Virtual carbon and water flows embodied in global fashion trade - a case study of denim products

Minyi Zhao[1], Ya Zhou[1,], Jing Meng[2], Heran Zheng[3], Yanpeng Cai[1], Yuli Shan[4], Dabo Guan[5], Zhifeng Yang[1]*

[1] Key Laboratory of City Cluster Environmental Safety and Green Development, Ministry of Education, Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, 510006, China

[2] The Bartlett School of Construction and Project Management, University College London, London, WC1E 7HB, United Kingdom

[3] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), Høgskoleringen 5, 7034, Trondheim, Norway

[4] Integrated Research for Energy, Environment and Society (IREES), Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen 9747 AG, Netherlands

[5] Department of Earth System Sciences, Tsinghua University, Beijing 100080, China

* Corresponding address: yazhou@gdut.edu.cn (YZ)

Abstract

The environmental impacts of the fashion industry have been aroused wide concerns. The globalization and fragmentation of the textile and fashion system have led to the uneven distribution of environmental consequences. As denim is the fabric of jeans that is representative of fashion, this study assessed virtual carbon and water flows embodied in the global denim-product trade, and footprints of denim production were quantified by life-cycle assessment and water footprint assessment. Results indicated that virtual carbon embodied in the global denim trade increased obviously from 14.8 Mt CO_2e in 2001 to 16.0 Mt CO_2e in 2018, and the virtual water consumption dropped from 5.6 billion m^3 to 4.7 billion m^3 from 2001 to 2018. The denim fabric production and cotton fibre production respectively contribute the most of the carbon emissions and water consumption. Polyester blended denim has 5% larger carbon footprint and 72% lower water footprint than cotton denim, and contributes to increasing embodied carbon emissions (from 4% in 2001 to 43% in 2018). Increasing the utilization of polyester blended denim would save water but face more pressures on carbon emission reduction. In the past two decades, virtual carbon and water flows embodied in the global denim trade are relocating, main jean consumers (i.e., the USA, EU-15, and Japan) withdraw the denim manufacturing supply chain and developing countries (i.e., China, India, and Pakistan) with higher carbon and water footprint undertake main global denim production, facing increasing climate-related risks and water crisis. The global South

cooperation helps share successful experiences, save production cost, and lessen resource consumption and environmental emissions. The production and consumption of denim should be shifted to circular and sustainable ways and new business models are required. The analysis framework can provide the basis for exploring environmental flows of product-level trade, and results can offer a basis for environmental policies and control strategies of the fashion industry, and as well as the sustainable production and consumption of garment.

Keywords: Denim; Fashion industry; International trade; footprint; Life-cycle assessment; Sustainability

1 Introduction

1.1 Background

Driven by the growing middle-class population across the globe and rising per capita sales in mature economies, clothing production has doubled from 2000 to 2015 and is expected to continue a rapid increase over the coming decade (Remy, Speelman et al. 2016, (EMF) 2017). The fashion industry is one of the most wasteful and polluting industries, producing 1.2 billion tonnes of CO_2 equivalent (CO_2eq) (occupying 10% of global CO_2 emissions) and consumed 79 billion cubic metres of water in 2015 ((EMF) 2017, Agenda and Group 2017). Fabric production and clothing manufacturing contribute to most of the environmental impacts of the fashion industry (Fotostock 2018). Due to the competitive advantage in labour costs, textile and garment production is mainly located in the Global South (Perry, Wood et al. 2014). The globalization of the fashion industry associated with embodied virtual flows has resulted in substantial inequities of environmental consequences (Trust 2011, Mair, Druckman et al. 2016, Peters, Li et al. 2021). In this study, we examine how international outsourcing of textile production affects resource and environmental flows.

1.2 Literature review

Many studies investigated that international trade has shifted water, carbon and pollution from developed countries to developing countries by manufacturing industry (Davis, Peters et al. 2011, Peters, Minx et al. 2011, Trust 2011, Lenzen, Moran et al. 2012, MoosaviRad, Kara et al. 2013, Kanemoto, Moran et al. 2014, He and Hertwich 2019, Soligno, Malik et al. 2019). Environmental impacts embodied in clothing consumption (i.e., individual product, national consumption) are of great concern, and the literature from research method, databases and aims are summarized in Table 1. Some studies conducted environmentally extended input-output analysis (EEIOA) to investigate carbon emissions embodied in the trade and captured the socio-economic and carbon impacts from the clothing supply chains, and found that over half of carbon emissions of clothing consumption sourced from developing countries (Trust 2011, Andrew and Peters 2013). Western European textiles and clothing consumption remained dependent on low-cost labour from China, India, and Brazil (Andrew and Peters 2013, Mair, Druckman et al. 2016). Peters, Li et al. (2021) formulated the multiregional environmentally extended input-output model to assess the climate and water resources impacts of the clothing and footwear value chain and indicated that eliminating fossil-fueled electricity supplies could largely reduce the absolute carbon footprint of the fashion industry. EEIOA provides sectoral average emissions and has difficulties in identifying micro-level impacts induced by changes in textile and clothing materials. Polyester exceeded cotton and contributed more than half of fabric production in 2017 (Niinimäki, Peters et al. 2020), which brings higher climate burden and lower land occupation and water pressure than cotton (Karthik and Murugan 2017).

Life-cycle assessment (LCA) process analysis decomposes the research objective into sub-processes and combines activity data with relevant environmental factors to assess the environmental impacts. With the superiority of exploring key drivers of impacts (Hellweg and Canals 2014), processed LCA has been widely used in the environmental analysis of individual apparel products as well as global or national clothing consumption. For example, Roos, Sandin et al. (2015) assessed the environmental impact of the T-shirt, a pair of jeans, a dress, a jacket, and a hospital uniform, and then scaled up to the environmental impact of Swedish fashion consumption in 2012. Quantis (2018) looked into the environmental impacts of the global apparel annual production throughout its entire value chain from raw material extraction to end-of-life processes. For 91.5% of clothing consumption in Australia came from import, Moazzem, Daver et al. (2018) assessed the greenhouse gases (GHGs) emissions of apparel in cotton, wool, and polyester fabrics which were scaled up based on the import quantity of clothing in the year 2015 in Australia for simplification. Developing countries support affluent consumer lifestyles in more economically developed countries with a high environmental price (Lenzen, Moran et al. 2012, Niinimäki, Peters et al. 2020). Browne, Rizet et al. (2005) and Steinberger, Friot et al. (2009) evaluated the environmental impacts of representative products (i.e. jeans, T-shirt, jacket made in Asia countries) and garment supply chain in Europe, explored the spatial pattern of pollutant emissions and illustrated the potential displacement of pollution in the globalized economy. Clarke-Sather and Cobb (2019) compared the environmental impacts of legging production in Sri Lanka and the United State and found that greater impacts occurred in Sri Lanka due to electricity generation differences. The limitation of LCA studies of international outsourcing lies in the assumption of the hypothetical case study which cannot trace back the textile production place and difficulties in accurately evaluating the embodied environmental flows in international trade.

