$) is used to quantify the potential eutrophication impact of wastewater pollutants on the water environment, with phosphate (PO$_4^{3-}$) used as a reference substance to measure the biomass-forming ability of different pollutants. The $WF_{EU}$ is calculated as follows (Heijungs et al. 1992):

$$WF_{EU} = \sum_{i} EUP_i \times M_i$$  (2)

where $WF_{EU}$ (kg PO$_4^{3-}$ eq) is the water eutrophication footprint, $EUP_i$ (kg PO$_4^{3-}$ eq/kg pollutant) is the characteristic factor of eutrophication pollutant $i$, and $M_i$ is the emission of pollutant $i$.

Water acidification footprint

The water acidification footprint ($WF_{AC}$) is used to quantify the potential acidification impact of wastewater pollutants on the water environment, with sulfur dioxide (SO$_2$) used as a reference substance to measure the hydrogen ion (H$^+$)-releasing ability of pollutants. The $WF_{AC}$ is calculated as follows (Bai et al. 2015):

$$WF_{AC} = \sum_{i} ACP_i \times M_i$$  (3)

where $WF_{AC}$ (kg SO$_2$ eq) is the water acidification footprint, $ACP_i$ (kg SO$_2$ eq/kg pollutant) is the characteristic factor of the acidification pollutant $i$, and $M_i$ is the emission of pollutant $i$.

Water ecotoxicity footprint

The water ecotoxicity footprint ($WF_{AET}$) is used to measure the potential ecotoxicity impact of wastewater pollutants on the water environment, with its characteristic factor based on the maximum tolerance concentrations (MTCs) determined according to the Environmental Protection Agency (EPA). Therefore, the $WF_{AET}$ is calculated as follows (Heijungs et al. 1992):

$$WF_{AET} = \sum_{i} AETP_i \times M_i$$  (4)

where $WF_{AET}$ (m$^3$ H$_2$O eq) is the water ecotoxicity footprint, $AETP_i$ (m$^3$ H$_2$O eq/mg pollutant) is the characteristic factor of ecotoxicity pollutant $i$, and $M_i$ is the emission of pollutant $i$.

Water alkaline footprint

A large amount of alkaline wastewater is discharged during viscose staple fiber production as well as during the dyeing and finishing process (Figure 2), resulting in a serious environmental impact. Combining the characteristic factors of alkaline pollutants and their emissions, the water alkaline footprint ($WF_{AL}$) is calculated as follows (Chen et al. 2020):

$$WF_{AL} = \sum_{i} ALP_i \times M_i$$  (5)

where $WF_{AL}$ (kg OH$^-$ eq) is the water alkaline footprint, $ALP_i$ (kg OH$^-$ eq/kg pollutant) is the characteristic factor of alkaline pollutant $i$, and $M_i$ is the emission of pollutant $i$. 
Life cycle assessment (LCA) polygon method

Due to the multi-dimensional characteristics of water footprint assessment results, it is challenging to comprehensively evaluate the total environmental impact of products or processes on water resources. Within this context, the life cycle assessment (LCA) polygon method is considered a tool for comparing results from inventory analyses (Georgakellos 2005, 2006; Daniel et al. 2004). In this study, we used LCA polygons to develop a method to comprehensively evaluate the results from water footprint analyses, including water resources and environmental impacts. The development of the evaluation model includes the following steps (Daniel et al. 2004):

(a) Determine the evaluation boundary

According to the purpose of the study, combine the characteristics of the input and output variables of the textile and apparel products with the full life cycle process or part of the life cycle process and list the calculations related to water.

(b) Draw the LCA polygon

In a hypothetical system of environmental impacts including water scarcity, eutrophication, acidification, alkalinity, and ecotoxicity, a regular pentagon is formed, with each radius of the circumscribed circle representing a measurement axis for each environmental impact category, and each axis representing different quantitative indicator values with individual characteristics (scales and units). The polygon formed according to the actual value of each quantization index is the LCA polygon.

