Estimating the environmental and economic impacts of widespread adoption of potential technology solutions to reduce water use and pollution: Application to China's textile industry

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Abstract

Numerous technologies are emerging to reduce water use and pollution in China's textile industry, including several that are promoted by the China National Textile and Apparel Council as cleaner technologies in their five-year development guideline published in 2016. Though these technologies appear promising, the complexity of the industry makes it difficult to predict and compare the environmental and economic impacts of widespread adoption of these technologies. We draw on existing studies to estimate the potential scale of applicability of these technologies, and then estimate the potential economic and environmental benefits of encouraging their widespread adoption. Several of them, if implemented on a large scale, could drastically reduce water use and pollution with a payback of less than a year. Our approach to estimating the environmental and economic impacts of widespread adoption of promising technologies is also relevant for impact assessment in other complex industries with a wide range of products and processes.

Keywords: water consumption, textile, technology, China

1. Introduction

The textile industry is a major contributor to global water consumption and pollution, in particular in China, the world's largest exporter of textiles (Hasanbeigi and Price, 2015), though also increasingly in emerging economies such as Vietnam (Nayak et al., 2019). Wang (1999) already reported that despite water shortages being critical in China, water consumption per unit of industrial production is 5-10 times greater than in developed countries. There is a large literature on potential technological solutions to these problems, and the China National Textile and Apparel Council (CNTAC, 2016) selected several such emerging technologies to be promoted as cleaner technologies for the

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textile industry in their five-year development guideline published in 2016. Although these technologies appear promising, it is sometimes difficult to estimate the environmental and economic impacts of adopting these solutions on a large scale, due to the complexity of the industry.

For instance, which of these two technologies discussed in Tong et al. (2012) has greater potential benefit: (a) cold pad-batch pretreatment for cotton fabric, which they use an estimate from Chen (2009) of potential water savings of 50%, or (b) digital printing for cotton, chemical fiber and silk fabric, for which they use an estimate from Gu (2002) of potential savings of 30%? For policy-makers the answer to this question is important, as it informs them which technology they should prioritize more. An estimate, even if only highly approximate, of the water savings potential and economic effects of widespread adoption of these technologies is also relevant for policy-makers, as it would provide an order-of-magnitude estimate of how much they might consider investing in supporting these technologies.

The answer to this comparison depends on the relative contribution of cotton fiber, chemical fiber, and silk to total water consumption in the textile industry, and to the relative contribution of the pretreatment stage and the dyeing and finishing stage to total water consumption associated with each type of fabric. Although the textile industry is one of the most common domains for water footprint studies (Aivazidou and Tsolakis 2019), comparisons are hindered by a lack of standardization in the measures and methods used. For instance, one study may focus on direct water withdrawals of an entire process, while another might measure direct and indirect water consumption of the pretreatment and dyeing stages only. Wang et al. (2013) point out the importance of analyzing water footprints at the level of individual process stages.

Moreover, to answer this comparison, one would need information about the economic payback of the technologies in question. In their comprehensive review of the literature, de Oliveira Neto et al. (2019) observe that many studies do not provide information about the economic payback, and even fewer do so while looking at individual process stages separately. Chen et al. (2017) provide a case study illustrating how a more detailed evaluation tool that takes this complex structure into account can help manufacturers better understand the impacts of such emerging technologies.

The contribution of this paper is to provide a methodology to estimate the potential economic and environmental impacts of widespread adoption of emerging technologies, which is non-trivial due to the complex structure of the industry and the lack of standardization among existing studies. We focus on a set of promising technologies already identified by CNTAC (2016) shown in Table 1, to be able to make meaningful comparisons. However, the approach we outline is equally applicable to other technologies, other countries and to other complex water-intensive industries such as food processing (Klemeš et al. 2008) and others. Finally, our methodology combines water efficiency and energy savings so it could be used as a tool to "support policy-makers and investors into more resource efficient strategies and investment choices" (UN-WDPAC 2014).

2. Assessment of aggregate water use and pollution in China's textile industry

In order to estimate the potential environmental and economic impacts of the widespread adoption of various water-related technologies, we must first understand the overall water consumption and pollution that is associated with China's textile industry. We must also understand how this associated water consumption and pollution breaks down across different process steps and different types of fabric. To do this, we drew on several sources of information. We identified scientific papers published in English or Chinese that provided data that would help us determine the breakdown of total water consumption and pollution by fiber and by process stage. In addition, we used statistical data and reports from national and international agencies, including the World Trade Organization (WTO), various Chinese government agencies, the China National Textile and Apparel Council (CNTAC), and related associations (the China Cotton Textile Association (CCTA), the China Filament Weaving Association (CFWA), and the China Wool Textile Association (CWTA)).

