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WATER FOOTPRINT OF TEXTILE INDUSTRY: A CASE STUDY OF CHINA

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Abstract

The textile industry is one of the most water intensive and polluting industries. China is the world's largest producer of textile products. For the sustainable development of China's textile industry, the environmental impacts caused by its water consumption and wastewater discharge must be identified. In this paper, we analysed the water footprint of China's textile industry based on the water footprint framework proposed in the ISO 14046. The results showed that both water scarcity footprint and water eutrophication footprint increased from 1996 to 2015, despite the fluctuation periods. Water ecotoxicity footprint decreased during the selected researched years. Among the three sub-sectors of China's textile industry, the water footprints of the manufacture of textiles sector were larger than those of manufacture of textile wearing apparel, foot-ware, and caps sector and manufacture of chemical fibres sector. The water footprint intensity of China's textile industry has decreased through the efforts of government administrative control measures and producers' actions on freshwater saving and wastewater treatment.

Key words: textile industry, water ecotoxicity, water eutrophication, water footprint, water scarcity

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1. Introduction

Textiles can include half-finished products (yarn, fabric) and fully-finished products (garments, caps, household textiles, etc.) made from fibres, which are generally subdivided into natural and synthetic depending on their origin (Rouette, 2001). Raw natural fibres are mainly derived from plants (cotton, kapok, flax, hemp, etc.) and animals (lamb, goat, silkworm, etc.). Synthetic fibres are produced by combining natural and synthetic polymers in factories. Fibres are further processed by industrial processes (spinning, weaving, knitting, dyeing, finishing, sewing, etc.) into fully finished products for use, after which they are discarded. Therefore, the life cycle of textiles, from cradle to grave, can be divided into agricultural cultivation, industrial production, and after-production (i.e., logistics, retail, use).

Water is an indispensable input along the life cycle of textiles. It is used to irrigate plants, feed animals, and as solvent in wet processes and laundering. It is estimated that industrial water use presents the most significant increase among the three discussed categories (i.e., agricultural, industrial, and domestic), at approximately 76% from 1995 to 2025 (Cardone, 2004). Large amounts of freshwater are used in retting, scouring, reeling, sizing, dyeing, finishing, washing, bleaching, and other wet processes. As a result, wastewater contains a complex mixture of organic and inorganic chemicals which are discharged to natural water bodies. The textile industry is one of the most water intensive and

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polluting industries (Kumar and Pavithra, 2019; Valh et al., 2011).

For a cleaner textile production, it is important to quantify water consumption and wastewater discharge. Furthermore, water-related environmental impact assessment is fundamental for the sustainable development of textile manufactures. Water footprint (WF) is a multi-dimensional indicator that water consumption and water degradation. WF is a tool that measures and assesses the impacts of water consumption and effluent discharges caused by the production process (Hoekstra and Hung, 2002; Hoekstra et al., 2011). This methodology has been widely applied by many researchers to product, sector, and diet assessments, in catchment, national, and global scales (Hoekstra, 2016). There have also been WF assessments regarding cotton (Chapagain et al., 2006; Joa et al., 2014; Rudenko et al., 2013), fabric (Chen et al., 2017; Wang et al., 2013a), jeans (Chico et al., 2013), zippers (Zhang et al., 2014), and the textile industry (Pal et al., 2017; Wang et al., 2013b).

The first proposed WF methodology (i.e., comprising green, blue, and grey WFs) and the international standard on water footprint (ISO 14046) present two slightly different accounting approaches. The ISO 14046 focuses on the assessment of impacts related to water, and it reports potential impacts (e.g., water scarcity and degradation) caused by water consumption and wastewater discharge (Boulay et al., 2013). There have been case studies using the ISO 14046 methodological framework for pasta sauce (Ridoutt and Pfister, 2010), milk (Huang et al., 2014; Palhares and Pezzopane, 2015; Ridoutt and Hodges, 2017), beef cattle and sheep (Zonderland-Thomassen et al., 2014), crude steel (Ma et al, 2018), silk (He et al, 2018; Yang et al., 2020), viscose staple fiber (Zhu et al., 2019), and the dairy industry (Bai et al., 2018).

