The Journal of The Textile Institute

ISSN: 0040-5000 (Print) 1754-2340 (Online) Journal homepage: www.tandfonline.com/journals/tjti20

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THE JOURNAL OF THE TEXTILE INSTITUTE, 2018
VOL. 109, NO. 12, 1574–1585
https://doi.org/10.1080/00405000.2018.1434113

Assessing environmental impact of textile supply chain using life cycle assessment methodology

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ABSTRACT
The environmental impact of textile supply chain of selected cotton, wool and polyester apparels consumed in Australia was accessed in this study using life cycle assessment methodology. The environmental impact category, climate change was used for this assessment. Climate change is related to the emissions of greenhouse gases to the atmosphere and the reference unit of climate change impact category is kg CO_2 equivalent. The environmental impact of these apparels was then scaled up based on their total consumption in Australia in 2015. The results highlight the differences in environmental impact between the three apparels. This study demonstrates that the main contributor to climate change is the consumer use stage for cotton and polyester apparel whereas wool apparel production process contributes more impact than consumer use stage. Energy use is the main factor of environmental impact. Sensitivity analysis was carried out based on the different parameters used to develop baseline model, such as change of transport from airfreight to sea freight; change of transport distance, change of consumer laundering behaviour. Around 10% CO_2 equivalent emission can be reduced from base case by reducing washing machine energy up to 40%. A high efficient washing machine and full load machine wash can save energy and reduce carbon emission.

ARTICLE HISTORY
Received 23 July 2017
Accepted 25 January 2018

KEYWORDS
Sustainability; greenhouse gas emission; life cycle assessment; garment care behaviour

Introduction

Every manufactured product starts its life cycle from raw material extraction and processing, then it passes through product manufacturing, distribution and use and finally, the cycle ends up with a disposal process. All of the stages of the life cycle of manufactured products have a range of environmental impact variety. Textiles are one of the most important consumable products and the environmental impact from textile products is very significant due to the wide range of use such as fashion, apparel, industrial textiles, geotextiles, agro textiles and hygienic textiles (Muthu, 2014). The textile supply chain is very complex and cannot be expressed within a single sector as it is highly global and decentralised (Muthu, 2014). Therefore, understanding the environmental sustainability is vital in the textile and clothing supply chain.

According to the North American magazine, Textile World, North Americans are the largest consumer of new textile products and Australians are the second largest consumer of new textile products based on average use per person (Carmichael, 2016). Each Australian buys an average of 27 kg new textile products annually and after a certain time they donate or dispose of 23 kg of the textile product through charity organisations or other disposal options. Each North American consumer buys 37 kg and each Western European consumer buys 22 kg textile products annually (Carmichael, 2016). The main apparel origin countries for Australia are China, Bangladesh, India, Cambodia, Vietnam and Indonesia according to the import volume (United Nations Department of Economic and Social Affairs, 2015). All apparel clothing items imported to Australia are under two harmonised tariff classification 61 (knitted apparel) and 62 (woven apparel). In this study, three apparels produced by three mostly consumed fibres, cotton, polyester and wool were modelled using life cycle assessment (LCA) methodology and the results of this model were scaled up based on the current scenario of the consumption of these three fibres in Australia. Clothing trade data of the year 2015 was used to estimate the quantity of these apparels. Clothing trade data for the year 2015 was collected from UN Comrade Database (United Nations Department of Economic and Social Affairs, 2015). This study aims to build a LCA model of the three apparels to identify the potential impact reduction scenario from clothing consumption. This was done by developing a model of supply chain of these apparels from raw material extraction to end of life stage in Australia.

LCA methodological phases

Life cycle assessment is a technique to identify the potential environmental impact of any product or process using a systematic set of procedures. Specific procedures and standards are followed

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to assess the environmental impact of a product or process. LCA consists of four steps according to the standard ISO14040:2006, Step (1) – goal and scope definition, Step (2) – life cycle inventory (LCI) analysis, Step (3) – life cycle impact assessment (LCIA) and Step (4) – life cycle interpretation, as shown in Figure 1 (International Organization for Standardization, 2006).

The purposes of the LCA study are defined during goal and scope definition. Another part of goal and scope definition is defining the functional unit and system boundaries. The first part of the inventory analysis is defining process flow chart based on the goal and scope definition. The functional unit is the reference flow materials in the flow chart. In this stage, appropriate data related to the process such as input materials, energy, water, output materials, emissions and waste are collected from the reliable sources. Life cycle impact analysis is followed by the inventory analysis. In the impact assessment stage, the data and information collected during the inventory analysis are processed to measure the contribution of different environmental impact. In the life cycle interpretation step the results are reviewed and identified the significant issues based on the result of LCI and LCIA phases (International Organization for Standardization, 2006).

Goal of the LCA study

The goal of current LCA study is to provide the environmental impact of climate change of three apparels consumed in Australia. This was performed by the LCA assessment of the baseline scenario of selected apparels, cotton knit shirt, polyester knit shirt and wool sweater. The functional unit of this study was 'use of one kilogram selected apparel over the life time'. Then the results of the functional unit were scaled up based on total consumption of these three apparels in Australia in 2015. This study allows us to understand the environmental significance of different stages of life cycle of different apparels and to identify the potential impact reduction scenario, such as increasing lifetime of clothing, improving consumer laundering behaviour, implementing recycling and selecting fibre type.

Sensitivity analysis was performed based on the different parameters used in this study. This LCA study was based on full life cycle of selected apparels. Therefore, the system boundary was considered from cradle to grave. Generally, the life cycle of a clothing product can be divided into four different stages; production, transport and distribution, use and disposal as shown in Table 1.