Table 1. A summary of environmental issues of clothing consumption

Reference	Method	Databases	Aims
(Trust 2011)	IO	GTAP MRIO	international carbon flows of clothing in 2007
(Mair, Druckman et al. 2016)	IO	World Input Output Database	socioeconomic and environmental sustainability aspects of Western European textiles and clothing consumption between 1995 and 2009
(Andrew and Peters 2013)	MRIO	GTAP MRIO	the GHGs emissions and value-added of France, Norway and United Kingdom's clothing consumption in 2011
(Peters, Li et al. 2021)	MRIO	Eora database	the climate and water resources impact of clothing and footwear value chain
(Chapagain, Hoekstra et al. 2006)	Water footprint	CROPWAT model	the water footprint of worldwide cotton consumption in 1997-2001
(Moazzem, Daver et al. 2018)	LCA	Ecoinvent database and literature	the environmental impact of clothing consumption in Australia in 2015
(Roos, Sandin et al. 2015)	LCA	Ecoinvent database and literature	the environmental impact of Swedish fashion consumption in 2012
(Quantis 2018)	LCA	World Apparel Life Cycle Database and Ecoinvent database	the global apparel annual production’s impacts throughout its entire value chain in 2016
(Steinberger, Friot et al. 2009)	LCA	Ecoinvent database and literature	the spatial pattern of pollutant emissions and illustrate the potential displacement of pollution in a globalized economy
(Browne, Rizet et al. 2005)	LCA	Literature and research information	energy consumption in both the UK and French jeans supply chains
(Clarke-Sather and Cobb 2019)	LCA	Interviews with the business owners or public information	social, environmental and economic benefits and burdens of athleisure apparel products, from onshoring to the U.S. and offshoring to Sri Lanka to produce

The material balance approach based on product's environmental intensity factor and bilateral trade flow of commodities was developed within the ecological footprint framework (Kitzes, Galli et al. 2009) and has been successfully applied in evaluating product-level carbon and water footprint embodied in global trade (Hoekstra and Mekonnen 2012, Sato 2014), as well as water resources, groundwater depletion and unsustainable virtual water consumption embodied in international food trade (Dalin and Conway 2016, Dalin, Wada et al. 2017, Rosa, Chiarelli et al. 2019). Based on a combination of the product's environmental intensity factor and international trade matrix, the environmental impact embodied in trade from the life cycle phase of products can be explored. For the textile industry, Chapagain, Hoekstra et al. (2006) assessed the 'water footprint' of worldwide cotton consumption in 1997-2001 and found that about 84% of the water footprint of cotton consumption in the EU25 region is located outside Europe, with major impacts, particularly in India and Uzbekistan.

1.3 Aims

Denim is the fabric of jeans that is representative of fashion. The entire life cycle of one pair of jeans with 100% cotton (340g) produced 33.4 kg CO_2-e and consumed 3.781 m^3 water, and denim production accounts for more than 80% of the environmental impacts of the production of a pair of jeans (Co 2015, Karthik and Murugan 2017). Wasteful lifestyles bring a dramatic increase in global denim fabric production from 2.7 billion meters in 2006, and worldwide supply for denim will increase by 8% (Annapoorani 2017). North America, Western Europe, Japan, and Korea occupied 71% of the world's jeans consumption with 14% of the population (Newbery 2005). Jeans production for the developed world continues to outsource to low-cost countries, the developing countries in Asia produces around 50% of the world denim (a large proportion of it is produced in China and India and part of occurred in countries such as Bangladesh, Indonesia, Pakistan and Turkey) (Annapoorani 2017), aggravating resource and environmental flows from developed countries to developing countries.

Some researchers assessed the carbon and water footprints of individual denim products from life cycle stages (Chico, Aldaya et al. 2013, Co 2015, Karthik and Murugan 2017). For example, Vos (2019) assessed the spatially explicit water footprint throughout the life cycle of blue jeans and highlighted "hot spots" of negative impacts on water resources for a global apparel company. Few studies focused on environmental issues of international outsourcing denim production and virtual flows embodied in denim-product trade from the temporal and spatial dimensions. The origin of fibre production and material have great effects on the environmental footprint of related fibres (Chapagain, Hoekstra et al. 2006). In recent years considerable polyester fibres have been applied into denim to prompt lower-valued items, increasing the production of blends denim (Annapoorani 2017). The environmental impacts driven by the rapid growth of artificial fibers were not receiving enough attention.

To fill these research gaps, this study explored virtual carbon and water flows embodied in denim-product trade from their life cycle stages by combing environmental emission factors and international trade martix. Carbon and water footprint of denim-product production in major denim-manufacturing countries were respectively estimated by life-cycle assessment and water footprint assessment. The temporal changes of virtual flows of cotton denim and polyester blended denim were explored. The analysis framework can provide the basis for exploring environmental flows of product-level trade, and results can offer a basis for environmental policies and control strategies of the fashion industry, and as well as the sustainable production and consumption of garment.

The rest of the paper is structured as follows: Section 2 introduces the methods, research scope, and life cycle inventory of denim; Section 3 analyzes and discusses the results of spatially explicit carbon and water footprint in major denim-manufacturing regions as well as virtual carbon and water flows embodied in global denim trade by country/region; Section 4 makes suggestions for a more sustainable future for production and consumption of textiles and clothing; finally, Section 5 concludes the research and clarifies the limitations.

2 Methods

2.1 Embodied flow accounting framework

Based on the material balance approach, carbon and water flows embodied in the denim products are calculated by multiplying the bilateral trade flows of denim products by the emission factors of each denim product in the exporting country/region (Chapagain, Hoekstra et al. 2006, Hoekstra and Mekonnen 2012, Sato 2014):

$$EPET(r,s,c,n) = T(r,s,c,n) \times EPF(r,c) \quad (1)$$

EPET(r,s,c,n) shows the environmental flows matrix embodied in the trade from country/region *r* of denim product *c* in the year *n*. *EPF(r,c)* means the cradle-to-gate environmental emission factor of denim product *c* in exporting country/region *r*. *T(r,s,c,n)* is the trade flow matrix of denim product *c* from a country/region *r* to another country/region *s* in the year *n*, which is expressed in physical quantities.

The imported and exported volume (in tonnes) and countries/regions of origin of cotton denim and blends denim were reported (Harmonized Systems codes were presented in Table 2. Due to unequal export and import data, import data were recorded with greater accuracy for regulation purposes, which was applied for calculation (Qu, Li et al. 2018). For some countries/regions, some trade flows were not directly from the countries/regions of origin, but via the transit countries/regions (e.g. Hong Kong, China) (Finogenova, Dolganova et al. 2019). Imports reported by transit countries/regions include domestic use and subsequent re-exports. To avoid double-counting, by removing re-export from imports, the retained imports in transit countries/regions were applied to build the trade flow matrix of denim products.

Taking 2018 as an example, the virtual flows matrix of countries/regions embodied in the global denim trade in 2018 were quantified by multiplying the trade flow matrix of denim products in 2018 by the associated environmental emission factors for the exporting countries. The emission factors of different countries/regions were obtained from peer-review literature and Ecoinvent dataset (v3.5), which were assumed to be uniform within the research period due to the data availability. Global denim trade data (in ton) were mainly collected from the trade statistics database for international business development from the International Trade Centre (ITC 2020). When the physical denim trade data was reported as 1000 square meters (i.e., India in 2018), physical import denim trade data (in tonnes) from United Nations (UN) Comtrade Database (Comtrade) was used. If import data was deficient, the export data reported in UN Comtrade Database was used to fill data gaps.

Table 2. HS code and classification of denim products

Classification	HS Code	Description
Cotton denim	520942	Denim, containing >= 85% cotton by weight and weighing > 200 g/m², made of yarn of different colors
Blends denim	521142	Denim, containing predominantly, but < 85% cotton by weight, mixed principally or solely with man-made fibers and weighing > 200 g/m², made of yarn of different colors

2.2 Environmental emission factor of denim products

Due to the globalization and fragmentation of denim production, denim production occurs in different countries/regions, and the product-level country/region-special emission factor is applied for embodied flow accounting. The carbon emission factor of denim products embodied in trade in different levels (i.e., global, national, and regional) was quantified from the life cycle phases based on the life cycle assessment method, the GHG emissions are presented in 100-year global warming potential (GWP_{100})

(IPCC 2007). The consumptive water footprint (WF) was applied to estimate the water consumption embodied in denim-product trade, which measures the consumption of blue water and green water (Hoekstra 2017). The scope of this study includes the fibre production and fabric production of denim, covering the raw material extraction, processing, transportation, and manufacturing of denim (cradle-to-gate), and the loss during the production is included.