The textile industry in China is an important part of the national economy and has maintained rapid growth after China's reform and opening. In 2016, domestic textile enterprises contributed more than 963 billion dollars in revenue and 124 billion dollars in exported value according to the data of the National Bureau Statistics of China (NBSC, 2017). Nevertheless, the textile industry consumes large amounts of freshwater and discharges large amounts of wastewater with many types of pollutants, causing severe impacts to the regional environment every year. In 2015, the textile industry consumed 2.95 billion tonnes of freshwater and emitted 2.39 billion tonnes of wastewater, which contributed 7.6% of freshwater consumption and 13.2% of the total water emission in the industry sector (MEPC, 2015).

Water footprint, as an effective indicator to assess the environmental impact related to water, was applied widely in the textile products. The majority of related studies of the water footprint in the textile industry focused on the evaluation of WF of products, and there are few comprehensive assessments of water consumption and water degradation of the textile industry. Wang et al. (2013a, 2017) analysed the blue and grey WF of China's textile industry using time series data, which gave an overview of water consumption and emission in the textile industry form the perspective of water volume. The WF assessment of the textile industry based on ISO 14046 standard, which can provide a comprehensive analysis of environmental impact related to water of textile industry, is rarely applied in the textile industry. The main objective of our study is to assess the environmental impacts of China's textile industry related to water quantity and quality using the WF methodology defined in ISO 14046. The WF of the textile industry form 1996-2015 is assessed, to provide an overview of water-related environmental impacts in the textile industry, and to investigate the effect policies and standards on the water in China with the assessment of water footprint intensity. The different performance related to water use, reuse, and the environmental impact caused by wastewater emission in the sub-sector was identified.

2. Methodology

2.1 Methods

According to the ISO 14046, WF is a "metric(s) that quantifies the potential environmental impacts related to water". Freshwater consumption by textile industries causes regional freshwater scarcity, and it can be assessed through water scarcity footprint (WSF). In this study, WSF was calculated according to the method (see Eq. 1) (Ridoutt and Pfister, 2010; Bai et al., 2018).

$$WSF = \sum_{i=1}^{n} a_{SF,i} \times V_i = \sum_{i=1}^{n} \frac{WSI_i}{WSI_{gl}} \times V_i \tag{1}$$

where: WSF - m^3 H_2O_{eq}; V_i (m^3) is freshwater consumption per unit time in position i; $\alpha_{SF,i}$ are characteristic factors corresponding to V_i; i represents different geographical locations; WSI_i is the water stress index at position i; and WSI_{gl} is the global average water stress index.

Textile effluents contain high concentrations of chemical oxygen demand (COD), nutrients (nitrogen and phosphorous), and toxic compounds (e.g., lead, cadmium, mercury, arsenic). Therefore, it can cause water degradation to receiving water bodies. Water eutrophication footprint (WEF) and water ecotoxicity footprint (WETF) can be used to evaluate the potential of their respective environmental impacts. Eqs. (2-3) are the calculation methods (Jane et al., 1995; Peter et al., 2002; Bai et al., 2016) for WEF and WETF.

$$WEF = \sum_{i=1}^{n} a_{EF,i} \times M_{EF,i} \tag{2}$$

where: WEF is in kg $PO_4^{3-}{}_{eq}$; $\alpha_{EF,i}$ (kg $PO_4^{3-}{}_{eq}$/kg) is the characteristic factor of the eutrophication pollutant i; $M_{EF,i}$ (kg) is the emission of eutrophication pollutant i; and i is the eutrophication pollutant type (e.g., COD and NH_3-N).

$$WETF = \sum_{i=1}^{n} a_{ETF,i} \times M_{ETF,i} \tag{3}$$

where: *WETF* is in m^3 H_2O_{eq}; $\alpha_{ETF,i}$ (m^3 H_2O_{eq}/kg) is the characteristic factor of toxic pollutant *i*; $M_{ETF,i}$ (kg) is the emission of toxic pollutant *i*; and *i* is the toxic pollutant type.