Allocation

Some of the manufacturing processes produce co-products along with the main products. In this case, it is required to allocate the environmental burden to the products and co-products. Allocation can be done by economic allocation, mass allocation or by system expansion. Most of the processes within the textile supply chain produce a single product, though some of the processes produce co-products, such as lanolin from wool scouring. Lanolin has a market value to produce other products. In this case, we considered mass allocation to allocate the impacts to the product and co-product from the processes. The recovery amount of lanolin from raw wool is typically less than 10%; hence, mass allocation was made based on the recovery amount (Henry et al., 2015; International Wool Textile Organisation, 2016).

Impact assessment method and LCA Software

Open LCA (software developed by GreenDelta in 2006) and the CML-baseline impact assessment method developed by the University of Leiden in the Netherlands in 2001 were used for the developing the inventory and assessing environmental impact, respectively. Impact categories included in the CML baseline method are acidification, climate change, depletion of abiotic resources, eco toxicity, eutrophication, global warming potential, human toxicity, ozone layer depletion and photochemical oxidation (Acero, Rodríguez, & Ciroth, 2015). In this assessment, we considered impact category climate change.

Life cycle inventory

Inventory data of textile chain is required to build the life cycle model. There are some studies available that provide textile general processing data (energy, water and resources). Some studies reported some data but it is difficult to identify what is included and excluded in the process data, and some studies reported data for a specific process with a wide range. Life cycle inventory data is divided into two categories foreground data and background

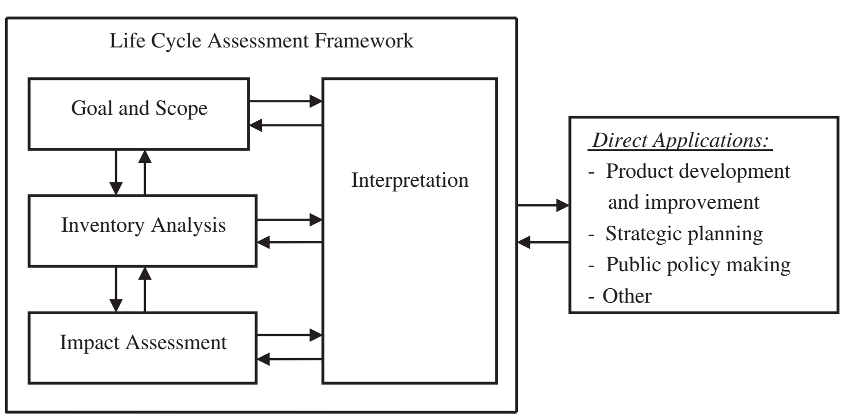

Figure 1. Phases of LCA study (International Organization for Standardization, 2006).

Table 1. System boundary of this study (including and excluding).

Within system boundaries	Production stage	• Production and transportation of raw fibres • Production of yarn • Production of fabric (e.g. knit, woven) • Wet processes of fabrics (e.g. scouring, bleaching, dyeing etc.) • Production of apparel
	Transport and distribution	• Distribution and transportation of apparel product from production location to user location
	Use stage	• Use of clothing (e.g. washing, drying, ironing) • Consumer transport
	End of life stage	• Clothing end of life (e.g. disposal option; reuse, recycling, landfill)
Without system boundaries		• Packaging of apparel • Transportation of chemicals and auxiliaries • Clothing accessories (e.g. buttons, zippers etc.) • Solid waste transport and recycling to other processes • Product care label and other labels • Manufacturing and maintenance of production machine (e.g. weaving looms, knitting machine, washing machines etc.) • Maintenance of building and other office equipment

data. Foreground data was (e.g. spinning, wet processing) mainly collected from the secondary data source, European Union (EU) reference document for best available technique for textile (Integrated Pollution Prevention and Control [IPPC], 2003) and other published references, and background data (e.g. energy production, chemical and auxiliaries production) was collected from ecoinvent v3 databases (Wernet et al., 2016). The European Union (EU) reference is a valuable reference and major resource of textile processing data for environmental practice (IPPC, 2003). In this study, most of the inventory data of textile processing was collected from EU reference document (IPPC, 2003). Some other data that is not available in this reference was collected from other sources (Cardoso, 2013). Energy and water consumption was modelled based on the literature survey and EU reference document (IPPC, 2003). Chemicals and auxiliaries productions were modelled using the ecoinvent v3 datasets. Some assumptions were made when specific dyes and chemicals are not in the ecoinvent data-set. Alternative or similar types of chemicals (e.g. organic or inorganic) were considered in this case. Estimated output emissions from the processes were calculated in the estimation of discharge and emission section. A general diagram of the supply chain of clothing from cradle to grave is shown in Figure 2.

Production stage

The main stages involved in the production processes are illustrated in Figure 3. Generally, all apparels are produced through a similar production chain, including fibre production, yarn production, fabric production, wet processing and apparel production. Production stages vary depending on the fibre, fabric and end product type. Resources used in the production stages are electricity, heat, water, chemicals, auxiliaries and dyes. The main factors or parameters that differentiate the environmental impact of different textile products are the use of resources (e.g. raw materials, energy and water).

Raw material production

Cotton. Cotton is one of the most common fibres used in the textiles industry for apparel production. The LCI of cotton includes cultivation of fibres, pesticide use, fertiliser use, energy use, water use and transportation (Muthu, 2014). The main overseas producers of cotton apparel for Australia in 2015 are China, Bangladesh, India, Cambodia, Vietnam and Indonesia according to UN Comtrade database (United Nations Department of Economic and Social Affairs, 2015). These overseas producers use raw cotton to produce cotton yarn. Available inventories for cotton production in ecoinvent v3 are based on three main cotton producing countries: the US, China and Australia. Ecoinvent v3 database for cotton production covers 'cradle to gate' inventory data: cultivation of raw materials, chemical, energy, water, fertiliser and pesticide input and emissions from the processes. A proxy country mix model database of raw cotton production was created based on the share percentage of raw cotton producers for these overseas apparel producers. All of the data was aggregated from UN Comtrade database (United Nations Department of Economic and Social Affairs, 2015).