Several studies quantify the sizeable impact of the textile industry. Li et al. (2008) find that in 2002, the textile industry was one of the five highest water-consuming industries in China (together with thermal power, iron and steel, paper production, and the petrochemical industry). Yin et al. (2016) conclude that among 17 major industries between 1997 and 2007, China's textile and garment industry was one of the eight most polluting industries. Oita et al. (2016), Yang et al. (2016) and Zhang et al. (2013) report that textile exports from China are a substantial cause of water pollution in China. Xu et al. (2018) provide an overview of a wide range of textile environmental policies that have been implemented in China, and conclude that water pollution has been the main target so far.

Table 1

Selected technologies identified by the China National Textile and Apparel Council (CNTAC) as cleaner technologies for the textile industry in their five-year development guideline published in 2016 (CNTAC 2016).

Technology	Process stage to which the technology applies
Reuse of cooling water	Common
Reuse of low concentration production sewage	Common
Reuse of steam condensate	Common
Workers' efficiency improvement based on measurement of water and energy consumption on machine level	Common
Cold pad-batch pretreatment for cotton and chemical fiber fabric	Pre-treatment
Cold pad-batch dyeing for cotton, chemical fiber and silk fabric	Dyeing/printing
Air flow dyeing for chemical fiber fabric	Dyeing/printing
Digital printing for cotton, chemical fiber and silk fabric	Dyeing/printing

Source: CNTAC (2016).

Fig. 1 illustrates the structure of the textile production process. It highlights the three main production stages: *fiber*, *yarn*, and *finished fabric*, for several of the main textile products, including *cotton*, *chemical fibers*, *wool*, and *blended textiles*. Each production stage has several processes. For processes such as *pretreatment*, *dyeing/printing*, and *finishing*, water is the principal medium for applying chemicals (e.g., dyes, acids, surfactants, enzymes, stabilizers, salts, fixing and complex agents) that impart the desired properties to the textile product. Water is also used to remove impurities during processes such as *cotton lint ginning*, *cotton fiber combing and carding*, *silk fiber reeling*, *flax fiber degumming*, and *wool fiber scouring*. Therefore, a large number of residual chemicals and impurities enter the sewage system, which increases pollutant loads (Brik et al., 2006). Textile sewage is characterized by its high color, chemical oxygen demand (COD), and salt content (Tanapongpipat et al., 2008). All these characteristics degrade water quality. Because our focus is on the textile manufacturing industry, we do not consider the garment production or end-of-life stages. Muthu et al. (2012) provide a comprehensive comparison of different fibers; in our study, we take the fibers as given and compare ways of reducing the impacts associated with turning them into garments.

3. Methods

In order to illustrate our approach to estimating the benefits of widespread adoption, we selected the set of technologies shown in Table 1. Some of these are already relatively widely adopted (such as the four “common” technologies), and we can use data published in NRDC reports by Greer and Lin (2010) and Greer et al. (2010, 2013) for several of them. Others are more experimental (those related to pre-treatment and dyeing and printing); to illustrate our approach for those cases, we use data obtained from three manufacturers that we interacted with. The NRDC reports do provide some estimates of water savings and economic payback for some of those technologies too, but they do not provide enough information about water consumption before adoption for us to be able to perform our extrapolation.

Our first interviewee is the director of the Sustainability Department of an ISO 14001–certified large-scale manufacturer, “X”, in Suzhou, Eastern China, that performs chemical fiber fabric pretreatment, dyeing/printing, and finishing. The second is the production manager of an ISO 14001–certified large-scale manufacturer, “Y”, in Hangzhou, Eastern China, that performs pretreatment of cotton, chemical fiber, and silk fabric as well as dyeing/printing and finishing. The third is the production manager of a small-scale chemical fiber manufacturer, “Z”, in Changzhou, Eastern China, that performs fabric pretreatment, dyeing/printing, and finishing.

We do not claim that the data from these manufacturers are representative, we only use them to illustrate how one can extrapolate the water savings and economic effects that would result from widespread adoption of a technology when one the data are limited to a case study involving only a specific process stage and type of fabric. One can use the same extrapolation approach to other estimates of the water savings and economic effects of these technologies, for instance such as those provided by de Oliveira Neto et al. (2019).