(c) Calculate the LCA polygon area

The area of the LCA polygon is used to represent the value of the environmental load in terms of water resources. The larger the area of the LCA polygon, the more severe the environmental load. The order of water footprint indicators will affect the area of the polygon, and to make the results more accurate, all possible polygonal areas should be calculated and averaged using the following equation (Daniel et al. 2004):

$$S_{pol, av} = nS_{av} = \frac{1}{2} \sin \left( \frac{360}{n} \right) \left\{ \frac{2}{n(n-1)} \sum_{i=1}^{n-1} R_i R_{i+1} \right\}$$

where $S_{pol, av}$ is the area of the LCA polygon, $S_{av}$ is the average area of all possible polygons, $n$ is the number of possible polygons, and $R$ is the side of the LCA polygon.

Data collection

The weight of 1,000 blouses and men’s suits were calculated according to specifications, fabric, and linings. Following this, the consumption of raw materials was estimated from the end to the start of the production process according to the loss rate. The conversion processes and results are shown in Figures 3–5.

In this study, cotton linters were used as the raw material for viscose staple fibers using caustic soda pulping and the Wuhe machine method (Zhang 1984). Data relating to water consumption and wastewater discharge from the production process were mainly obtained from monitoring data of chemical fiber plants with an annual output of approximately 125,000 tons and accessed through an environmental data platform (www.ipe.org.cn), as well as from relevant literature (Ke 1987; Yang 1989; Han 1998; Zhang 2005; Xiao 2013). Water usage and wastewater discharge data for the nylon and polyester production

![Figure 3](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.040/854706/ws2021040.pdf)
processes were obtained from the *First National Pollutant Source Census Industrial Pollution Source Discharge Coefficient Handbook (FNPSCIPSDCH 2010)*.

Water consumption and wastewater pollutant discharge related to the cleaning of equipment used for textile processes were not included in our calculations. Blouse fabric was pre-treated before scouring, and reactive dyes were subsequently used for one-step dyeing in overflow dyeing machines; finally, the post-processing was softened. Data for water consumption and wastewater pollutant discharge related to the dyeing and finishing of blouse fabric was obtained from the monitoring data of chemical fiber printing and dyeing enterprises and accessed through an environmental data platform ([www.ipe.org.cn](http://www.ipe.org.cn)). Men’s suit fabric and lining was pre-treated according to fiber composition (e.g., degreased), followed by the reactive dye/acid dye or reactive dye/direct dye one-bath one-step method for neutral color dyeing using overflow dyeing machines; finally, the post-processing was shaped or softened. Data related to water consumption and wastewater pollutant discharge for
the processes related to men’s suit fabric, including the lining dyeing and finishing stages, were obtained from statistical data found in related studies (Zhu 2002; Fan & Wang 2004; Wu 2015) and from both monitoring and measurement data of chemical fiber printing and dyeing plants, which were accessed from an environmental data platform (www.ipe.org.cn).

In general, machine washing is used by consumers to wash blouses. In this study the washing of blouses by consumers was set to 50 machine washes, with washing machines having a capacity of 10 kg and a water consumption standard of 125 L. In contrast, men’s suits are generally dry cleaned, which uses considerably limited water; therefore, it was considered negligible. The environmental impact categories and characteristic factors used in this study are shown in Table 2 (Heijungs et al. 1992).

RESULTS AND DISCUSSION

The WFSC and the WFDE related to three types of typical viscose staple fiber garments were calculated using Equations (1)–(5), and LCA polygons were drawn based on the results obtained from water footprint analyses. The area of each LCA polygon was calculated based on Equation (6) to obtain a single integrated value for multiple indicator results.

Results of water scarcity footprint (WFSC) analysis

The WFSC of three types of viscose staple fiber apparel as well as viscose staple fiber production is shown in Figure 6.

<table>
<thead>
<tr>
<th>Environmental impact category</th>
<th>Pollutant</th>
<th>Characteristic factor</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water eutrophication</td>
<td>COD</td>
<td>0.022</td>
<td>kg PO₄³⁻ eq/kg</td>
</tr>
<tr>
<td></td>
<td>BOD₅</td>
<td>0.022</td>
<td>pollutant</td>
</tr>
<tr>
<td></td>
<td>NH₃N</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Water acidification</td>
<td>H₂SO₄</td>
<td>0.65</td>
<td>kg SO₂ eq/kg</td>
</tr>
<tr>
<td></td>
<td>Chloride</td>
<td>0.88</td>
<td>pollutant</td>
</tr>
<tr>
<td>Water alkalinity</td>
<td>NaOH</td>
<td>0.425</td>
<td>kg OH⁻ eq/kg</td>
</tr>
<tr>
<td></td>
<td>Na₂CO₃</td>
<td>0.321</td>
<td>pollutant</td>
</tr>
<tr>
<td>Water ecotoxicity</td>
<td>Zn²⁺</td>
<td>0.38</td>
<td>m³ H₂O eq/mg</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>2</td>
<td>pollutant</td>
</tr>
</tbody>
</table>