Polyester. Polyester is the most consumed synthetic fibre for apparel production. The LCI of polyester fibres includes production of fibre, energy, water and transportation. The ecoinvent v3 inventory for polyethylene terephthalate, amorphous grade was used for polyester raw material production. Four inventories of polyethylene terephthalate, amorphous grade are available in ecoinvent v3 from four geographical locations; RER (Europe), CA–QC (Canada), RoW (rest of the world) and global (GLO). In this study, we created a proxy country mix model database of raw polyester using the share percentage of polyethylene terephthalate production from these geographical locations. The inventory for polyethylene terephthalate (PET) production used in the model includes 'cradle to gate' inventory which includes the main raw materials, dimethyl terephthalate (DMT) and ethylene glycol, energy, water, related transportation and emissions.

Wool. China is the world's largest wool producing country, followed by Australia, New Zealand and UK (Americal Sheep Industry Association, 2016). For the inventory of wool production Australian wool production inventory, 'Wool, sheep, at farm/US U/AusSD U' was used due to the unavailability of the data-set of China's wool production in

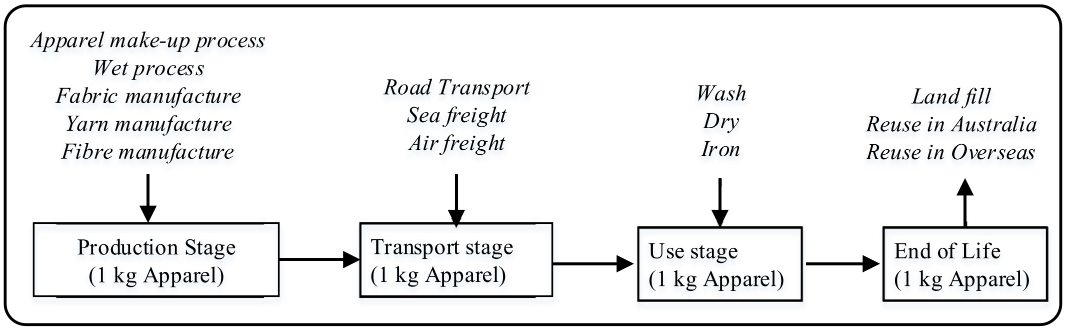

Figure 2. System boundary (General flow diagram of the supply chain) of clothing from cradle to grave.

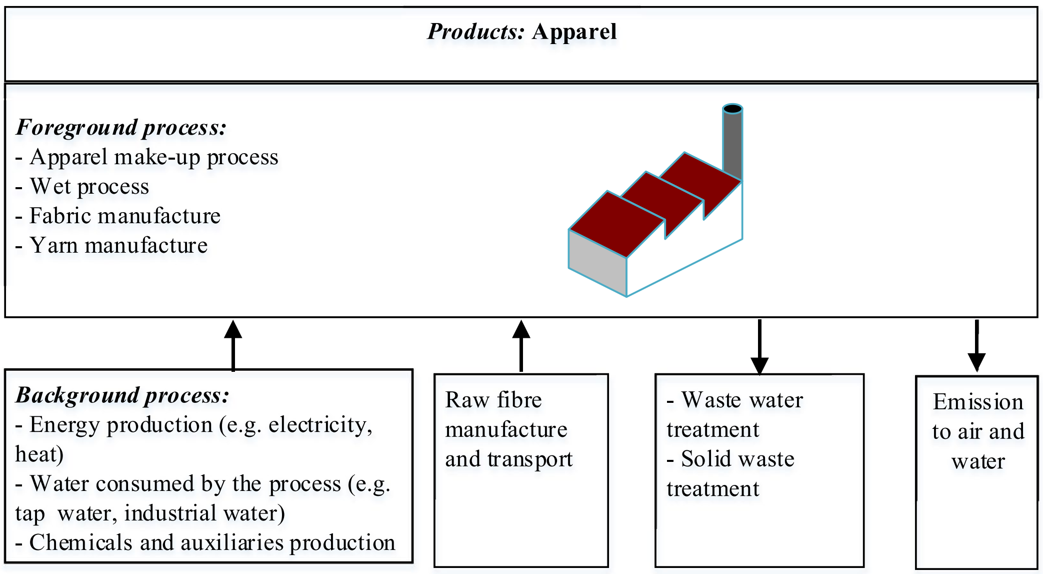

Figure 3. The life cycle stages considered within the system boundaries of industrial system for modelling the inventory.

ecoinvent v3. This inventory refers to the production of 1 kg of wool with co-product sheep live weight. One sheep deliver 4.2 kg wool/year and 62.8 kg live weight/year in a multi-output process. Economic allocation factor 22.8% to wool was used in this data-set. The system boundary is at the farm gate. Apparel manufacturing process from wool includes raw wool scouring, washing, dyeing, spinning, covering (with nylon for socks), yarn dyeing, knitting (apparel parts/socks), sewing and finishing.

Yarn manufacturing

The yarn spinning process includes opening, carding, combing, roving and spinning. Energy consumption, spinning waste, spindle oil and dust are the major factors for environmental concern of spinning process. Energy consumption of spinning process differs based on the yarn type; e.g. yarn used for knitting, yarn used for weaving, combed yarn and carded yarn. The energy consumption of different types was collected from the reference (Koç & Kaplan, 2007). For simplification of the model, average energy consumption for spinning of combed and carded knitting yarn 1.76 kWh/kg was considered. Fibre loss in the spinning process is higher for cotton yarn, average 13–16% and loss percentage for polyester yarn is average 4% (Bansode, 2013). In the case of wool spinning, the loss percentage is about 10% (Strand, 2015).