In order to be able to extrapolate meaningfully, we need to know the breakdown of current water withdrawals by process step and fabric type. We found assessments for four kinds of textile: cotton (six studies), cotton and chemical fiber blends (one study), chemical fibers (two studies) and wool (two studies). However, it is challenging to compare these assessments because of the variety in the recognized process steps and indicators used. Some studies focus on water withdrawal while others assess water consumption; some studies focus on direct water use while others include indirect use.

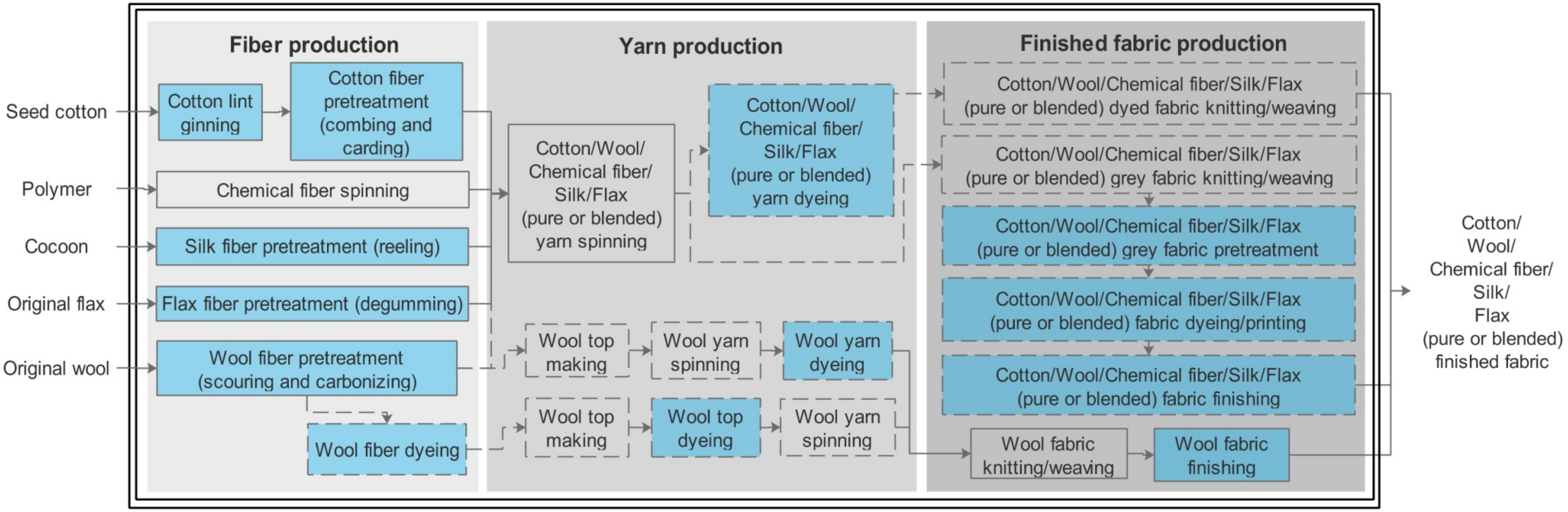


Fig.1. The system boundary of the textile industry and its production stages, as well as processes for the main textile products. (Dotted boxes indicate optional processes, while solid-line boxes indicate required processes. Boxes in blue indicate water-intensive processes

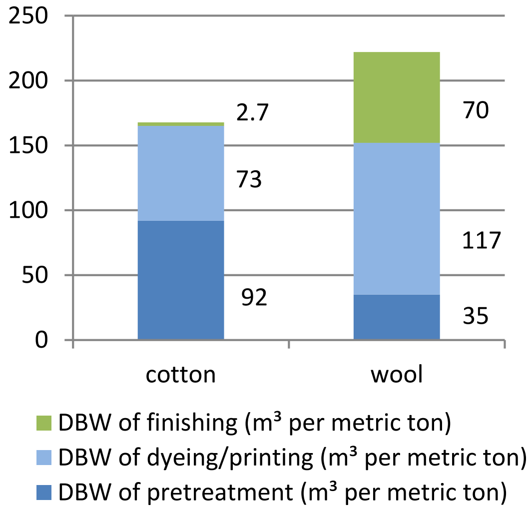
In this analysis, we focus on direct water withdrawals, as that is the metric most commonly used, but we do not mean to suggest that that is the only metric that matters; the same approach can be used for other metrics such as indirect water consumption or direct sewage. For brevity we will use “DBW” (for direct blue water withdrawals). Zhang et al. (2019) argue that focusing on blue water withdrawals is appropriate as it is most directly related to local water stress.