Results presented in Figure 6 show the WFSC of blouses to be larger than that of men’s suits, with the washing of blouses by consumers having the highest WFSC value of 225.57 m³ H₂O eq/1,000 pieces in terms of production processes, and accounting for 92% of the total WFSC related to blouses. The total WFSC of (a) men’s suits made of 100% viscose staple fiber and (b) blended men’s suits made of 55% viscose staple fiber and 45% nylon was 89.59 and 65.81 m³ H₂O eq/1,000 pieces, respectively. The WFSC for suit (a) and suit (b) was mainly influenced by the viscose staple fiber production process with a value of 65.95 and 38.87 m³ H₂O eq/ton relatively. In the fiber production process, the presoaking process had the highest WFSC of 31.76 m³ H₂O eq/ton, representing 34% of the total viscose staple fiber production stage WFSC, followed by the scouring process with a value of 22.23 m³ H₂O eq/ton, which are the main steps that consumed considerable amounts of fresh water for dissolving into pulp in an alkaline environment and reducing the amount of impurity on the viscose fiber, and thus the whiteness index and oil rate can be improved for the scouring process (Shen & Patel 2010). The difference between the WFSC of blouses and men’s suits was mainly due to differences in viscose staple fiber production and different washing processes by consumers. In total, 154.90 kg of viscose staple fiber was used for the production of 1,000 blouses, while 709.90 and 418.40 kg was used for the production of 100% viscose staple fiber and 55% viscose staple fiber blended men’s suits, respectively. The main reason for the difference is that a large amount of water (225.57 m³, based on water usage for 50 machine washes of 1,000 blouses) was used by the washing of blouses by consumers, while for men’s suits treated with dry cleaning, little water was consumed.

Results of water degradation footprint analysis

The water degradation footprint (WF EU, WF AC, WF AL and WF AET) of three types of viscose staple fiber apparel as well as viscose staple fiber production is shown in Figures 7–10.

Results from our WF EU analysis indicated that blouses had the highest WF EU footprint, followed by 100% viscose staple fiber men’s suits (a) and 55% viscose staple fiber blended men’s suits (b). In the production chain of the three garment types, the viscose staple fiber production as
well as fabric dyeing and finishing processes were partly responsible for the WFEU of 1.58, 6.42, and 3.94 kg PO$_4^{3-}$/C0$_{eq}$/1,000 pieces, respectively, of which viscose staple fiber production accounted for more than 89%. The difference between the WFEU values of the three types of clothing was due to the washing of blouses by consumers (51.45 kg PO$_4^{3-}$/C0$_{eq}$/1,000 pieces), accounting for 77% of the total WFEU of blouses, and mainly caused by the presence of COD, BOD$_5$, and NH$_3$N in the wastewater from washing machines. Although the dry cleaning of men's suits did not influence the overall WFEU, the lining dyeing and finishing process of 0.40 kg PO$_4^{3-}$/C0$_{eq}$/1,000 pieces did affect the overall WFEU. Furthermore, the WFEU caused by the production of viscose staple fiber was 8.25 kg PO$_4^{3-}$/C0$_{eq}$/ton, of which the presoaking process had the largest WFEU of 6.78 kg PO$_4^{3-}$/C0$_{eq}$/ton, accounting for 82% of the total WFEU of viscose staple fiber production. The main pollutants were COD, BOD$_5$, and NH$_3$N, which are mainly from a large amount of organic impurities such as cellulose in the wastewater (black liquor) from the presoaking process, with COD concentrations of as high as 8,000 mg/L (Zhang 1984; Ke 1987).