The intensity of each WF indicator (i.e., WSF, WEF, WETF) was also calculated to provide a full scene of the relationship between environmental impacts and the economical production of China's textile industry. The intensity was defined as environmental impacts per industrial output value. For instance, WSF intensity represents the freshwater scarcity caused per unit of total industrial output value. It can be calculated according to (Eq. 4).

$$WSFI = \frac{WSF}{TIOV} \tag{4}$$

where: *WSFI* is *WSF* intensity in m^3 H_2O_{eq}/(1000 USD), and *TIOV* (in billion USD) is the total industrial output value of the textile industry.

2.2 Data

According to Eqs. (1-4), the data needed for the study include water consumption, waste pollutants, and economic production. According to China's industrial classification for national economic activities (GB/T 4754-2017), China's textile industry includes three sub-sectors, namely the manufacture of textiles (MT); manufacture of textile wearing apparel, foot-ware, and caps (MTWAFC); and manufacture of chemical fibres (MCF). Data on water use and economic production are provided in the Annual Statistic Report on Environment in China every year. These reports collect information from terminal facilities along industrial processes. Textiles factories are located in many different regions in China. However, the water stress index of each location was not available. Therefore, the national average WSI for China was used instead. TIOV data were collected and calculated using producer price index based on 2015 constant prices.

3. Results and analysis

Fig. 1 shows the WSF of China's textile industry from 1996 to 2015. The water consumed by China's textile industry including freshwater and reused water were investigated. WSF was also calculated based on reused water to illustrate its contribution. The total WSF of China's textile industry increased from 1996 to 2007, when it reached the peak value. There was a slight fluctuation from 2007 to 2010. A sharp decrease occurred in 2011, but it increased again in 2014. The WSF of the component sectors were different from each other. The WSF of the MCF sector was the largest, followed by that of the MT and the MTWAFC sectors, in that order. The two kinds of WSF (i.e., calculated with consumed freshwater or reused water) also yielded different results. Contrary to the WSF results for the MCF sector, the WSFs calculated with consumed freshwater were lager than those calculated with reused water for the MT and MTWAFC sectors.

Freshwater consumption can directly cause water scarcity. Therefore, water reuse in the textile industry can reduce the consumption of freshwater and mitigate the water scarcity impact on regional water resources. Thus, the water scarcity impact of the MT sector was the largest (Fig. 1), followed by those of the MCF and MTWAFC sectors, in that order.