Most of the production of denim jeans around the world is 100% cotton, and the market for stretch denim is one of the fastest-growing segments of jeans manufacture (Paul 2015). Cotton blends that use polyester and lycra are becoming more popular. The ratio of polyester blend and spandex is less than 40% and 3%, respectively. Denim with 100% cotton fiber (cotton denim) and denim with 70:30 cotton/polyester blends (blends denim) are considered in this study. Polyester fiber production includes polyethylene terephthalate production, and melt spinning of polyester (PES) to fibers. The fabric production of cotton denim and blends denim is assumed to be consistent, and differences lie in fiber production. The functional unit is 1000 kg of cotton/blends denim, indicating that producing 1000 kg of cotton denim needs 1090 kg cotton fiber, and producing 1000 kg of blends denim need 763 cotton fiber and 327 kg polyester fiber.

The life cycle inventories for denim products were compiled from peer-review literature and the attributional dataset of Ecoinvent (v3.5). The electricity production mix is considered to reflect the difference in carbon emission factor among the countries/regions (Patouillard, Bulle et al. 2018) and the dataset “market group for electricity, low voltage” of different country/region from the Ecoinvent database was used. The virtual flows of 21 countries/regions contributing 70% of global denim-product trade volume were quantified at the national/regional level, and that of the rest accounting for 30% of was estimated at the global level (See Table S1 for details).

The cotton fibre production covers raw material production from the field through ginning and fertilizer, inputs of pesticide, chemical, energy, and water and carbon emissions were included, which was sourced from the “market for cotton fibre” dataset in the global level, Ecoinvent (V3.5) (2018). For polyester fiber production, the polyester chips are produced through polycondensation of terephthalic acid (TPA) with ethylene glycol (Aizenshtein 2009, Kuczenski and Geyer 2010). TPA is a xylene derivative, which is produced from petroleum naphtha, and ethylene glycol is made from the oxidation of ethylene, which is a petroleum feedstock. The dried polyester polymer is transported to extruders where it is melted and pumped to spinning packs held in a spin manifold (Roos, Sandin et al. 2015). The global (GLO) dataset “market for polyethylene terephthalate, granulate, amorphous” from the Ecoinvent database was used for polyester polymer production (Sutter 2007). Inventories of melt spinning of polyester (PES) to fibers came from Roos, Sandin et al. (2015). In fabric production, textile fibers are spun into yarn, through preparation, dyeing, and finishing then weaved into the fabric. Different processes (e.g., opening, carding, combing, drawing, roving, spinning, and winding) are carried out using cotton and other fibers to form a yarn, the chemical, electricity, heat, and water input and carbon emissions from the processes are included. The carbon footprint of fabric production was sourced from "textile production, woven cotton (GLO)" of Ecoinvent (2018). The life cycle phase and data source of denim production are listed in Table 3.

Green water is precipitation and soil moisture consumed, which is particularly relevant in crop production. Blue water refers to the consumption of any surface and groundwater, and in the case of agricultural production particularly, irrigation water (Hoekstra, Chapagain et al. 2011). During the denim production, the cotton fiber production consumes green and blue water, the fabric production and polyester fiber production consume blue water. In the Ecoinvent database, the water flows in the agricultural processes of natural water supply from soil and precipitation, and green water is considered to happen outside the product system (Pfister 2015), which is not suitable for consumptive water footprint assessment. The WF of cotton fiber production (Chapagain, Hoekstra et al. 2006) was applied and the water footprint of worldwide cotton consumption in spatial detail levels was assessed by the CROPWAT model. The blue WF of fabric production covering the process of bleaching, dyeing, printing, and finishing was sourced from USEPA (1996). The blue WF of polyester fiber production was estimated by the "Water, river" database in Ecoinvent (2018).

Table 3. Life cycle phase and data source of footprint intensity in the denim production

Life cycle phase	Indicator	
	Carbon footprint	Water footprint
Cotton fibre production	market for cotton fibre – GLO, Ecoinvent (V3.5)	Chapagain, Hoekstra et al. (2006)
Polyethylene terephthalate production	market for polyethylene terephthalate, granulate, amorphous – GLO	the same as the source of carbon footprint
Melt spinning of PES to fibers	market for lubricating oil - RoW	
	market for manganese - GLO	
	market for cobalt - GLO	

	market for antimony - GLO	
	market for phosphoric acid, industrial grade, without water, in 85% solution state - GLO	
	market group for electricity, low voltage - GLO	
Fabric production	textile production, woven cotton - GLO	USEPA (1996)

3 Results analysis

3.1 Virtual carbon and water embodied in global denim trade

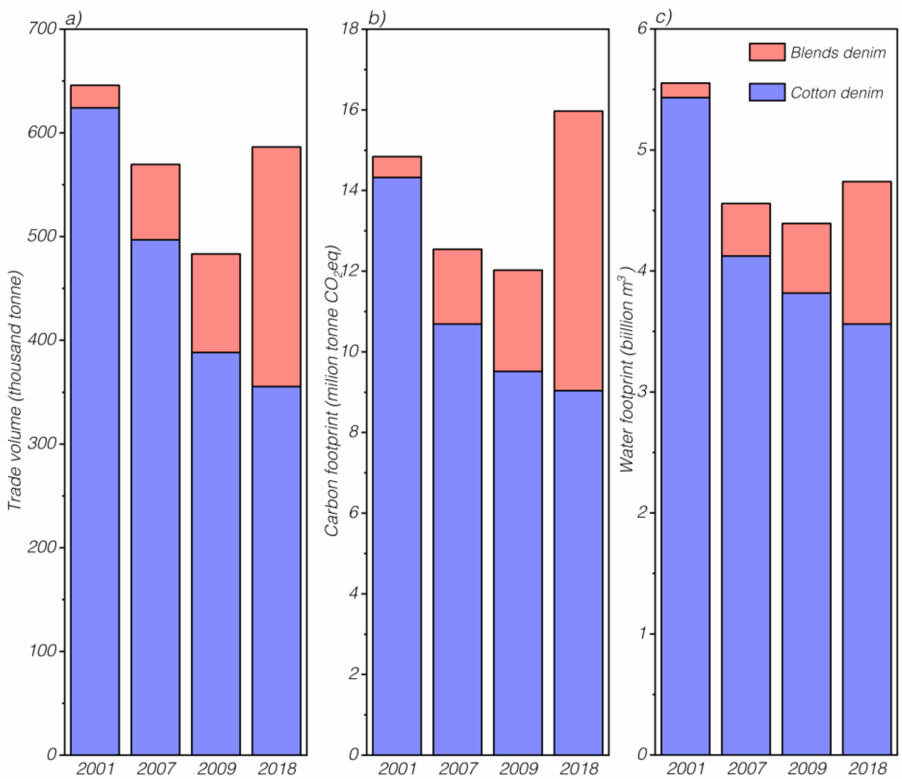

Figure 1 Total carbon and water embodied in global denim trade.