Wet processing

Textile wet processing involved pre-treatment, dyeing and finishing. Standard input parameters for wet processes were used to build the wet process model for this study. Secondary data was collected from the best available technique for textile (IPPC, 2003). Dyeing process involves different dyes, chemicals (salts, acids, etc.) and auxiliaries (surfactants, dispersing agents, levelling agents, etc.). The liquor ratio is the mass ratio between textile material and liquid during dyeing. Maintaining a low liquor ratio is important for wet processing. Consumption of chemicals and auxiliaries for wet processing was calculated based on the EU reference document, the best available technique for textile (IPPC, 2003). The material loss in wet processing process is 3–10% (Strand, 2015). The main environmental concern associated with the wet processes is the wastewater generated. The wastewater contains unfixed chemicals, auxiliaries and dyes (IPPC, 2003). Emission estimation from wastewater was stated in the estimation of discharge and emission section.

Apparel make-up process

Apparel make-up process is the last step before transportation and distribution to the final consumer. It includes different steps which require electricity and steam. There is very limited literature on apparel make-up process. It is difficult to identify the energy requirement of all apparel products individually. Use of energy varies significantly depending on the factory, machine efficiency, product design and fabric type (Islam, 2016). Due to the unavailability of specific data of energy use in the make-up process, data from another LCA study by Roos, Sandin, Zamani, and Peters (2015) was adopted. Fabric loss is an issue in apparel make-up process. Fabric loss occurs in different stages of apparel manufacturing e.g. cutting, sewing, finishing, inspection and marking. A study of fabric wastages in knit T-shirt manufacturing in Bangladesh by Rahman and Haque (2016) reported that on average 26.5% fabric was wasted at various stages during knit T-shirt manufacturing of which 13.57% wastage was in cutting section, 6.91% in inspection, 4.31% in sewing section and 1.72% in the finishing section. Another report by Cartwright et al. (Cartwright et al., 2011) stated that 8–10% fabrics were lost during cutting and sewing of cotton or polyester shirt. For this study, we adapted fabric loss data 13% for cotton and polyester shirt during the make-up process from JRC scientific and technical reports, and 10–12% for wool sweater (Beton et al., 2014).

Estimation of discharge and emission from textile processing

Different resources are used in apparel production process, causing various environmental impact to air, water and soil. Textile wet processing is the most significant stage in terms of environmental emissions due to the large volumes of wastewater with contaminants generated during wet processing. Textile other processes generate little or no wastewater emission compared to wet processes (Babu, Parande, Raghu, & Kumar, 1995). Most of the chemicals and auxiliaries used in the wet processing are discharged through wastewater. Wastewater emissions are mainly caused by the chemicals and auxiliaries used in the processes (Environmental Directorate OECD, 2004). The discharge rate of the dyes and chemicals depends on their fixation capacity. Fixation capacity of chemicals, auxiliaries and dyestuffs depends on their affinity to the fibre, the liquor ratio, temperature, time, pH and additives. Fixation capacity of different dyes is stated in the emission scenario document on textile finishing industry published by OECD (Environmental Directorate OECD, 2004). A very small amount of chemicals and auxiliaries remain with the textile materials after pre-treatment and dyeing, thus most of them are discharged with wastewater (Schönberger & Schäfer, 2003). Basic chemicals such as inorganic salts, acids and oxidising agents are released to approximately 100% in wastewater; therefore, their fixation rate (F_{fixation}) zero can be assumed (Environmental Directorate OECD, 2004). The fixation rate for auxiliaries such as detergents, complexing agents, desizing agents can also be considered zero as they are also released approximately 100% in wastewater (Environmental Directorate OECD, 2004). In this study, the average unfixed dyestuffs discharged with wastewater were estimated using the fixation percentage of dyestuff (Environmental Directorate OECD, 2004). Estimation of wastewater amount was done based on the model Equation (1) which was based on the references, emission scenario document on textile finishing industry published by OECD (Environmental Directorate OECD, 2004) and life cycle assessment of dyeing technology for cotton fabrics studied by Yuan, Zhu, Shi, Liu and Huang (2013).

$$Q_{\text{waste water}} = Q_{\text{total water}} + Q_{\text{chemicals/auxiliaries}} * \left(1 - F_{\text{fixation}} - F_{\text{air}}\right) \quad (1)$$

where, $Q_{\text{waste water}}$ = total amount of wastewater generated; $Q_{\text{total water}}$ = amount of water used in the process (We assume no evaporation loss); $Q_{\text{chemicals/auxiliaries}}$ = amount of chemicals and auxiliaries used in the process; F_{fixation} = degree of fixation of chemical/auxiliaries in the textile material; F_{air} = air emission of chemical/auxiliaries used in production process.

CH_4 production from wastewater depends on the type of wastewater treatment, the amount of degradable organic material in the wastewater and the temperature. Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are the common parameters to measure the organic component of the wastewater. The BOD is an aerobic parameter and refers to the amount of carbon that is aerobically biodegradable (IPCC, 2006). The parameter COD refers to the total amount of material available for chemical oxidation for both biodegradable and non-biodegradable. BOD is mainly used for domestic wastewater and COD is used for industrial wastewater (IPCC, 2006). The theoretical COD value of any product or substance can be calculated from the oxidation equation of this product or substance (Henze & Comeau, 2008). Theoretical COD can also be calculated from the specific emission factor of COD of chemical/auxiliaries or specific emission factor of COD of the process (IPPC, 2003). Wastewater treatment plant, class 3 was used in the model. Average wastewater treatment plant capacity is 24,865 m^3 wastewater/year (for class 3) (Doka, 2003). In this study, we converted this value for the amount of wastewater generated for one functional unit using the lifetime of wastewater treatment plant 30 years (Doka, 2003). To estimate COD and BOD of wastewater, textile wastewater standard characteristic of some textile manufacturing countries was used in this study. To protect the environment from harmful wastewater, the government of textile production countries fixed the wastewater characterisation parameters which can may be discharged in the environment after wastewater treatment process. We considered the average value of wastewater characterisation parameters from the reference (Dey & Islam, 2015). CH_4 emission from industrial wastewater after waste water treatment was calculated using IPCC guideline (Equations (2)–(4)) (IPCC, 2006).