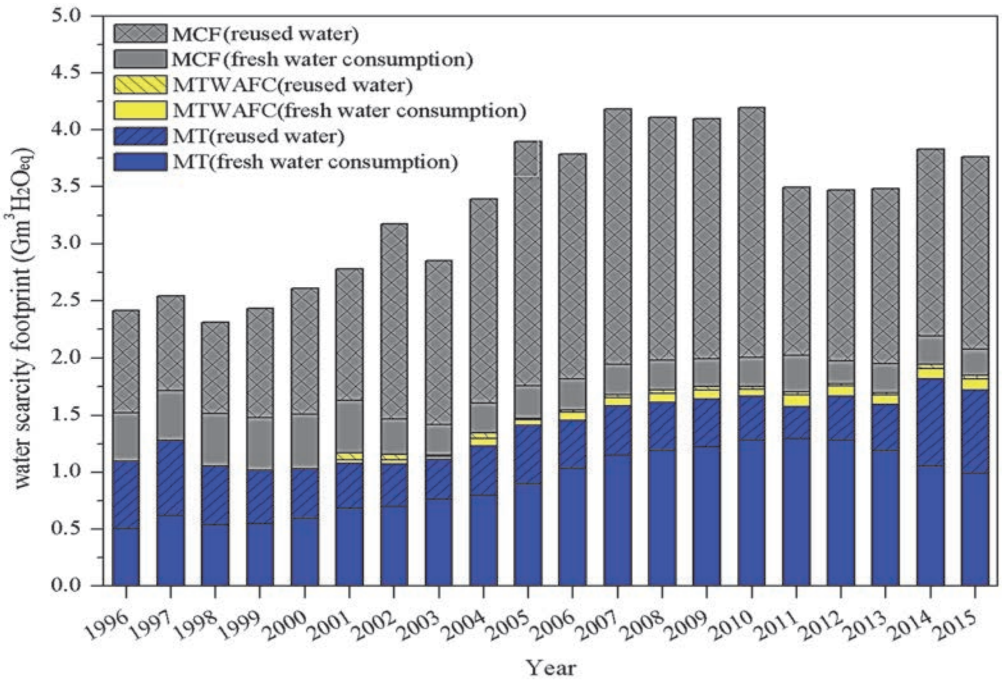

Fig. 1. WSF of China's textile industry

The WSFI of China's textile industry calculated with freshwater consumption is shown in Fig. 2. The WSFI of the three sectors presented decreasing trends in the selected research years, especially for the MCF sector. Before 2007, the WSFI of the MCF sector was the largest. However, it decreased significantly between 1998 and 2002, with an 11% average yearly drop.

In China's textile industry, the original generated wastewater must be treated before discharge into the receiving water body. The original generated pollutants are removed during wastewater treatment. To illustrate the contribution of wastewater treatment on the mitigation of water eutrophication, WEF was calculated with original generated pollutants (i.e., COD and NH_3-N) and discharged pollutants, according to (Eq. 2). The results are shown in Figs. 3 -4.

The original WEF of China's textile industry increased yearly before 2011, and it decreased after that (Fig. 3). WEF caused by original generated NH_3-N was larger than that caused by original generated COD, despite the original generated COD being significantly larger than NH_3-N. The WEF of the MT sector was the largest, followed by the MCF and MTWAFC sectors. The water eutrophication impact presented in Fig. 4 decreased largely compared to those presented in Fig. 3. For example, the total discharged WEF of China's textile industry was approximately 29% of the total original generated WEF in 2011. The increasing rate of discharged WEF was also smaller.