The international denim trade increased from 3.01 billion US$ to 3.98 billion US$ over the period 2001-2018, and the trade volume has declined from 646 thousand to 586 thousand tonnes (kt) in 2018. China has played an important role in the textile and clothing global value chains (GVCs) since the accession of China to the WTO in 2001. The global financial crisis in 2008 has a great influence on CO_2 emissions embodied in China's domestic and foreign trade (Mi, Meng et al. 2017). Thus, 2001, 2007, 2009, and 2018 are selected to analyze the temporal changes of carbon and consumptive water embodied in the denim trade. Cotton denim showed a steady decrease, and its trade volume dropped from 624 kt in 2001 to 355 kt in 2018. Due to low production cost and high elasticity, the trade volume of polyester blended denim increased obviously from 21.7 kt in 2001 to 231.0 kt in 2018, with an annual rate of 14.9%. Carbon emissions and water consumption embodied in the global denim trade are estimated based on a combination of footprint intensity at the country/region-level with international denim trade data. As shown in Figure 1b), the global denim-product trade caused 14.8 million tonnes (Mt) equivalent of carbon dioxide (CO_2e) in 2001, and increase to 16.0 Mt CO_2e in 2018, while the water consumption dropped from 5.6 to 4.7 billion m^3. The contribution of blends denim in total carbon emission increased from 4% in 2001 to 43% in 2018. Replacing cotton denim with polyester blended denim would face more pressures on carbon emission reduction.

3.2 Carbon and water footprints of denim products at the national/regional level

As shown in Figure 2a), at the global average, producing per tonne cotton denim (in the blue bar) caused 23.2 tonnes CO_2e, while 85% of carbon mainly comes from fabric production (19.6 tonnes CO_2e). This is attributed to the fact that forming a yarn from cotton fibers in the spinning process consumes a large amount of energy, the wet processing consumes much steam (Muthu 2015). Comparing with cotton denim blends denim production caused more than 5% GHG emissions (24.4 tonnes CO_2e). Blends denim partly consists of polyester fibers originated from petroleum, and the production of the synthetic fiber requires an enormous amount of energy, causing a higher carbon footprint than cotton denim. Cotton fiber production, polyester fiber production, and fabric production contribute respectively 2.5, 2.3, and 19.6 tonnes of carbon footprint in blends denim production. The water footprint (WF) of cotton denim is 9870 m^3/ton (5120 m^3/ton for blue WF and 4648 m^3/ton for green WF). Cotton fibre production contributes to the largest water footprint (95%), and fabric production only required 496 m^3 blue WF per tonne denim products (USEPA 1996). The water footprint of blends denim (3738 m^3/ton blue WF and 3253 m^3/ton green WF) was 72% lower than that of cotton denim due to a negligible amount of water consumption of polyester fiber (15.2 m^3/ton fiber).

Electricity consumption was the major source of carbon emissions in denim production (71% of the total amount). The total electricity consumption was 17.6 MWh per tonne cotton denim and 18.5 MWh for blends denim. Electricity is selected as the localization factor to reflect the national/regional-level carbon footprint to decrease the uncertainty (Steinberger, Friot et al. 2009, Patouillard, Bulle et al. 2018). We apply carbon emission factors under the national/regional electricity production mix to evaluate the denim-product carbon footprint of main denim export countries/regions (as presented in Figure 1a)). India has the largest carbon footprint among the exported countries/regions (41.3 kg CO_2e), 1.8 times higher than the global level, followed by China (29.3 kg CO_2e). The coal-dominated electricity generation structure of these countries increases the carbon footprint embodied in denim products. Denim production in Colombia and Brazil has the lowest carbon emission intensity attributed to the hydropower-based electricity mix. It is essential for accelerating energy transition for the cotton supply base to decrease the denim carbon footprint.

The water footprint of denim products highly depends on the climate condition of cotton production and irrigation pattern of the production area, leading to large variations in countries/regions. As shown in Figure 2b), the cotton production in China, the USA, and EU-15 is less water-intensive, and that in India, Turkmenistan, and Pakistan are the most water-intensive. The climatic condition with low evaporative demand (500–600 mm) is optimum for cotton production in the USA and Brazil. Due to cotton production without artificial irrigation, the USA and Brazil have less blue water footprint per tonne denim product. Turkmenistan has the largest blue water footprint of cotton production, followed by Egypt, Pakistan, Turkey, and India. Egypt, Turkmenistan, and Turkey with high evaporative demand (1000–1300 mm) and limited effective rainfall (0–100 mm) have to fill the shortage of rain by full irrigation. India takes a particular position with high evaporative demand (800–1000 mm), low effective rainfall (400 mm), depending on partial irrigation (between a quarter and a third of the harvesting area) (Chapagain, Hoekstra et al. 2006). Due to low-density planting and low yields, India contributes the largest water footprint. The carbon and water footprint hotspots were centered in India (Figures 2b) and 2d)), priority should be given to reduce environmental footprints of denim production in India.

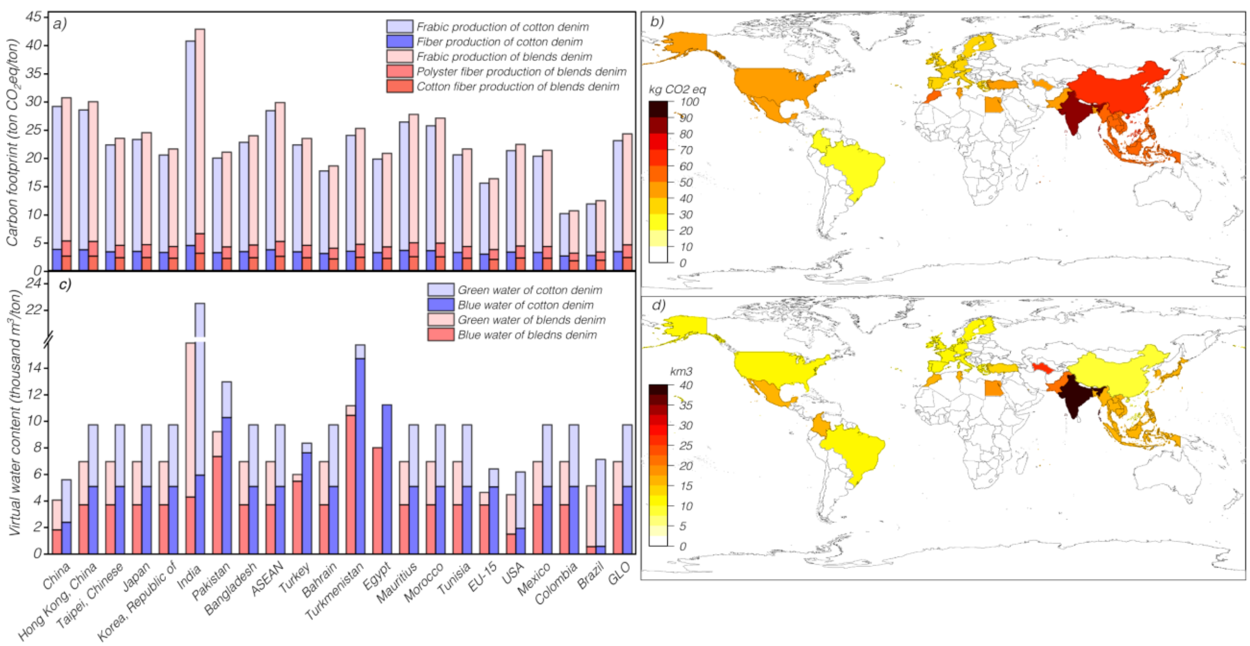

Figure 2 Carbon and water footprints for denim products in different fabrics and spatial distribution.

ASEAN denotes Association of South-East Asian Nations Aggregation, EU 15 means European Union Aggregation.