$$CH_4 \text{ Emission} = [(\text{TOW} - S)\,\text{EF} - R] \quad (2)$$

where, TOW = total organically degradable material in wastewater from industry, kg COD; EF = emission factor, kg CH_4/kg COD; S = organic component removed as sludge, kg COD; R = amount of CH_4 recovered, kg CH_4.

Note that only a few countries may have sludge removal data and CH_4 recovery data. The default for sludge removal (S) and CH_4 recovery can be assumed zero according to IPCC guideline (IPCC, 2006).

$$\text{EF} = \text{Bo} * \text{MCF} \quad (3)$$

where, EF = emission factor CH_4, kg CH_4/kg BOD; Bo = maximum CH_4 producing capacity, kg CH_4/kg BOD; MCF = methane correction factor (fraction).

As country-specific data of Bo is unavailable, default factor for Bo, 0.25 kg CH_4/kg COD from IPCC (IPCC, 2006) was used. A default value of MCF is 0.3 for aerobic treatment plant was considered to calculate CH_4 emission (IPCC, 2006). For the amount of wastewater, it is assumed that all of the unfixed dyestuff, chemicals and auxiliaries are discharged into wastewater, and no evaporation loss (Yuan et al., 2013). Air emissions from wet processing are caused by the textile materials, auxiliaries/chemicals and the machines. The fraction of a substance in a chemical agent released to air depends upon its volatility (Environmental Directorate OECD, 2004). Its default value is zero assuming the substance is a non-volatile compound (Environmental Directorate OECD, 2004). In this study, the emission from inorganic chemical substance was calculated using Equation (4).

$$E_{\text{Emission}} = Q_f * \left(\text{MW}_p / \text{EW}_f\right) \quad (4)$$

where, E_{Emission} = emission of pollutant from chemical substance; Q_f = chemical substance amount, kg/kg textile; MW_p = molecular weight of pollutant emitted from chemical substance, kg/kg- mole; EW_f = elemental weight of chemical substance, kg/kg-mole.

Transport and distribution

Transport and distribution are one of the important parts of life cycle modelling. Modelling of the transport and distribution process is difficult as this process occurs several times in the supply chain. Average sea distance and air distance from apparel origin countries to Australia are considered to build the transportation model of this life cycle assessment. Travel distance was estimated by averaging the individual distance from the major port of apparel origin countries to Australia. Online distance calculator tools were used to calculate travel distance (DistanceFromTo, 2016; Sea-Distance.org., 2017). In addition to the sea and air freight, local (overseas) truck was considered for inland transportation of finished apparel from the production plant to the port. The average road distance from the production plant to seaport was assumed 500 km for each country. The ecoinvent v3 database was used for the LCI of each transport mode. Ecoinvent data base used for the passenger car in Australia is 'transport, passenger car, diesel, EURO5, city car/CH U/AusSD U', which is based on the current standard ADR 79/04 (Euro 5 standards) for the light vehicles in Australia (Department of Infrastructure and Regional Development, 2016). For raw materials (raw fibre) transportation, travel distance was considered from China to other apparel producing countries. About 92% of the textile finished products are transported by maritime freight and only 8% are transported by air freight (Beton et al., 2014). This allocation percentage was used to develop the transportation model of the finished product.

Use stage

The consumer use stage has significant environmental impact on the full life cycle of textile products. The main influencing factors of environmental impact from the use stage are the frequency of wear and wash, drying, ironing, types of drying, machine load, wash temperature, detergent use and the lifetime of clothing. To model the consumer use stage, it is necessary to include data related to consumer caring behaviour for their purchased clothing such as washing, drying and ironing frequency. The caring behaviour pattern differs from country to country. Australian consumer's behaviour pattern data was adopted from the study performed by Grace, Gane and Garcia, (2009). The data source of consumer's behaviour pattern was Australian bureau of statistics (ABS) as shown in Table 2 (Grace et al., 2009).

A washing process requires the input of water and detergent. Cloth drying and ironing require no input of materials. But all of the processes involved in the use stage require the input of energy. Another important factor is the life time of clothing (Beton et al., 2014). In this study, life time was considered based on the total number of washes over the use stage. Data for electricity, domestic tap water and wastewater (derived from the washing machine) treatment was taken from the Australian Life Cycle Inventory Database, AusLCI (Grant, 2015). It was assumed that the wastewater to be purified in a moderately large municipal wastewater treatment plant (capacity class 2) in Australia. Detergent production process model was developed for this study based on the life cycle study of laundry detergent performed by Procter & Gamble Company (P & G) (Saouter & Hoof, 2002).

Washing

It can be assumed that the proportion of household clothing wash in Australia by hand is very small. Therefore, 100% machine washing is considered for this study. Washing process was modelled using consumer use behaviour as stated in Table 2. According to a survey by Canstar Blue (2016), 36% Australians consider purchasing a front loader washing machine while most of the Australians consider purchasing top loader washing machine due to the easy operating features. Fisher & Paykel brand washing machine is in the top rank for top loader

Table 2. Consumer use behaviour (Grace et al., 2009).