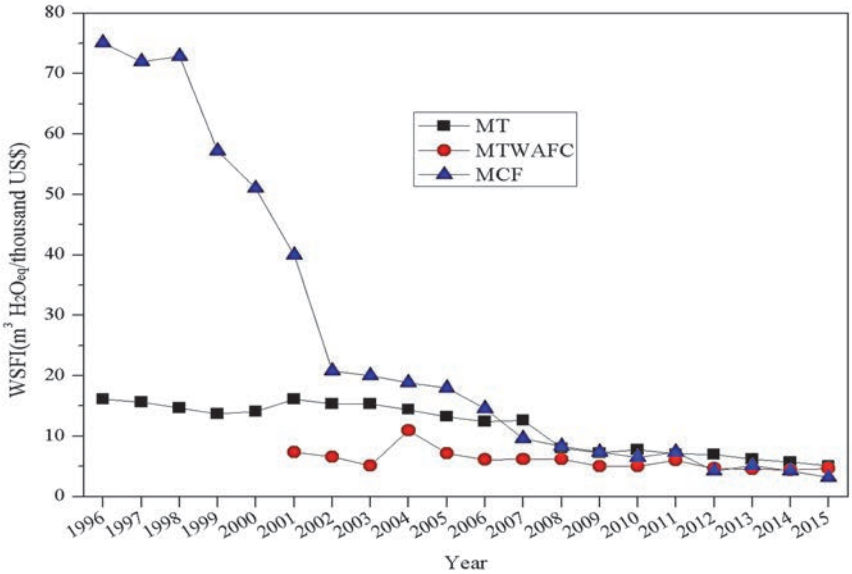

Fig. 2. WSFI of China's textile industry

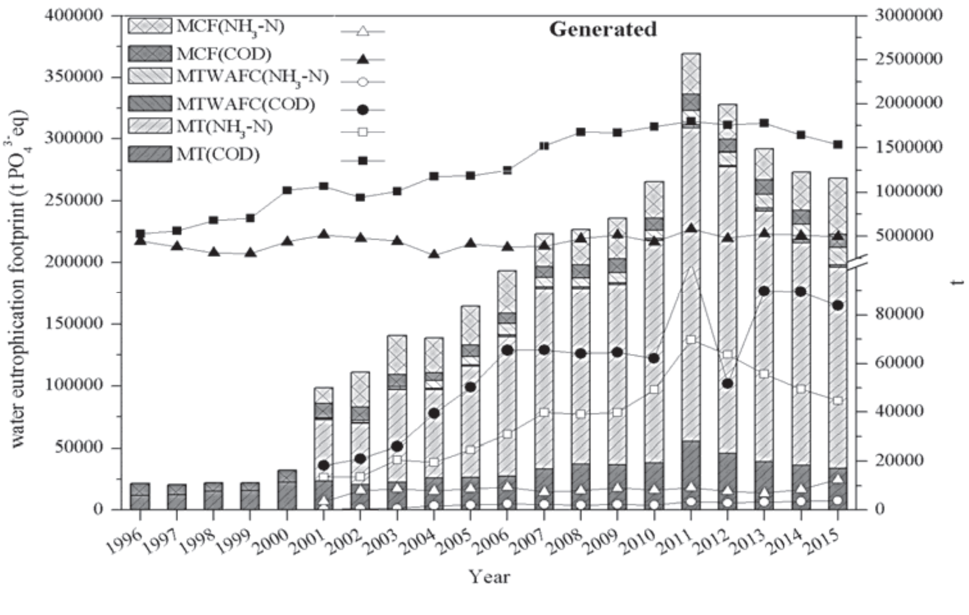

Fig. 3. WEF (considering generated pollutants) of China's textile industry

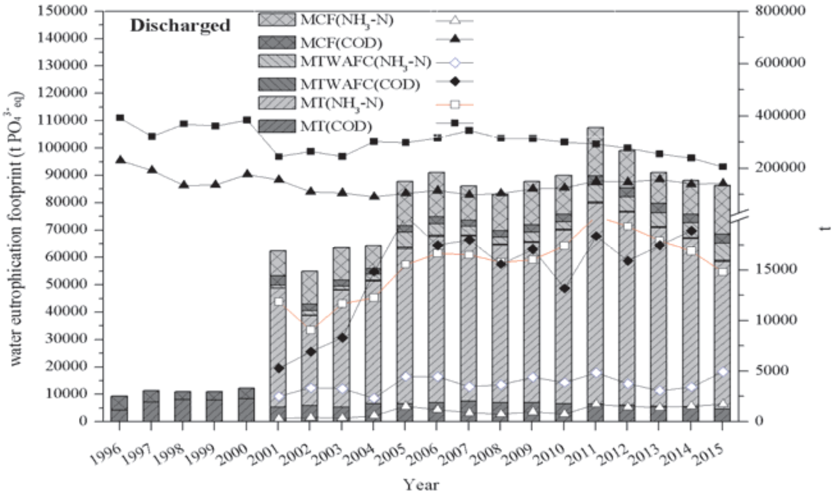

Fig. 4. WEF (considering discharged pollutants) of China's textile industry

Data on generated and discharged NH_3-N of China's textile industry between 1996 and 2000 was not published in the statistical yearbooks. Therefore, the WEFI from 2001 to 2015 was calculated and are shown in Fig. 5. The WEFI of the MT and MCF sectors decreased as a whole. The WEFI of the MTWAFC sector was the smallest and fluctuated less during the selected research years. Fig. 6 shows the WETF of China's textile industry with discharged water pollutants from 1996 to 2015. The total WETF showed a decreasing trend, and it significantly decreased after 2004.

The WETF of the MT sector was significantly larger than those of the two other sectors. It represented more than 99% of the total WETF, which is usually caused by heavy metals (i.e., mercury, cadmium, chromium VI, total chromium, lead, and arsenic) discharged in the wastewater. Mercury, cadmium, and chromium VI were the three characteristic pollutants that caused WETF.