3.3 Virtual carbon and water flows embodied in global denim trade by country/region

Figure 3 presents carbon flows embodied in denim products for key countries/regions. For Hong Kong plays significant roles in the global trade, India, Pakistan, and Bangladesh maintain strength textile and clothing exports, environmental impacts embodied in international trade of these countries/regions are presented separately (Tahir and Mughal 2012, Lee, Wang et al. 2018, Meng, Mi et al. 2018, Qu, Li et al. 2018), and the rest (i.e. Turkmenistan, Turkey, Egypt, Bahrain, etc.) are merged into other developing countries. Carbon flows embodied in denim products are increasing from 14.8 Mt CO_2e in 2001 to 16.0 Mt CO_2e 2018, while carbon flows in blends denim are growing dramatically with an annual rate of 16.5%. As the largest cotton and polyester producer in the world, China plays a dominant role in the global denim trade. China is one of the largest carbon exporters in the past two decades, and embodied carbon in denim-product export increases from 2.1 Mt CO_2e (14% of total carbon flows) in 2001 to 8.8 Mt CO_2e (55%) in 2018, while embodied carbon in blends denim export comes to 83% in total carbon flows of blends denim in 2018. The USA and EU-15 are the first (2.71 Mt) and third (1.87 Mt) carbon exporter of cotton denim in 2001, contributing 32% of the total virtual carbon exports in the global cotton denim trade. The cotton production and associated carbon flow are relocating from the USA, EU-15 to India, and Pakistan in the past two decades. From 2001 to 2018, the exported carbon of the USA and EU-15 drop rapidly by 14% and 10% respectively, and India and Pakistan become the second (16%, 1.44 Mt) and third (14%, 1.27 Mt) virtual carbon exporter of cotton denim in 2018. Bangladesh and Southeast Asia Nations become the main virtual carbon importer of denim products in the same year, occupying 27% and 18% of total embodied carbon flows, respectively. China, South Asian Nation, and Southeast Asian Nation are the trading centers of the global virtual carbon flow of denim. Denim made by China and India is transported to Bangladesh and Southeast Asia Nations to conduct sewing and make jeans which are the carbon exporters of jeans.

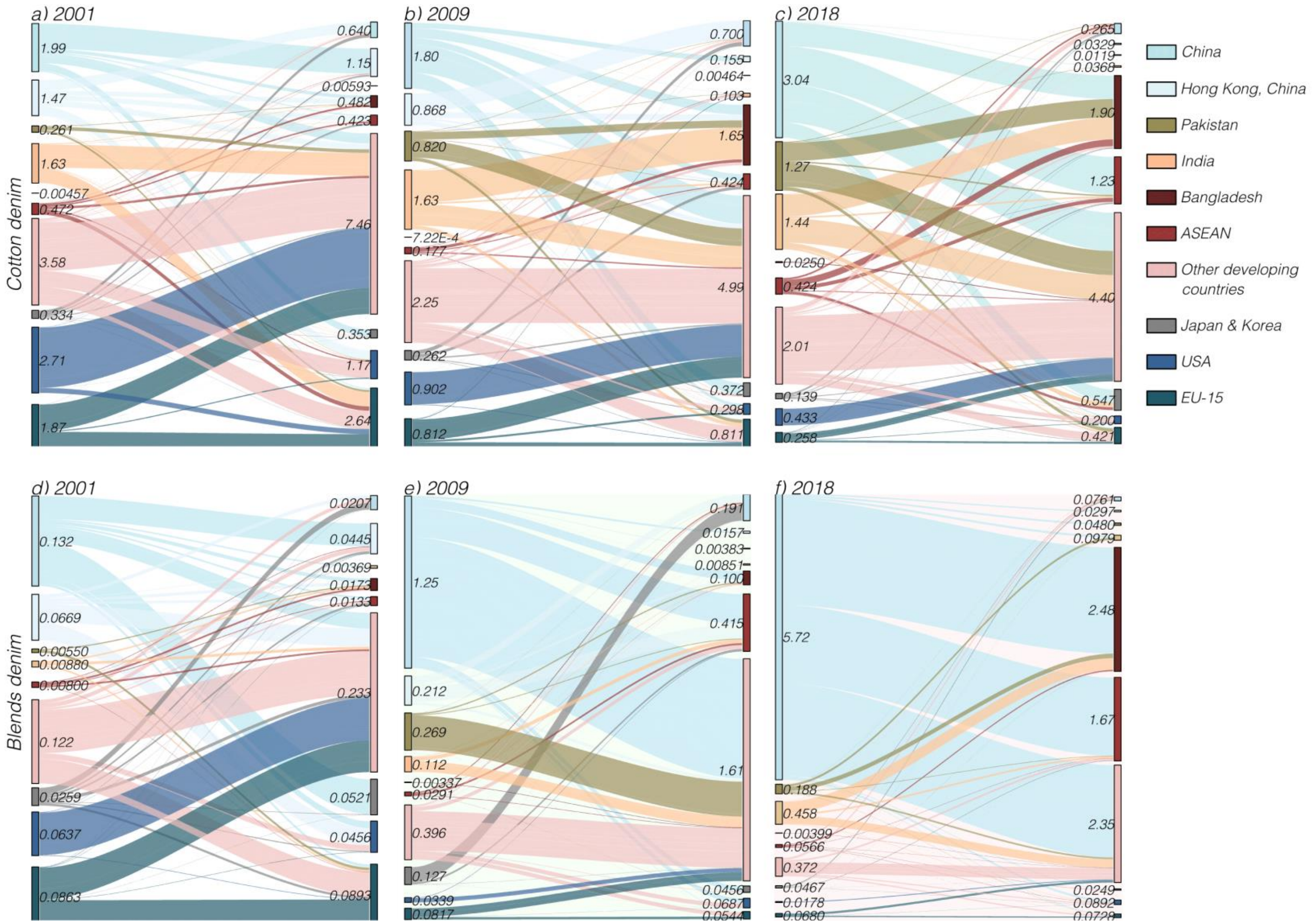

Figure 3 Embodied carbon flows in denim trade by country/region (Mt CO_2e).