The assessments also vary in how they break down processes into individual steps. Some assessments separately analyze yarn spinning, fabric weaving and knitting, fabric pretreatment, fabric dyeing and printing, and fabric finishing, while other assessments combine all these steps into one process. Very few studies were directly comparable because of these differences.

Fig. 2 shows the breakdown that we will use later. The figure compares cotton with wool, and shows that the largest direct water withdrawals for cotton occur during pretreatment, while for wool the largest withdrawals occur in the dyeing/printing stage. We use this observation later in our extrapolation of the economic and environmental impacts of emerging technologies.

The indicators we use to assess cost-effectiveness are (a) reduction in annual DBW, (b) up-front investment cost, (c) annual net economic benefit, and (d) payback in years (defined as up-front investment cost divided by annual net economic benefit). Annual net economic benefit includes cost reductions due to reductions in annual DBW, energy and chemical materials cost, and outsourced sewage treatment cost. To be conservative, we use the lowest cost provided by the manufacturers we interviewed for the analyses in Section 5, shown in Table 2.

In the next section, we first assess the potential impact of widespread adoption of technologies that are not process-specific. This is relatively straightforward, though relies on several assumptions that we explain below. Then in section 5, we assess the potential impact of widespread adoption of process-specific technologies. This is more challenging as we need to account for the breakdown of total water use across different fibers and production stages.



Sources: DBW of cotton is the average of the data from Zhang et al. (2015), Wang et al. (2009), Yuan et al. (2013). DBW of wool is the average of the data from Hassan and Shao (2015) and Wu and Liu (2014).

Fig.2. Direct blue water withdrawal of cotton and wool textile production.

Table 2

Cost data used to estimate economic benefits

Input	Cost
Water (DBW)	CNY 2 per m^3
Outsourced sewage treatment	CNY 3 per m^3
Electricity	CNY 0.8 per kWh
Steam	CNY 200 per m^3
Gas	CNY 2.54 per m^3
Dyes	CNY 80 per kg
Other chemical materials	CNY 4 per kg

Source: estimates from the three manufacturers we interacted with (referred to as X, Y and Z).

4. Assessing water savings and economic effects of widespread adoption of common technologies

The first four technologies in Table 1 are labeled “common” as they are not limited to specific process stages or fibers. The next four are labeled “process-specific” as they only apply to specific process steps and fibers. In order to be able to compare the potential water savings and economic effects of these technologies, we need to standardize them. We do this by extrapolating the environmental and economic impacts to the scenario in which they are widely adopted in China’s textile industry. Table 3 shows the results.

For the common technologies, we scale annual water withdrawals, up-front investment cost, and annual net economic benefit up, from the water withdrawals of a typical plant to the annual water withdrawals of the entire Chinese textile industry in 2014, estimated at 4.095 billion m^3 in China's Environmental Statistics Report 2014 (National Bureau of Statistics of China, 2015). We use data for 2014 to be consistent with the data contained in the five-year development guidelines from CNTAC (2016), CCTA (2016), CFWA (2016), and CWTA (2016).

Table 3 confirms that reusing cooling water, process water, and condensate all offer substantial potential reductions in DBW, with a payback of months. Widespread adoption of reusing condensate could reduce annual DBW by up to 0.089 billion m^3. This is equal to the annual domestic water withdrawal for 1.6 million Chinese individuals, according to the estimated domestic per capita water withdrawal of 56.04 m^3 in 2014 (National Bureau of Statistics of China, 2015). Note that, for consistency with our focus on water withdrawals, we also draw the comparison to water withdrawals of Chinese individuals, rather than water footprint (which includes indirect water use); Cai et al. (2019) report that water footprint per capita in 2012 was 2,826.5 m^3 per year.

This extrapolation makes a number of significant assumptions, so it should be considered as an illustration rather than a definitive prediction. First, the extrapolation ignores economies of scale. Widespread adoption of a technology could lead to lower costs due to learning or other effects, or it could lead to higher costs in the case of material shortages. Second, this extrapolation ignores possible limitations on adoption (such as scarcity of land or availability of equipment). Third, we treat the technologies as independent from one another; applying a technology that reduces DBW will reduce the potential value of another technology that further reduces DBW, as it would reduce the baseline amount of water used by the system.