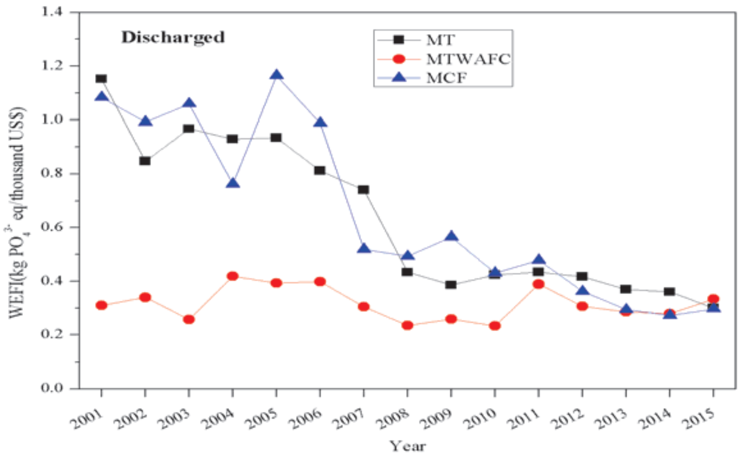

Fig. 5. WEFI (considering discharged pollutants) of China's textile industry

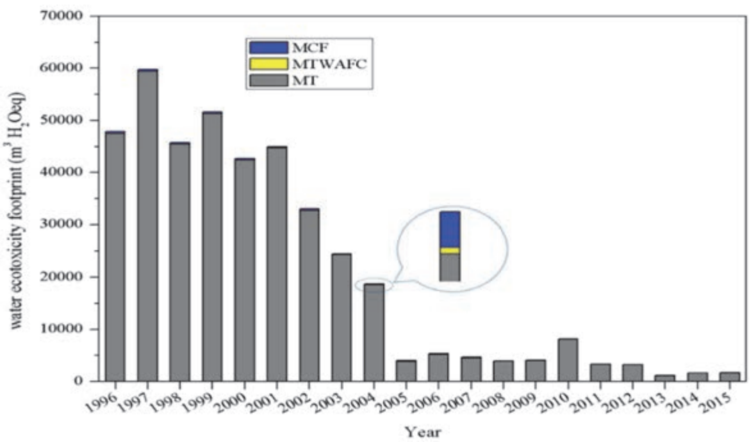

Fig. 6. WETF of China's textile industry

4. Discussions

Water is essential in the industrial processing of textile products. A large amount of fresh water is used in key processes such as desizing, scouring, bleaching, and mercerizing because textile chemicals used in wet processes are generally in the form of water baths. Semi- and fully-finished textile products generally contain very little water or are dry. Therefore, nearly all the input water is discharged during the process. However, the discharged water from wet processing machines generally contains high concentrations of pollutants (e.g., COD, NH_3-N, heavy metals, salts) that contaminate surface and groundwater. Besides, freshwater appropriation and effluent emissions cause regional water scarcity and water degradation impacts. As those wet processes mainly occur in the MT sector, WSF, WEF, and WETF of MT were the largest contributor to the WF of the whole textile industry. WCF sector also consumed significant freshwater and caused wastewater emission. Contrary to the MT sector among which around 80% were small-and medium-sized enterprises, the enterprises in MCF sector are large-scale with advanced technology. Attributing the advanced equipment and technology in the MCF sector, the higher wastewater treatment ability allows a high rate of water reuse in this sector.

China is the world's largest producer and exporter of textiles and clothing. China's textile industry includes complete production chains. It produces high amounts of fiber, yarns, fabrics, and end products (e.g. clothing, caps) for industrial or commercial use (domestically or abroad). However, the rapid development of China's textile industry led to serious environmental destruction in the past 40 years. Since China's reformation and opening, the world's textiles production transferred to China because of its cheap labor and other preferential policies. Thus, China's textile industry gained a new opportunity of further and faster development when China officially joined WTO in 2001. However, freshwater saving and wastewater treatment were not highly considered because the main focus of textile production was profit from 1996 to 2005. The water scarcity footprint and WEF increased rapidly at this period. The main contributor to the significant increase during this time is the expansion of the textile industry. As environmental degradation became increasingly obvious and serious, labor costs rose, thus, world economic fluctuations, freshwater consumption, and wastewater discharge gained more attention. Many waters saving and wastewater disposal technologies have been proposed and applied to textile wet processes. For example, the use of enzymes in wet processing (scouring, degumming, bleaching, etc.) can reduce rinse water consumption (e.g., 20-50% reduction for wool scouring) and pollutants loads (e.g., 20-40% reduction of COD and BOD for wool scouring) in wastewater (Chatha et al., 2017; Madhu and Chakraborty, 2017;).