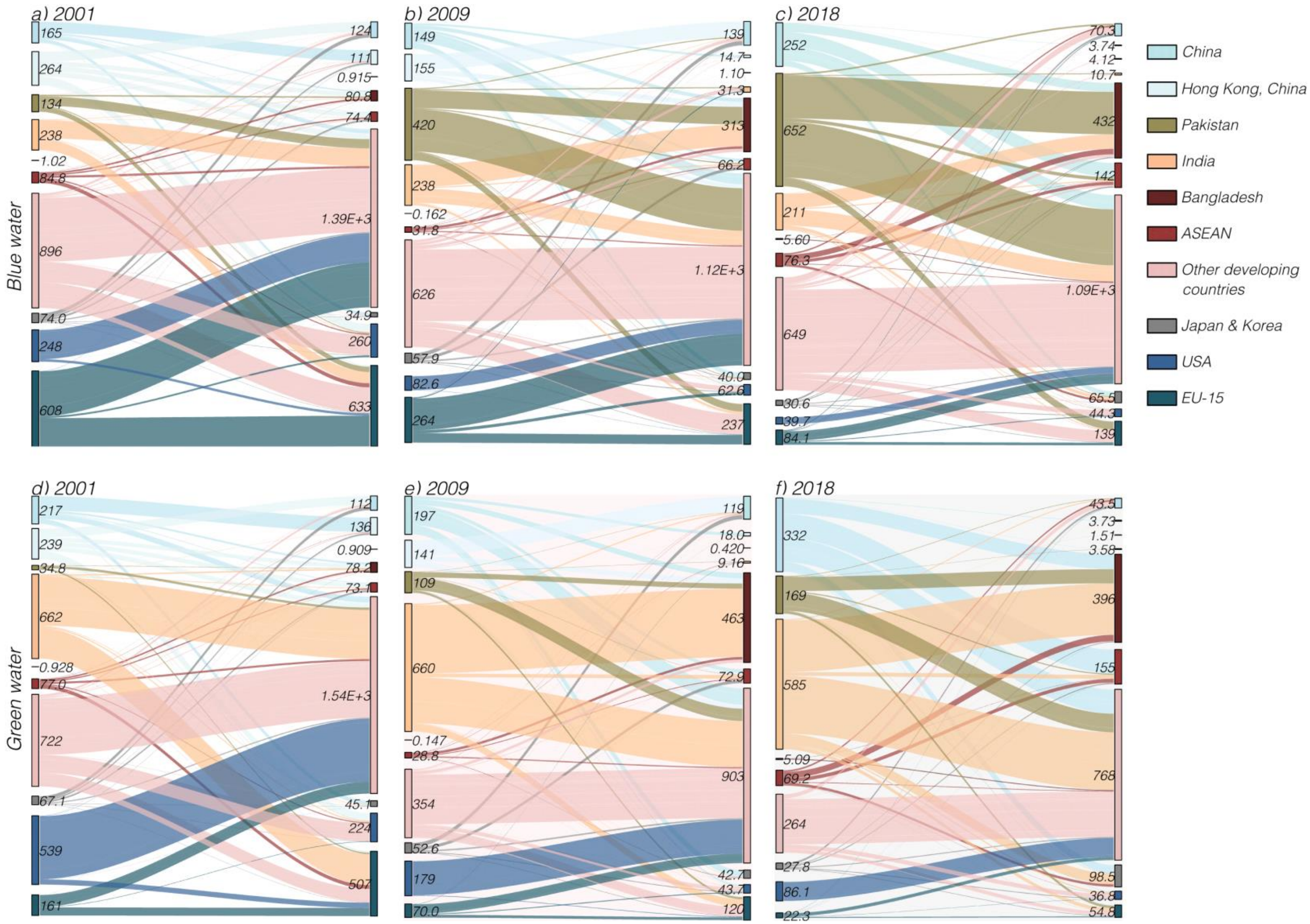

Figure 4 Virtual water flows in cotton denim trade by country/region (M m^3).

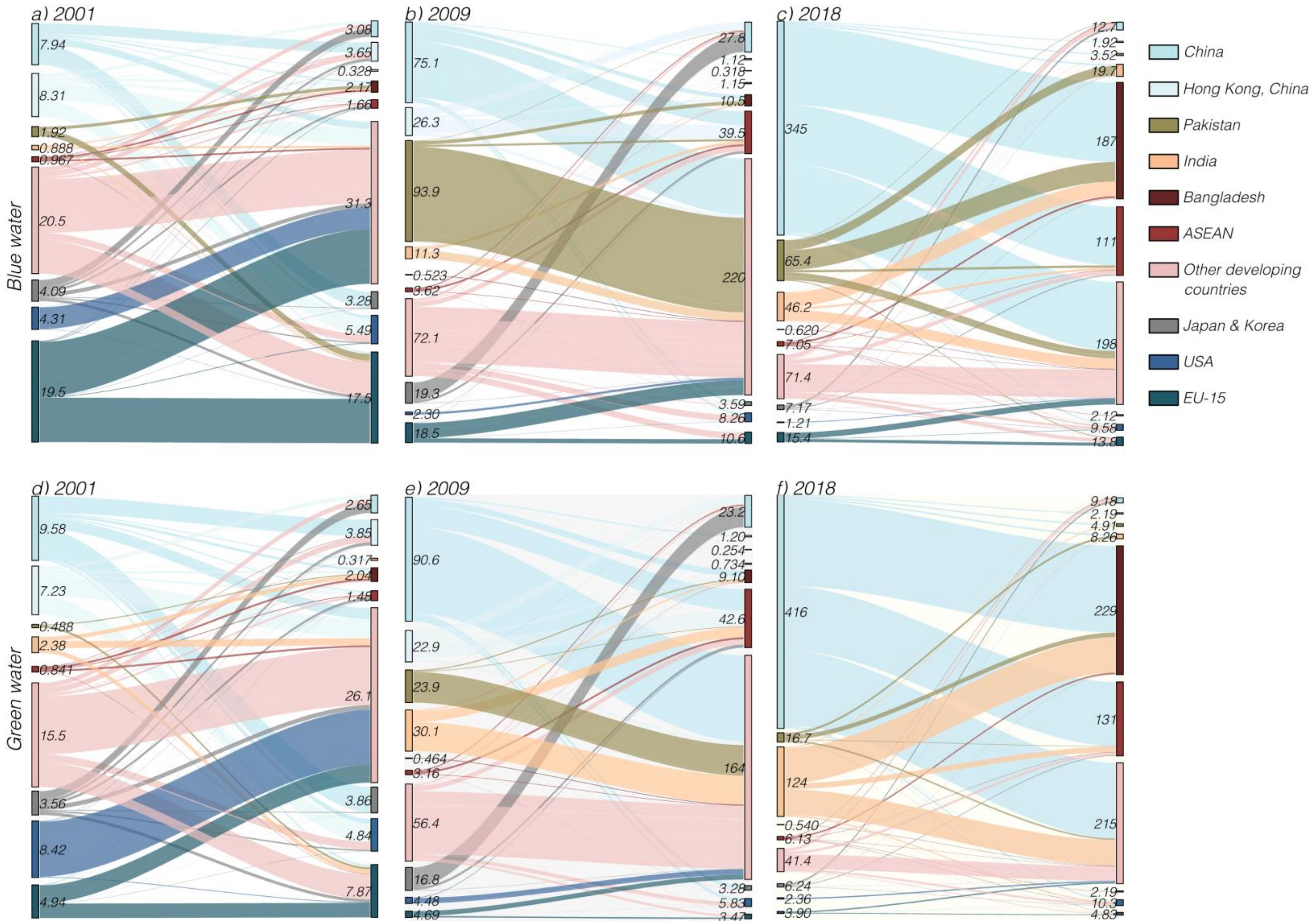

Figure 5 Virtual water flows in blends denim trade by country/region (Mm³).

The virtual blue water flows in denim products (Figures 4 and 5) are decreasing from 2781 million m^3 (Mm^3) in 2001 to 2559 Mm^3 in 2018, and the green water flows are decreasing from 2766 Mm^3 in 2001 to 2179 Mm^3 in 2018. EU-15, USA, Japan, and Korea contributed 34% of blue water flows and 28% of green water flows in cotton denim exports in 2001. Similar to the embodied carbon flows, consumptive water embodied in denim export of these countries/regions experienced an obvious decrease in 2018, only occupying 7.7% of blue water flows and 8.7% of green water flows in cotton denim. China has the highest consumptive water embodied in blends denim export in 2018 (45% from the blue water and 55% from green water). Since the water footprint per tonne of denim products in China, EU-15 and the United States is significantly lower than the global average, the percentage of water embodied in exports in denim products from these countries/regions is lower than that of their trade volume in exports. In 2018, the trade volume in exports of cotton denim in Pakistan is less than one-half in China, and that in India is less than one third, Pakistan and India with high water footprint intensity are the second and third exporters of cotton denim. China is the largest water embodied exporter (1345 Mm^3), followed by India (966 Mm^3) and Pakistan (903 Mm^3), while Pakistan contributes the largest blue water exporter of cotton denim (652 Mm^3, 33% of total blue water flows) which is 2.6 times higher time that of China (252 Mm^3). Similar to embodied carbon flows, the cotton production activities and virtual water flows are relocating from EU-15 and the USA to developing countries/regions. India is the largest green water exporter in the cotton denim trade (585 Mm^3), accounting for 37% of total green water flows. Reallocating cotton production base to countries with high green water footprint could reduce the blue water consumption of cotton cultivation and bring considerable water-saving benefits.