Table 3

Annual DBW reduction, upfront investment cost, annual net economic benefit, and payback of selected technologies for China's textile industry, promoted as cleaner technology for textile industry by CNTAC (2016).

Category	Technology		Annual DBW before adoption (million m^3 / year)	Annual DBW reduction rate	Annual DBW reduction (billion m^3 / year) in case of widespread adoption	Upfront investment cost for widespread adoption (billion CNY)	Annual net economic benefit from widespread adoption (billion CNY/year)	Payback (years)	Adoption status (2015)
Common technology	Reuse of cooling water		0.96 [a]	7.4% [a]	0-0.152 [b]	0-0.026 [c]	0-0.56 [d]	< 0.047	> 50% [j]
	Reuse of process water		0.96 [a]	11.2% [a]	0-0.230 [b]	0-0.462 [c]	0-7.51 [d]	0.062	> 50% [j]
	Reuse of condensate		0.96 [a]	4.4% [a]	0-0.089 [b]	0-0.506 [c]	0-3.54 [d]	0.143	> 50% [j]
	Workers' efficiency improvement based on measurement of water and energy consumption at machine level		0.29 [e]	3% [e]	0.123 [e]	1.412 [e]	14.361 [e]	0.098	< 5% [j]
Process-specific technology	Pre-treatment	Cold pad-batch pretreatment for cotton and chemical fiber fabric	0.0033 [f]	90% [f]	0.84 [f]	42.273 [f]	26.491 [f]	1.60	> 1 [f]
	Dyeing/ printing	Cold pad-batch dyeing for cotton, chemical fiber and silk fabric	0.008 [g]	83% [g]	1.411 [g]	29.750 [g]	40.375 [g]	0.737	> 1 [g]
		Air flow dyeing for chemical fiber fabric	0.016 [h]	93% [h]	0.688 [h]	37.000 [h]	10.638 [h]	3.478	> 1 [h]
		Digital printing for cotton, chemical fiber and silk fabric	0.007 [i]	98% [i]	1.666 [i]	130.769 [i]	10.985 [i]	11.905	> 1 [i]

Notes:

a. Greer and Lin (2010). In this NRDC report, the authors claim that a potential total water savings of 738 m^3 per day at a typical plant corresponds to 23% of such a plant's total consumption. Estimated daily consumption is therefore 738/0.23 = 3,209 m^3 per day, or 962,609 m^3 per year (assuming 300 production days). They claim potential savings of 238 m^3 per day from reuse of cooling water, or 238/3,209 = 7.4%, and similarly for reuse of process water and condensate.

b. Total DBW of China's textile industry in 2014 was 4.095 billion m^3, as reported in China's Environmental Statistics Report 2014 (National Bureau of Statistics of China, 2015). If the entire textile in China industry adopted Reuse of cooling water (and if no firm had adopted it yet), the potential reduction in DBW is 7.4% x 4.095 = 0.30 billion m^3. Since the penetration of Reuse of cooling water, in China's textile industry by 2015 already exceeds 50% (CNTAC, 2016), the

f. Source: Manufacturer X implemented this approach, for 264 tons of chemical fiber fabric, and achieved a 90% reduction in DBW from 33,000 m^3 previously. Table 4 shows that pretreatment of chemical fiber accounts for 0.93 billion m^3 of water per year, so the 90% reduction achieved by Manufactrurer X would correspond to a reduction of 0.93 x 90% = 0.84 billion m^3 of water in the case of widespread adoption. Manufacturer X reported an upfront investment of 150,000 CNY and annual benefits of 94,000 CNY (including savings in electricity, water and steam and in increase in chemical materials). Nationwide adoption involves scaling these figures upwards by a factor 0.93 billion / 33,000 = 281,818.

g. Source: Manufacturer Y implemented this for 132 tons of cotton, chemical fiber and silk fabric in 2014, and achieved an 83% reduction in DBW from 8,000 m^3 previously. Table 4 shows that dyeing and printing accounts for 1.7 billion m^3 of water per year, so the 83%

estimates of annual DBW reduction, up-front investment cost and annual net economic benefit of these three technologies will be less than 50% of that value for widespread adoption, as those values assume that current penetration is zero. The same applies to Reuse of process water and Reuse of condensate.