Ultrasonic treatments in wet processing can reduce 20% of water consumption and 20-30% of effluent production because less dyes and chemicals are consumed (Vouters et al., 2004). For supercritical CO_2 dyeing technology, water usage is almost eliminated and there is no wastewater discharge (Long et al., 2014; Zhang et al., 2015). Digital ink-jet printing technology reduces water consumption and is highly effective for printing using dyestuff palette (Christina, 2015). Foam finishing technology can effectively reduce water consumption (up to 80%) and wastewater discharge (Ramachandran et al., 2008).

Textile wastewater can be treated by physical, chemical, biochemical, or hybrid methods (Chandrakant et al., 2016). Each category has many specific treatment technologies, such as flocculation; adsorption; advanced oxidation processes; chemical oxidation; aerobic, anaerobic, and anoxic approaches; etc. These treatment technologies are highly effective for different kinds of wastewater. More wastewater treatment equipment are available and the wastewater treatment ability was expanded from 1996 to 2015 in textile industry of China (see Fig. 7), despite the slight decrease after 2011. The MT sector treated the largest daily amount of wastewater.

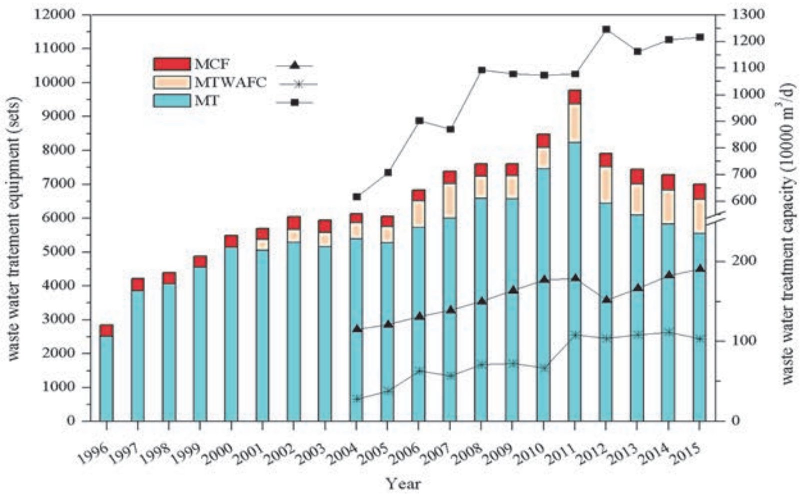

Fig. 7. Equipment and capacity of the wastewater treatment of China's textile industry

The government of China was becoming increasingly aware of the environmental impacts of the textile industry. It has issued many policies (e.g., five-year plans, industry entry criteria) and standards (e.g., cleaner production standards, water pollutants discharge standards) that restrict freshwater appropriation and wastewater discharge between 2005-2015, as reviewed by Wang et al. (2013b). The management and restrictions of water consumption were conducted before the strict wastewater emission restrictions. Between 2006-2010, under the guideline of Textile Industry 11th Five-Year Development Plan, water extraction per one hundred meters fabric decreases from 4t to 2.5t, the water reuse rate increases from 7% to 15%, by equipment upgrade and technology improvement (MIITC, 2006). A further strength of the restriction of pollutant emission in the textile industry was seen in 2011-2015. Ministry of ecology and environment considered the textile industry as one of the key control sectors and COD and NH_4-N were decided as controlled indicators, which drove the adjustment of sector structure, the substitution of backward technologies and equipment in the textile industry (MIITC, 2011).

With the effort of the government effort through policies, standards, and advanced technology and upgrade equipment, the increase rate WSF and WEF grow is relatively flat between 2006-2010. Although China was initially unaffected by the global economic downturn of 2009, the market was stimulated by the recovered global demand around 2011, which led to an increase of WSF and WEF. However, the effect of the development of water-saving technology and water consumption standard began to be shown again in WFS during 2011-2015.