	Consumer use behaviour	Assumption used
Washing machine load	26% (full load)	26% of Australians use their washing machine with the full load, so we can assume 74% Australians use half load
Wash temperature	80% (cold water)	80% Australians use cold water to wash their clothing, so we can assume 20% Australian use warm water
Tumble dryer owner	55% (household)	
Tumble dryer use frequency	In summer – 39% population uses dryer very rarely In summer – 16% of population uses frequently In winter – 23% population uses rarely In winter – 32% population uses frequently Average use in summer and winter: 31% population uses dryer rarely 24% population uses dryer frequently 45% population uses dryer moderately	Assuming that rarely means they use tumble dryer 10%, frequently means they use tumble dryer 90% and moderately means they use tumble dryer 50% in both seasons

washing machine (Canstar Blue, 2016). The Australian government provides some house appliances datasets online for public access and reuse purpose (Australian Government Department of the Environment & Energy, 2016). According to this datasets, Fisher & Paykel brand, two-star top loader washing machine consumes 57 kWh/365 uses for cold washing and 505 kWh/365 uses for warm washing (Australian Government Department of the Environment & Energy, 2016). Therefore, energy consumption 0.15 kWh/cold wash and 1.38 kWh/warm wash were calculated for 2 to 2.5-star top loader washing machines for this life cycle assessment study. The capacity of the household washing machine used in Australia ranges between 3 and 10 kg (Canstar Blue, 2016). The capacity of the machine is an important factor, as a small machine will add extra wash cycle, energy and water bill for quantity washing. The most common washing machine capacity used in Australia is 6 kg considering the family size 4 people (Grace, 2010). Equations (5) and (6) were used to model the consumer washing stage.

$$\begin{aligned}&\text{Impact \% per garments based on machine load}\\&\quad = (100 \ * \ \text{garments weight})/\text{machine load}\end{aligned} \tag{5}$$

$$\begin{aligned}\text{Energy/garments} = {}&\text{Energy/wash(warm/cold)}\\&* \text{ impact \% per garments based on machine load (half/full)}\\&* \text{ population\% (who use warm cold/water)}\\&* \text{ population\% (who use half/full load)}\end{aligned} \tag{6}$$

Drying

Apparel drying was modelled using Equations (7)–(9) and consumer drying behaviour.

$$\begin{aligned}&\text{Impact\% per garment based on machine load}\\&\quad = (100 \ * \ \text{garment weight})/\text{machine load}\end{aligned} \tag{7}$$

$$\begin{aligned}&\text{Actual weight of garment to dry (frequently/rarely/moderately)}\\&\quad = \text{garment actual weight} \ * \ \text{population\% of dryer owner}\\&\qquad * \text{ population\% (who use dryer frequently/rarely/moderately)}\\&\qquad * \text{ population\% of actual dryer use among (frequently/rarely/moderately)}\end{aligned} \tag{8}$$

$$\begin{aligned}&\text{Energy per garment to dry}\\&\quad = \text{impact \% per garment} * \text{energy per drying cycle}\\&\qquad * \text{ actual weight of garment to dry }/100\end{aligned} \tag{9}$$

The capacity of the household tumble dryer can be measured by weight between 5 and 8 kg. Purchasing behaviour of the tumble dryer is influenced by the average household sizes; less than 5 kg load machine for household size 1 to 2 people, 5 to 7 kg load machine for household size 3 to 4 people and more than 7 kg load machine for household size more than 4 people (Canstar Blue, 2016). We can assume that Australian average household size is 4 people, so we can consider the average capacity of dryer is 6 kg (Grace, 2010). Energy consumption of dryer was calculated based on the average energy of two mostly used dryer in Australia, which is 5.33 kWh. This data was taken from the household appliances datasets provided by the Australian government (Australian Government Department of the Environment & Energy, 2016). There is no data available for population percentage based on dryer load percentage (full load or half load). Therefore, in this study, full load drying was considered, though it may be assumed that drying started after each load of washing for detailed modelling.

Ironing

Apparel ironing process was modelled based on the power of iron machine, ironing time and ironing behaviour (washing to ironing ratio). According to JRC scientific and technical reports conducted by European Commission wash to iron ratio is 100% for shirt and T-shirt (Beton et al., 2014). Ironing is essential for cotton apparel, but not necessary for polyester garments. Therefore, it is assumed wash to iron ratio is 40% for polyester apparel and 100% for cotton apparel. Ironing of wool sweater depends on the personal preference and present of the crease after laundering. Normally heavier types of sweater tend to crease less after laundering. In this case, ironing is not necessary for wool apparel (Woolmark, 2016). Therefore, wash to iron ratio 10% for wool apparel was considered using a report on consumer usual ironing preference of different clothing conducted by Ecobilan (2009). A typical reasonable ironing time 3 min for cotton and polyester apparel and 1 min for wool apparel was adopted from JRC report. This time was based on per kg apparel (Beton et al., 2014). The average power of a household iron is 600 watts in Australia (Essential Energy, 2016). Energy consumption of a household iron depends on the length of time to iron cloth. To estimate the energy consumption for ironing, apparel ironing time was multiplied with the average power of household iron, as shown in Equation (10).

$$\begin{aligned}&\text{Energy required to iron apparel}\\&\quad = \text{iron machine power} \ * \ \text{iron time}/1000\end{aligned} \tag{10}$$

End of life

Textile waste end of life management scenarios differ from country to country. In Australia, used clothing is mainly collected by charities and clothing recyclers. According to a discussion paper on textile waste in Australia, over 50 million kg of textile waste were collected through charity bins by different charity organisations and clothing recyclers in Australia. About 12.5 million kilos of the collected textile waste were unsuitable for recycling and reuse, which were sent to landfill. The rest of the collected clothing waste was recovered by recycling and reusing through charity shop and recycling organisation (Caulfield, 2009). From this statement, we can assume that 25% of the textile waste is disposed of through the landfill and another 75% textile waste is recovered through recycling and reuse. Australia has a big international market for used textiles (Caulfield, 2009). Therefore, in order to model the end of life scenario, it is assumed that 35% of the disposed textiles were reused in Australia locally by charity shop and 40% were reused in overseas through exportation. Based on a SATC (salvation army trading company) report, collection, processing and distribution of second-hand clothing consume 1.7 kWh energy per kg clothing (Collins & Aumônier, 2002). This data was adapted to calculate total energy for reuse in this study. Textile end of life through reusing, recycling can reduce the demand for virgin production. Though the reusing and recycling also require energy and other resources, the resources amount and pollutions are less than virgin textile production (Caulfield, 2009). Impacts from the used apparel exports to other country are not considered in this assessment because their impacts are ascribed to the used apparel receiving country (Thomas, Fishwick, Joyce, & van Santen, 2012).