c. Greer and Lin (2010) estimate an upfront investment cost of US$1,911 for a typical plant to implement Reuse of cooling water. With an exchange rate of US$ 1 = 6.5 CNY, this is CNY 12,422. A typical plant has DBW of 962,609 m^3 of water per year, relative to the industry-wide DBW of 4.095 billion m^3 per year. The investment cost for a typical plant needs to be scaled up by a factor 4.095 billion / 962,609 = 4,254 to achieve widespread adoption, i.e. 4,254 x 12,422 CNY = 0.05 billion CNY. As before, this assumes no current adoption; with current adoption over 50%, the costs need to be scaled down accordingly. The same applies to Reuse of process water and Reuse of condensate.

d. Greer and Lin (2010) estimate monthly benefits of US$3,373 for a typical plant to implement Reuse of cooling water. This translates to annual benefits of CNY 263,094 for a typical plant. Using the same scaling gives an estimate of 1.12 billion CNY for widespread adoption assuming no current adoption. The same applies to Reuse of process water and Reuse of condensate.

e. Source: Manufacturer Z. Manufacturer Z adopted this approach in 2015. The plant initially had DBW of 290,000 m^3 per year, and reduced that by 3%. That same reduction applied to the industry-wide DBW of 4.095 billion m^3 per year would yield a 0.123 billion ton reduction. Manufacturer Z reported a 100,000 CNY upfront investment, and 1,107,000 annual savings (mostly from reduced electricity consumption). Scaling their experience to the case of nationwide adoption involves multiplying by 4.095 billion / 290,000 = 14,121, so upfront investment cost for nationwide adoption would be 14,121 x 100,000 = 1.412 billion CNY, and annual savings would be 14,121 x 1,107,000 = 14,361 billion CNY.

reduction achieved by Manufacturer Y would correspond to a reduction of 1.7 x 83% = 1.411 billion m^3 of water in the case of widespread adoption. Manufacturer Y reported an upfront investment of 140,000 CNY and annual benefits of 190,000 CNY (for electricity, water and steam). Nationwide adoption involves scaling these figures upwards by a factor 1.7 billion / 8,000 = 212,500.

h. Source: Manufacturer X, and Chen (2008). Manufacturer X implemented this for 264 tons of chemical fiber fabric, and achieved a 93% reduction in DBW from 16,000 m^3 previously. Table 4 shows that dyeing and printing of chemical fiber accounts for 0.74 billion m^3 of water per year, so the 93% reduction achieved by Manufacturer X would correspond to a reduction of 0.74 x 93% = 0.688 billion m^3 of water in the case of widespread adoption. Manufacturer X reported an upfront investment of 800,000 CNY and annual benefits of 230,000 CNY (including savings in water and chemicals and an increase in electricity costs). Nationwide adoption involves scaling these figures upwards by a factor 0.74 billion / 16,000 = 46,250.

i. Source: Manufacturer Y, and Chen et al. (2015). Manufacturer Y implemented this for 39 m^3 of cotton, chemical fiber and silk fabric, and achieved a 98% reduction in DBW from 6,500 m^3 previously. Table 4 shows that dyeing and printing accounts for 1.7 billion m^3 of water per year, so the 98% reduction achieved by Manufacturer Y would correspond to a reduction of 1.7 x 98% = 1.666 billion m^3 of water in the case of widespread adoption. Manufacturer Y reported an upfront investment of 500,000 CNY and annual benefits of 42,000 CNY (including savings in water and steam and an increase in costs of electricity and chemicals). Nationwide adoption involves scaling these figures upwards by a factor 1.7 billion / 6,500 = 261,538.

j. CNTAC (2016).

5. Assessing water savings and economic effects of widespread adoption of process-specific technologies

Some of the other technologies identified by CNTAC as promising are process-specific, which makes it harder to estimate the effects of widespread adoption. Moreover, several of these technologies have not yet been studied as much in the literature. Some estimates do exist of the extent to which they can reduce water withdrawals, but little or no evidence exists of their economic costs and benefits. We encountered some of these technologies during our interactions with several textile manufacturers, so we can use their experience to construct an initial estimate of those economic effects to illustrate our extrapolation approach. These estimates are necessarily highly tentative, as they are based only on data from the three manufacturers. However, in order to assess whether they are worth investigating further, it is helpful to compare them with the technologies discussed in the previous section. To do this, we again must find a way to estimate the potential effects of these technologies if they were adopted widely, as shown in Table 3.