Water-saving technology development improves the WSFI of the textile industry. Meanwhile, for textile producers, the reduction of freshwater consumption can also save production costs because the technologies and equipment used can increase water recycling (see Table 1). Therefore, though the WSF of China's textile industry increased due to the industrial-scale expansion, the WSFI decreased in the selected research years. The decrease of WSFI illustrated that the efficiency of water consumption in the textile industry has been improved with the effort of government strategies and technology upgrade.

After the introduction of ecological footprint concept by Rees (1992), several other environmental footprints (e.g., carbon footprint, water footprint, nitrogen footprint) have been proposed for the quantification and assessment of environmental impacts (e.g., global warming, ecotoxicity, land use, human toxicity). The quantification and assessment of water related environmental impacts is not a new topic. The WF methodology focuses on the environmental impacts related to water. The existing WF frameworks have been demonstrated through many pilot researches. The framework with green, blue, and grey WF presented as volumetric results is convenient for summation and further comparison, which is important for the selection of sustainable products. However, this framework neglects the regional differences of water body background and cannot fully reflect the impacts of discharged water pollutants. The framework in ISO 14046 considers WSI and the specific impact regarding relevant water pollutants. It can give a more comprehensive understanding of environmental impacts caused by water consumption and wastewater discharge. Nevertheless, as the units of WF indicators (e.g., WSF, WEF, WETF) are different, it is difficult to quantify and compare the total impact. Some studies suggest making WF indicators dimensionless by using the LCA polygon method or grey target principle (He et al., 2018; Zhu et al., 2019). However, there is still much work to do on this topic, which should gain more attention in future research.

Table 1. Freshwater consumption and reused water in China's textile industry (%)

Year	*MT*		*MTWAFC*		*MCF*	
	Freshwater	*Reused water*	*Freshwater*	*Reused water*	*Freshwater*	*Reused water*
1996	46.44	53.56	—	—	32.30	67.70
1997	48.56	51.44	—	—	34.44	65.56
1998	50.91	49.09	—	—	36.38	63.62
1999	53.98	46.02	—	—	32.73	67.27
2000	58.00	42.00	—	—	30.46	69.54
2001	63.25	36.75	34.56	65.44	28.66	71.34
2002	65.47	34.53	39.23	60.77	15.15	84.85
2003	68.39	31.61	68.64	31.36	15.72	84.28
2004	64.82	35.18	56.46	43.54	12.70	87.30
2005	63.52	36.48	82.75	17.25	11.79	88.21
2006	71.17	28.83	81.70	18.30	12.32	87.68
2007	72.95	27.05	76.89	23.11	10.89	89.11
2008	73.97	26.03	73.10	26.90	10.99	89.01
2009	74.48	25.52	71.16	28.84	10.36	89.64
2010	77.15	22.85	73.11	26.89	10.47	89.53
2011	82.14	17.86	80.76	19.24	17.99	82.01
2012	77.02	22.98	81.87	18.13	11.65	88.35
2013	74.50	25.50	82.51	17.49	14.35	85.65
2014	58.01	41.99	73.49	26.51	12.96	87.04
2015	57.47	42.53	74.24	25.76	11.68	88.32

5. Conclusions

This paper presented a comprehensive WF analysis of China's textile industry based on the WF framework proposed in ISO 14046, which provided an overview of water usage in the textile industry. Due to the increasing textile industry scale in China, water appropriation and wastewater generation and discharge also increased. Therefore, WSF and WEF increased from 1996 to 2015, despite some fluctuation periods under the interventions of government and efforts of companies. Government administrative control measures and producers' actions to save fresh water and treat wastewater improved the WF intensity. WETF also decreased due to the restrictions on the discharge of heavy metal pollutants. This illustrated that water management and restriction with policy and standard by the government are essential as China produces the majority textile products and continuously expand in the future.

To improve the WF intensity could be the fundamental target in the future improvement of sustainability of textile industry. Besides, WT contributed the majority of WF, so more effort should be put on the WT sector to improve the water reuse rate and wastewater treatment efficiency through upgrading equipment and technology.

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