Common data selection for inventory analysis

Common data sources for electricity, heat, transport, waste management and water supply were used in the modelling for the production stage. Since this study is general, therefore global processes were used to model raw material production, transportation, electricity in the production stages as far as possible. Ecoinvent Global datasets were used as a common data source. Ecoinvent Global (GLO) datasets derived and represented data of global perspective (Wernet et al., 2016). All of the production processes use electricity. Electricity mix data-set for the main apparel producing countries was created based on the apparel import share of six biggest origin countries, China, Bangladesh, Vietnam, India, Indonesia and Cambodia.

LCIA and interpretation

The life cycle inventory results were analysed and interpreted in this section based on the impact category climate change (kg CO_2 equivalent, CO_2-e). Figure 4 shows the proportion of the contribution of CO_2-e emission from the supply chain of three apparels from production to end of life scenarios. Supply of raw fibre to produce finished apparel depends on the mass loss in the processes and fibre type. Around 1.7 kg cotton, 1.4 kg polyester and 2.1 kg wool are required to produce 1 kg of apparel from these fibres. Production of wool apparel requires relatively more supply of raw wool fibre due to the large percentage of mass loss during wool scouring and washing (Russell, 2009).

The higher environmental impacts of greenhouse gas for cotton and polyester apparel mainly occurred in the use stage, whereas, the use stage of wool apparel contributes relatively less impact than cotton and polyester apparel. The main reason is that the wool sweater requires less frequent washing, drying and ironing than cotton and polyester shirt. Impacts from use stage are associated with the life time of apparel, which is one year for cotton and polyester apparel and three years for wool apparel (Beton et al., 2014).

Environmental impact from wool raw material extraction process is comparatively higher than polyester and cotton, as shown in Figure 5. The wool fibre production process contributes the largest impact, 24.13 kg CO_2-e/kg apparel, accounting for 37.09% of the total life cycle impact of wool apparel. This

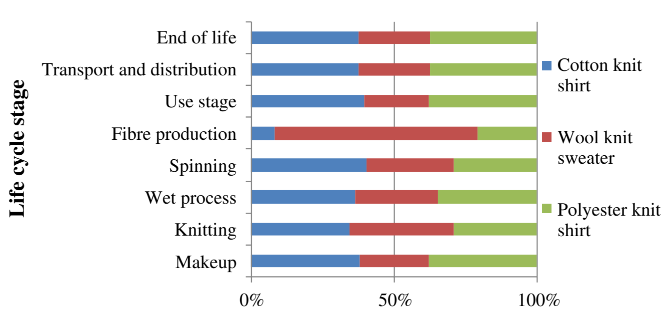

Figure 4. The proportion of the contribution of impact throughout different stages of life cycle.

is due to the impact from input and output from the agriculture of livestock (sheep). Fibre production process of polyester and cotton apparel contributes 10.87 and 4.25%, respectively, of their total life cycle. This difference is mainly due to the large amount of energy requirement for polyester fibre production. Environmental impact per kg apparel associated with transport, distribution and end of life stages for all of the apparels are considered the same. Transportation model was done based on 90% sea freight and 10% air freight. Transportation and distribution process for all of the apparels is the same and contributes minimum impact than other stages.

Figure 6 show the converted results for single apparel. To estimate the weight of each apparel, from the website reference (Alibaba.com, 2017; Beton et al., 2014), one kg of apparel can be expressed as equivalent to about three wool sweaters, five cotton shirts or nearly five polyester shirts. Wool sweater contributes the highest impact in terms of per apparel due to the relatively high mass comparing with other two apparels (Figure 6).

The use stage includes washing, drying and ironing. Figure 7 represents the impact breakdown of the use stage of three apparels. Washing is the highest contributor to climate change impact category. Cotton and polyester apparels display the highest impact in use stage while wool sweater represents lower impact in the use stage. Some apparels such as wool sweaters and jumpers require less frequent washing, drying and ironing. Other apparels, for example, cotton shirts, require frequent washing, drying and ironing.

Scaling up results

According to IBISWorld data, calculated revenue from total clothing wholesale during 2015–2016 is AU$8.3832 bn. This revenue included revenue from apparel produced locally (AU$0.69199 bn) and imported (AU$7.69121 bn). Most of the domestic demands of clothing are fulfilled by imported clothing. Only 8.25% revenue from clothing wholesale come from local clothing production and 91.75% come from imported clothing. Therefore, for simplification of the model, only import quantity was considered as the consumption of these three apparels for the year 2015. The environmental impact of selected three apparels in terms of climate change was scaled up based on their consumption in the year 2015 in Australia. Total consumption of cotton knit shirt, polyester knit shirt and the wool sweater was 63,210,125, 28,999,794 and 1,407,708 kg, respectively (United Nations Department of Economic and Social Affairs, 2015). Estimated environmental impact of climate change from this quantity was 4 million tonne CO_2-e emission, which includes 2.7 million tonne CO_2-e emission from cotton knit apparel and 1.2 million tonne CO_2-e emission from polyester knit apparel. Impact of climate change from cotton apparel is particularly high due to the large share of cotton knit apparel in the clothing market and then followed by polyester and wool knit apparel. The impact from wool knit apparel is relatively low due to its small share of apparel market. It can be mentioned here that a study performed on UK clothing consumption estimated that carbon footprint from UK clothing consumption is approximately 38 million tonnes CO_2-e emission in 2009. UK clothing consumption was around 2.5 million tonnes in 2009 (Thomas et al., 2012). As the majority of the apparels consumed in Australia