To reflect the virtual flows embodied in denim trade and human well-being of outsourcing countries/regions, the human development index (HDI) is applied to categorized countries/regions into four groups based on different human development levels. Figure 6 shows that developed countries with very high HDI withdraw the denim supply chain and developing countries with lower HDI undertake main global denim and jean manufacturing. For example, as the main carbon exporters of denim in 2001 and the largest jean consumers, the USA, EU-15, and Japan with very high HDI gradually withdraw the denim manufacturing supply chain. China with high HDI, India, and Pakistan with medium HDI undertake main global denim production, which is the three largest net carbon exporters. Bangladesh with medium HDI and the Southeast Asian Nations are net embodied carbon importers of denim products, undertaking jeans sewing tasks. Most of the Southeast Asian Nations entered the high human development level in the past two decades, while Cambodia and Vietnam contributing 78% of denim import in Southeast Asian Nations have medium human development. These countries/regions consume local natural resources but outsource the economic benefits to developed countries, facing increasing climate-related risks and water crises (David Eckstein 2019). Countries/regions with very high HDI should offer financial support and technical assistance to help medium and low human development countries/regions address challenges and mitigating environmental inequalities.

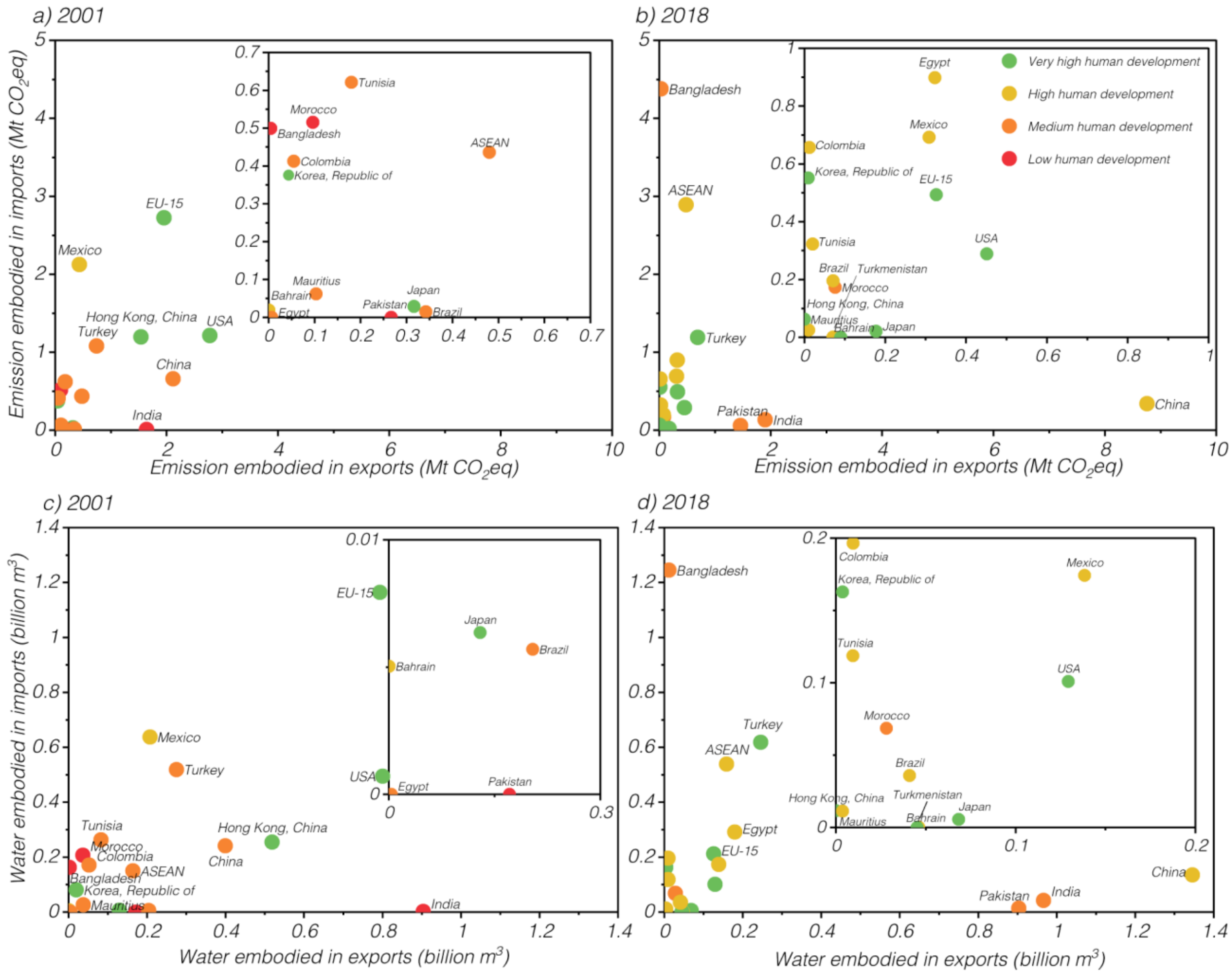

Figure 6 Carbon emission and water embodied in denim trade and human development level of trading country/region.

4 Discussions

4.1 Sensitivity analysis

With the characteristic of cheap price, wrinkle-free, and stretchability of polyester, consumption of polyester jeans has increased in the past two decades. A.P. Periyasamy (2017) highlighted the challenges of water-carbon conflicts in expanding the use of artificial fibers in blends denim. Taking 70:30 cotton/polyester blends as an example, the production of polyester fibre consumes a high level of energy, resulting in 53% GHG emissions than the production of cotton fibre. The water footprint of polyester fiber production (15.2 m^3/ton) is much less than that of cotton fiber production (8506 m^3/ton). To reflect the water-carbon linkage, we conducted the sensitivity analysis of polyester fiber content of denim and indicate that each additional 10% polyester fiber in denim reduces 9% water footprint, but increases 2% carbon footprint. With the increasing dual pressures of water scarcity and climate change, the fashion industry should pay more attention to both water conservation and carbon mitigation benefits.

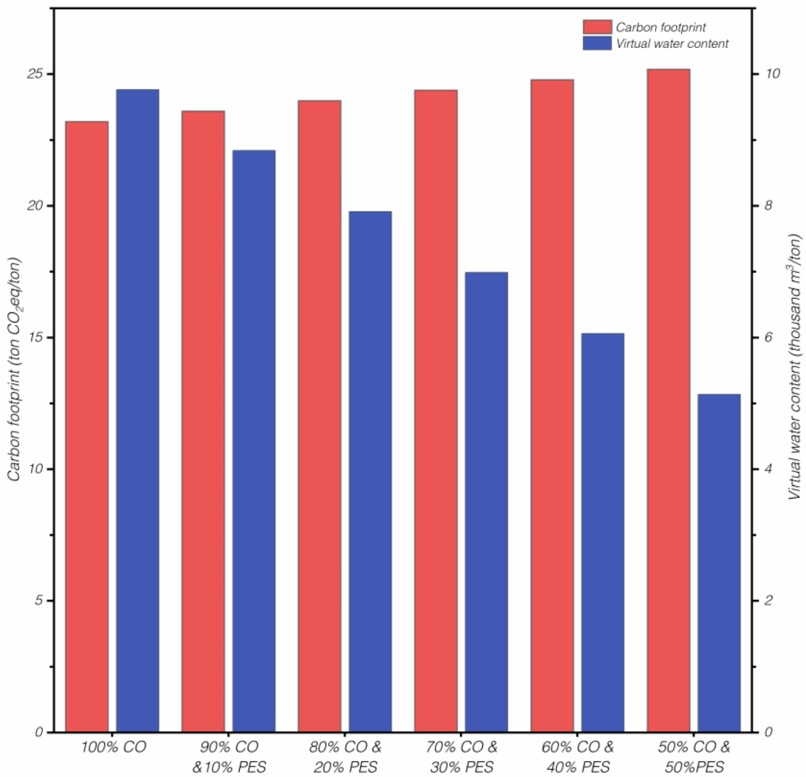

Figure 7 Sensitivity analysis of polyester fiber content of denim on carbon and water footprints.