We assess cost-effectiveness and classify technologies in the same way as in Section 4. In order to compare these technologies with each other and with the common and sewage technologies assessed in Section 4, we again must standardize the associated estimates according to how widely each technology could be adopted. This is more complicated than in Section 4, because each of these process-specific technologies can apply to a different range of processes, so we must first determine the appropriate scale of applicability. To do so, we estimate the proportion of total water use and pollution that can be attributed to the process in question. Then, we extrapolate the costs and benefits, as estimated in the corresponding study, to the level of China's textile industry as a whole. As before, the subsequent extrapolation is based on a number of strong assumptions, which we mentioned previously in Section 4. In addition, for the process-specific technologies we consider here, existing references do not provide enough assessment results for every specific process and every kind of textile. As a result, we may not allocate water withdrawals accurately, and may under- or overestimate the potential annual DBW reduction of some technologies.

The annual DBW of the entire Chinese textile industry is estimated at 4.095 billion m^3 in 2014 (National Bureau of Statistics of China, 2015). We need to break this down by process stage and by fabric. Table 4 summarizes how we do this and shows the estimated total annual DBW for the specific process steps of the three main kinds of textile.

First, recall that Fig. 2 showed the breakdown of water withdrawals for cotton and for wool into pre-treatment, dyeing and printing, and finishing. Because the production process for chemical fiber textiles and cotton textiles are similar (see Fig. 1), we apply the breakdown for cotton to chemical fiber as well. Fig. 2 only provides the breakdown per ton of output, so we need total output for each type of textile, which we obtain from other sources. In 2014, the total output for each main kind of textile product was as follows: 63 billion meters of cotton fabric (CCTA, 2016) (equal to 12.6 million tons under the assumption that the average weight per meter of cotton fabric is 0.2 kg/m (Minister of Industry and Information Technology of China, 2010)), 42.5 billion meters of chemical filament fabric (CFWA, 2016) (equal to 8.5 million tons under the same assumption of an average weight of 0.2 kg/m (Minister of Industry and Information Technology of China, 2010)), and 377,100 tons of wool fabric (CWTA, 2016).

How much of the total annual DBW of 4.095 billion m^3 can be attributed to pretreatment, dyeing/printing, and finishing? We know the breakdown of DBW into these three steps for cotton, chemical fiber, and wool, the three main textile products. Therefore, we use the breakdown from aggregating those three products to determine the breakdown of the DBW of the entire industry. One example of this process is as follows (and explained in footnote b in Table 4): The total DBW for the pretreatment for cotton, chemical fiber, and wool combined is 2.1 billion m^3 per year. The total DBW across all process steps for those three fabrics is 3.89 billion m^3 per year. Therefore, we assume that pretreatment accounts for $2.1 \div 3.89 = 54\%$ of the total industry-wide DBW, or $54\% \times 4.09$ billion = 2.21 billion m^3 per year.

To explain the next step, we use the first process-specific technology shown in Table 3 as an example: the cold pad-batch pretreatment for cotton and chemical fabric. From Manufacturer X, we learned that their annual DBW before adoption was 3,300m^3. This technology applies only to the pretreatment of chemical fiber textiles. Table 4 shows that the annual DBW for the pretreatment of chemical fiber textiles in China's textile industry is 930 million m^3, which is 281,818 times the annual output of Manufacturer X (i.e., $3,300 \times 281,818 = 930$ million). The up-front investment cost was estimated at approximately CNY 150,000; therefore, a simple estimate of the up-front cost to implement this technology in the pretreatment of all cotton and chemical fiber textiles in China would be CNY 150,000 × 281,818 = CNY 42.273 billion. This technology yielded a reduction in annual DBW of 90% at Manufacturer X. If it were scaled up to nationwide chemical fiber textile pretreatment, this would correspond to an annual DBW reduction of 90% x 930 million m^3 = 840 million m^3. Finally, the annual net economic benefits of this technology at Manufacturer X are estimated to be CNY 94,000, which would correspond to a nationwide net economic benefit of CNY 26.491 billion, resulting in a payback of 1.596 years.

We emphasize again that this extrapolation relies on a number of assumptions, listed above. We do not intend these extrapolations to be interpreted as precise estimates of the impact of nationwide adoption of these five process-specific technologies, but rather as a first approach to identifying which technologies are most promising and deserving of further study.