Figure 8 shows the WFAC related to three types of viscose staple fiber garments and the production of viscose staple fibers. Here it can be seen that the WFAC of the three types of garments was mainly affected by the viscose staple fiber production as well as the dyeing and finishing processes. The WFAC of men's suits (a) and men's suits (b) were more than four and two times higher than that of blouses, respectively. The dyeing and finishing of men's suits included dyeing and finishing of fabric and lining, with the WFAC of the lining dyeing and finishing accounting for 10% of their total WFAC, while blouses only included fabric dyeing and finishing. The WFAC in the dyeing and finishing stage was mainly derived from chloride. The WFAC of the production of viscose staple fiber was mainly due to the fact that fibers are spun in an acid salt bath, with H$_2$SO$_4$ in
the wastewater discharged from the two-bath, acid-station, and scouring processes (Shen & Patel 2010). The WFAC of viscose staple fiber production was 77.98 kg SO$_2$ eq/ton, whilst the WFAC of the scouring process and the two-bath process was 40.94 kg SO$_2$ eq/ton and 29.64 kg SO$_2$ eq/ton, respectively, accounting for 91% of the total viscose staple fiber production WFAC.

As seen in Figure 9, the WFAL of men’s 100% viscose staple fiber suits (a) and men’s 55% viscose staple fiber suits (b) were more than four and three times that of blouses, respectively. One reason for this is that men’s (a) and (b) suits used approximately five and three times as much viscose staple fibers as blouses, respectively. A second reason is that the dyeing and finishing stages of men’s suits included fabric and lining dyeing as well as finishing, while blouses only included fabric dyeing and finishing. The WFAL of blouses, men’s (a) suits, and men’s (b) suits was 11.55, 55.90, and 38.33 kg OH$^-$/1,000 pieces, respectively. In summary, the WFAL related to the production of viscose staple fiber was 40.25 kg OH$^-$/ton, with wastewater discharge WFAL from the presoaking process being the highest at 37.54 kg OH$^-$/ton and accounting for 93% of the WFAL of viscose staple fiber production. Water alkalization caused by the main pollutants NaOH and Na$_2$CO$_3$ originated mainly from the utilization of caustic soda in the viscose staple fiber production as well as dyeing and finishing process, functioning as a dissolution and dyeing auxiliary (Shen & Patel 2010; Wang 2017).

Figure 10 shows the WF$_{AET}$ resulting from three types of viscose staple fiber clothing and the production of viscose staple fiber. Results from our analysis indicate that the WF$_{AET}$ of blouses is caused by viscose staple fiber production, whilst the WF$_{AET}$ of men’s suits is caused by viscose staple fiber production as well as lining dyeing and finishing. The WF$_{AET}$ of lining dyeing and finishing is mainly due to the presence of Cu in the wastewater, which originated from the use of metal dyes and played a significant role in increasing the dyeing rate from the dyeing
Figure 8 | Results from water acidification footprint analysis.

Figure 9 | Results from water alkaline footprint (WF<sub>alk</sub>) analysis.
process (Zhang et al. 2018). In our study, the \( W_{FAET} \) of the viscose staple fiber production was 3,594,564.4 m\(^3\) H\(_2\)O eq/t, with the main pollutant Zn\(^{2+}\) coming from the input of ZnSO\(_4\) in the spinning stage. Some of the Zn\(^{2+}\) was discharged with the acid station wastewater, whilst some remained adhered to the fiber surface thereby entering the scouring stage and resulting in a higher Zn\(^{2+}\) content of the scouring wastewater (Shen & Patel 2010). The \( W_{FAET} \) of the scouring process was the largest with 2,876,296 m\(^3\) H\(_2\)O eq/t, accounting for 80% of the total viscose staple fiber production \( W_{FAET} \).

**Comparative evaluation of the impact on water resources**

The LCA polygons related to blouses, as well as men’s suits (a) and (b), are shown in Figure 11, with areas of 9,187.29, 23,999.93, and 9,977.91, respectively. From these results, it can be seen that men’s (a) suits reflected the highest environmental load of the three garment types in terms of water resources, followed by men’s (b) suits and blouses.

In summary, the main results from the LCA polygon calculations are the following:

(a) The \( W_{FAET} \) is the main driving factor for the environmental load in terms of water resources related to the production of the three types of clothing. The viscose
staple fiber production stage had the biggest impact on the WF_{AET} and the WF_{AET} of men’s suits was approximately three to five times that of blouses. 