4.2 Policy implications

4.2.1 Cleaner production

The production facilities in developing countries are out of date and the production technology would affect the environmental footprint of textile products (Karthik and Murugan 2017). The developing countries should abide by their environmental laws and regulations stringently to implement cleaner production and developed countries should shoulder the responsibility of providing technical support to reduce the carbon and water footprint of textiles achieving global cleaner production.

China is one of the largest carbon exporters in the past two decades, and embodied carbon in denim-product export increases from 2.1 Mt CO_2e (14% of total carbon flows) in 2001 to 8.8 Mt CO_2e (55%) in 2018. The cotton production and associated carbon flow are relocating from the USA, EU-15 to India, and Pakistan in the past two decades. From 2001 to 2018, the exported carbon of the USA and EU-15 drop rapidly by 14% and 10% respectively, and India and Pakistan become the second (16%, 1.44 Mt) and third (14%, 1.27 Mt) virtual carbon exporter of cotton denim in 2018. India has the largest carbon footprint among the exported countries (41.3 kg CO_2e), 1.8 times higher than the global level, followed by China (29.3 kg CO_2e). The coal-dominated electricity generation structure increases the carbon footprint embodied in denim products. More attention needs to be paid to carbon emission reduction in the textile and clothing industry in the future, especially in countries/regions with large polyester production and export (i.e., China). The effective and efficient production and transition to renewable energy systems are feasible solutions for tackling the challenges of climate change for the fashion industry ((EMF) 2017).

Cotton is the largest contributor to unsustainable irrigation water consumption (UWC) embodied in international crop trade, accounting for 33% (Rosa, Chiarelli et al. 2019). Some regions with high water-stress cultivation, including China, Pakistan, India, and Turkey, have high requirements for cotton irrigation (Gassert, Reig et al. 2013), aggravating the local water shortage. In China, 80-90% of the fabric, yarn, and plastic-based fibres are produced in water-scarce or water-stressed regions (Maxwell 2015). Increasing green water productivity in rain-fed agriculture in wet regions (i.e. Brazil) is one of the global solutions to the overexploitation of blue resources in water-scarce catchments (Arjen Y. Hoekstra 2013). For less developed countries with water scarcity, developed countries should provide technical assistance to change the traditional irrigation regime in cotton production. India with low planting density and yield leads to the high consumptive water use of cotton yield output per unit, and the furrow irrigation could be changed to trickle irrigation to promote efficient water use and ease the water pressure. Global South Cooperation should be fostered for sharing successful experiences (i.e., cotton growing and processing technology), increasing water productivity (i.e., planting mode and irrigation technique), and saving production cost (i.e., seeds, fertilizer, textile technology).

4.2.2 Responsible consumption

Responsible consumption requires global action. Europe and the United States are the largest jean consumers while emerging economies such as China and India witnessed a steady rise in demand (Periyasamy and Militky 2017). It has been forecasted that if 80% of the population of emerging markets were to achieve Western per capita clothing-consumption levels by 2025, and the CO_2 emissions and water use of the apparel industry will increase 77% and 20% respectively from 2015 to 2025 (Remy, Speelman et al. 2016). People should change their consumption patterns and abandon wasteful lifestyles, especially people in developed countries. Developing countries should avoid leapfrogging to post-industrial consumption patterns and lifestyles due to "advantages of backwardness". Priority should be given to increasing the practical service life of garments (Zamani, Sandin et al. 2017). Fashion businesses require to construct new business models such as renting, swapping, repairing, reselling, redesign and upcycling, all of which enable longer garment lifetimes and proposing a sustainable lifestyle for consumers (Armstrong, Niinimaki et al. 2015, Niinimäki, Peters et al. 2020).

5 Conclusions

Since jean is the representative of fashion, in this study denim was taken as an example and the virtual carbon emissions and water consumptions embodied in denim-product global trade were evaluated from life cycle stages. The temporal changes of embodied carbon and consumptive water flow of cotton denim and polyester blended denim were explored. Results indicate that from 2001 to 2018, virtual carbon embodied in the global denim-product trade increased obviously from 14.8 to 16.0 Mt CO_2e, and the virtual water consumption dropped from 5.6 to 4.7 billion m^3. The fabric production of denim contributes most of the carbon emissions (85%), and the blended denim contributes a dramatic increase in embodied carbon emissions (from 4% in 2001 to 43% in 2018). Increasing the utilization of polyester blended denim can save water but face more pressures on carbon emission reduction. More attention needs to be paid to carbon emission reduction, especially in countries/regions with large polyester production and export (i.e., China).

The virtual carbon and water flows embodied in the global denim trade are relocating, main jean consumers (i.e., the USA, EU-15, and Japan) withdraw the denim manufacturing supply chain and developing countries (i.e., China, India, and Pakistan) with higher carbon and water footprint undertake main global denim production, leading to the increasing embodied carbon export from developing countries (from 66% in 2001 to 94% in 2018). The effective and efficient production and transition to renewable energy systems and reducing the carbon emission intensity of denim production in the developing countries are vital for carbon emissions reduction of the global fashion industry. As cotton cultivation is water-intensive, the global denim trade aggravates the water crisis in the cotton production base (i.e., China, Pakistan, and India). Increasing water productively (especially green water), changing the traditional irrigation regime, and developing water-saving irrigation technologies are potential solutions for the water sustainability of the fashion industry. With increasing South-South trade, enhancing global South cooperation helps share successful experiences (i.e., technology and lifestyle), save production cost, and lessen resource consumption and environmental emissions. People both in developed and developing countries should change their consumption patterns and abandon wasteful lifestyles to enable longer garment lifetimes. The production and consumption of denim should be shifted to circular and sustainable ways and new business models are required, such as renting, swapping, repairing, reselling, redesign and upcycling.

There are uncertainties and limitations in this study. We made assumptions to simplify the material, composition of denim. Technical improvement and climatic conditions may lead to interannual variations in carbon and water footprint, emission factor is assumed to be uniform within the research period owing to data limitation. The use and disposal of denim are excluded. All inputs in denim production are assumed to be sourced domestically. In some cases, the production of intermediate inputs (i.e., cotton, yarn, and chemicals) may not occur in denim export countries/regions (e.g., Japan). In the future work, the multi-region input-output anaylsis tracking the trade flows would be incorporated to fill this gap by recording economic transactions within each nation and among nations at the sector level.

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Appendix. Supplementary tables

Table S1 Countries/regions of global denim trade.

Table S2 GHG emissions of cotton and blends denim by life cycle process among differenct countries/regions

Table S3 Comsuptive water of cotton and blends denim among different countries/regions

Table S4 The trade volume flows of cotton denim

Table S5 The trade volume flows of blends denim

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