Table 3 shows that widespread adoption of several of these process-specific technologies could yield significant benefits, of the same order of magnitude as the most promising technologies from the common technologies analyzed in Section 4. This is somewhat surprising, given that their potential scope is more limited. For instance, cold pad-batch dyeing for cotton, chemical fibers, and silk fabrics could potentially reduce DBW by 0.49–1.46 billion m^3 per year, even though this technology does not apply to all fibers or all process steps. The manufacturer that implemented this technology reported a payback of well under one year. Although the data available to us for these emerging technologies is highly preliminary, they indicate that these technologies are worthy targets for more thorough investigation.

6. Conclusions

Based on our findings in Sections 3, 4, and 5, we draw several conclusions related to the process of estimating environmental and economic impacts of emerging technologies to reduce water use and pollution. First, from the existing literature with assessments of emerging technologies, we find that many are excellent in themselves, but they are often not detailed enough and the indicators used not consistent enough to allow for meaningful comparisons between processes or between products, to identify hotspots, or to allow practitioners to quickly estimate water use and pollution for a given textile production facility.

Table 4

Annual DBW of specific processes of three main kinds of textile (cotton, chemical fiber, and wool) in China’s textile industry.

	DBW (m^3 per metric ton of output)			Annual output in 2014 (in millions of metric tons)			Total annual DBW (in billion m^3)				
	Cotton	Chemical fiber	Wool	Cotton	Chem. fiber	Wool	Cotton	Chem. fiber	Wool	Total DBW per step across all three kinds of textile	Total DBW per step as percentage of total for process
Pre-treatment	92 [a]	109=200 × 54.85% [b]	35 [a]	12.6[c]	8.5 [d]	0.3771 [e]	1.16	0.93	0.01	2.1	54%=2.1/(2.1+1.7+0.09)
Dyeing/ printing	73 [a]	87=200 × 43.53% [b]	117 [a]	12.6 [c]	8.5 [d]	0.3771 [e]	0.92	0.74	0.04	1.7	44%=1.7/(2.1+1.7+0.09)
Finishing	2.7 [a]	3.2=200 × 1.62% [b]	70 [a]	12.6 [c]	8.5 [d]	0.3771 [e]	0.03	0.03	0.03	0.09	2%=0.09/(2.1+1.7+0.09)

Notes:

a. Source: Fig. 2.

b. For chemical textile production, we only have data on DBW per metric ton for the aggregate process (200 m^3/metric ton) instead of for specific process steps. Chemical textiles and cotton textiles have similar production processes (see Fig. 1), thus we first allocated the DBW per metric ton for the total production of chemical textiles (200 m^3/metric ton) into DBW per metric ton of pretreatment, dyeing/printing, and then we finished by using the proportion of DBW per metric ton of pretreatment for cotton textiles (54.85%=92/(92+73+2.7)), of dyeing/printing for cotton textiles (43.53%=73/(92+73+2.7)), and of finishing for cotton textiles (1.62%=2.7/(92+73+2.7)) (see Fig. 2).

c. CCTA (2016), Minister of Industry and Information Technology of China (2010).

d. CFWA (2016), Minister of Industry and Information Technology of China (2010).

e. CWTA (2016).

Moreover, these assessments do not currently provide benchmarks for policy-makers or manufacturers. In 2015, two of the authors carried out field research at a large-scale wool yarn spinning and dyeing manufacturer in Eastern China, with an annual output of 8,000 tons of dyed wool top/yarn. The manager indicated that benchmarking their environmental performance against others would be very valuable, but currently impossible due to the lack of comparable information. Therefore, we propose the development of a unified and effective water use and pollution assessment standard at the process and product level. This standard should be developed through a joint effort of related stakeholders.

Second, all the technologies in Table 3 have great DBW savings potential, but the adoption of most of these technologies requires a certain up-front investment. In many cases, these investments would be recouped in a few years or less. Therefore, the Chinese and other governments and the textile industry council should further promote the economic benefits of these technologies so that textile manufacturers are willing to invest in these technologies independently. As a consequence, the textile industry in developing countries would be able to achieve considerable environmental and economic improvements simultaneously.

Finally, we have highlighted some challenges associated with providing assessments of environmental and economic impacts of emerging technologies in complex industries with wide variety of products and processes. The approach we propose here, of first determining the breakdown of total impacts by product type and process step, and then extrapolating the impacts of an emerging technology to the appropriate scale of potential adoption, allows for more comparable impact assessments of emerging technologies, and hence more meaningful evaluation of which emerging technologies governments and firms should prioritize.

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