(b) The WF_{SC} is the secondary driving factor related to the environmental load in terms of water resources related to the three types of garments. However, there are differences among three types that caused water scarcity. In terms of blouses, it is mainly influenced by the washing of blouses by consumers. With respect to men’s suits, it is attributed to the viscose staple fiber production as well as dyeing and finishing. The WF_{SC} of the viscose staple fiber production accounted for approximately 74% of the total WF_{SC} of the men’s suits (a) and 61% of the total WF_{SC} of the men’s suits (b).

(c) The WF_{AC} and WF_{AL} had relatively smaller impact on the environmental load in terms of water resources related to the three types of garments compared with the two indicators mentioned above. The water acidification of the three types of clothing stemming from the production of viscose staple fiber was mainly due to H_{2}SO_{4} in the wastewater discharged from the two-bath, acid-station, and scouring processes. Furthermore, it is the combined efforts of base input in the production of viscose staple fiber and fabric dyeing and finishing that caused water alkalization. Apparently, the WF_{EU} had the smallest impact on the size of the LCA polygon area. The water eutrophication was caused by the chemicals used in the production and consumption processes. Therefore, measures can be taken to reduce the use of chemicals and control pollution can effectively reduce the environmental load in terms of water resources by improving production and post-processing technology or adjusting product development strategies.

The LCA polygon of each production process of viscose staple fiber is shown in Figure 12, and the areas of presoaking, washing, stock solution, two-bath, acid-station, and scouring were 13.67, 0.52, 3.121.60, 292.86, 433.55, and 5,536.03. From our results, it can be seen that the scouring process showed the highest environmental load in terms of water resources followed by the stock solution, acid-station, two-bath, presoaking, and washing process. In summary, the main results from our LCA calculations are the following:

(a) The scouring process has four types of environmental impacts, with the actual value of each quantitative indicator being relatively large, resulting in the highest environmental load in terms of water resources.

(b) The highest water consumption and wastewater emission was related to the presoaking process, with wastewater containing a large amount of COD, BOD_{5}, and NaOH, resulting in the largest WF_{SC}, WF_{EU}, and WF_{AL}. However, as the presoaking process only involved these three types of environmental impacts, it only ranked fifth in terms of the environmental load related to water resources.

Therefore, our results indicate that the magnitude of the environmental load in terms of water resources is not only related to the actual value of the environmental impact quantitative indicators, but also to the number of environmental impact types involved. Industrial wastewater pollutants often exhibit diverse characteristics, which explains why traditional wastewater treatment models that focus on large quantities of conventional pollutants or heavy metals with high microtoxicity often result in a one-off treatment of wastewater and ignore the potential environmental impacts of other pollutants. To better reduce the environmental load related to water resources, wastewater treatment models should focus on the different characteristics of industrial wastewater pollutants.
CONCLUSIONS

The following conclusions can be drawn from our investigations and results:

(a) Sub-module calculations related to the water footprint of viscose fiber clothing showed good results in terms of calculation accuracy and the identification of various pollution factors and sources. Viscose staple fiber production showed the most significant environmental load in terms of water resources with its water footprint accounting for more than 50% of the total water footprints of the three types of clothing.

(b) In this study, the viscose staple fiber production as well as fabric dyeing and finishing processes showed the highest water alkaline footprint with NaOH and Na₂CO₃ being the main pollutants. The water alkaline footprints related to blouses as well as men’s (a) and (b) suits were 11.55, 55.90, and 38.33 kg OH-eq/1,000 pieces, respectively.

(c) The results from our calculation of the environmental load in terms of water resources were directly related to the number of types of environmental impacts and the actual value of the quantitative indicators. The water degradation footprint had a greater impact than the water scarcity footprint on environmental load in terms of water resources, with the water ecotoxicity footprint being the main driving factor, and Zn²⁺ and CS₂ the main pollutants.

(d) According to the results from our calculations of environmental load in terms of water resources for viscose staple fiber clothing, we suggest relevant management departments adjust pollutant discharge limits or increase the list of wastewater pollutant discharge limits as appropriate. Furthermore, we suggest that, based on the results of certain calculations and analyses, relevant production departments carry out technological improvements such as the recovery rate of black liquor in the presoaking process, improving the production processes and equipment to reduce the input of water and chemicals such as ZnSO₄ and other additives, appropriately adjusting the product development plan or production ratio to reduce the viscose staple fiber content of the product, and the development of household dry-cleaning machines.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


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