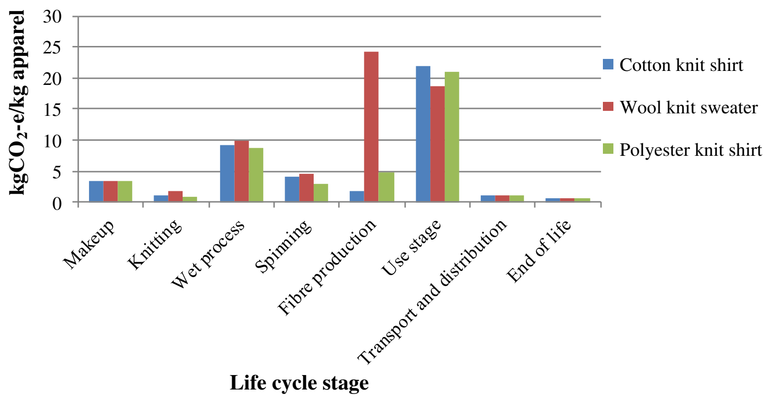

Figure 5. Breakdown of impact of climate change per kg apparel.

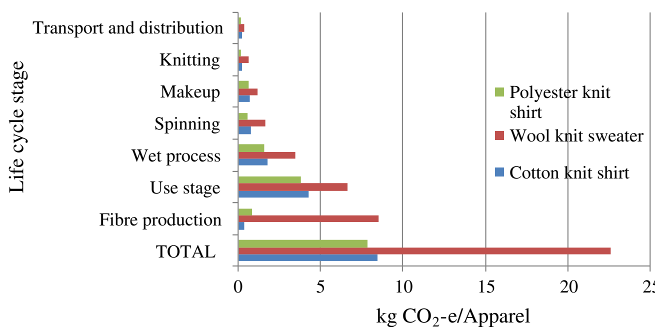

Figure 6. Kg CO_2-e emissions per apparel.

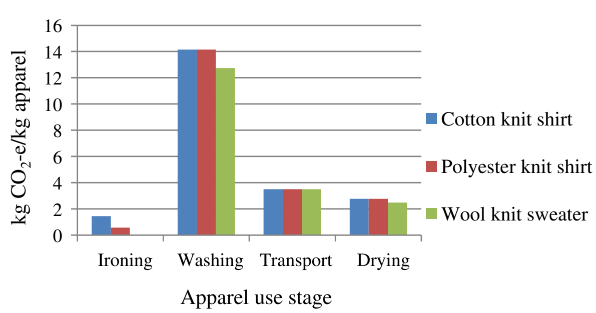

Figure 7. Use stage impact in kg CO_2-e/kg apparel.

are produced in overseas, it can be stated that most of the direct impact from apparel production occurred in overseas and direct impact from use and end of life stages occurred in Australia.

Sensitivity analysis

Change in user behaviour

The main contributing factors of environmental impact at the use stage are the use of electricity, water and wastewater treatment from the washing machine. In this study, we used average energy rating data for 2-star top loader (6 kg capacity) washing machines (Fisher & Paykel brand) which consume 0.15 kWh/cold wash and 1.38 kWh/warm wash (Australian Government Department of the Environment & Energy, 2016). A reduction of energy and water consumption can be achieved using household appliances with a high energy saving rating. More stars mean more energy and water savings, which ultimately cause less emission. Another way to achieve energy reduction is the use of front loader washing machine instead of the top loader machine, as front loader washing machine consumes less energy and water than top loader machine. According to the survey report of Canstar Blue (2016), most of the Australians consumers buy top loader washing machine. Great environmental savings can be achieved if consumers change their washing machine buying attitude to front loader washing machine.

Consumer transport is another contributor to greenhouse gas emission as the use stage starts transportation of clothing from retailer to consumer home, though this factor was not specially considered in this paper. Environmental savings can be achieved from the use stage if the consumer switches their transport mode from light passenger car to public bus or rail transport (Australian Government Climate Change Authority, 2012).

Since the consumer use stage contributes significantly to greenhouse gas emissions, it is important to analyse impact reduction of this stage in the life cycle of apparel. Sensitivity analysis was performed by changing different parameters in the use stage. Effective impact reductions can be achieved through behavioural changes in consumer use stages and the use of more energy efficient washing machine and dryer. From Figure 8, the use of more energy saving washing machine can reduce energy consumption, water consumption and environmental impact. Around 10% CO_2-e reduction can be achieved from the use stage by reducing washing machine energy up to 40%. 100% full load machine wash and the use of cold water are another way of impact reduction.

Consumer washing, drying and ironing frequency is an important factor in impact reduction. Sensitivity analysis of consumer washing, drying and ironing frequency was done by changing the parameters as shown in Figure 9. Around 33% CO_2-e emission from the use stage can be reduced by reducing consumer washing frequency up to 40% from the base case and around 23% CO_2-e emission can be reduced by reducing the frequency of washing, drying and ironing all up to 25%. Product lifetime is another important factor for reduction of impact. As the lifetime of the purchased apparel increases, the consumer can change their buying habit by reducing the number of new apparel. Therefore, the environmental impact can be avoided from the production of new apparels.

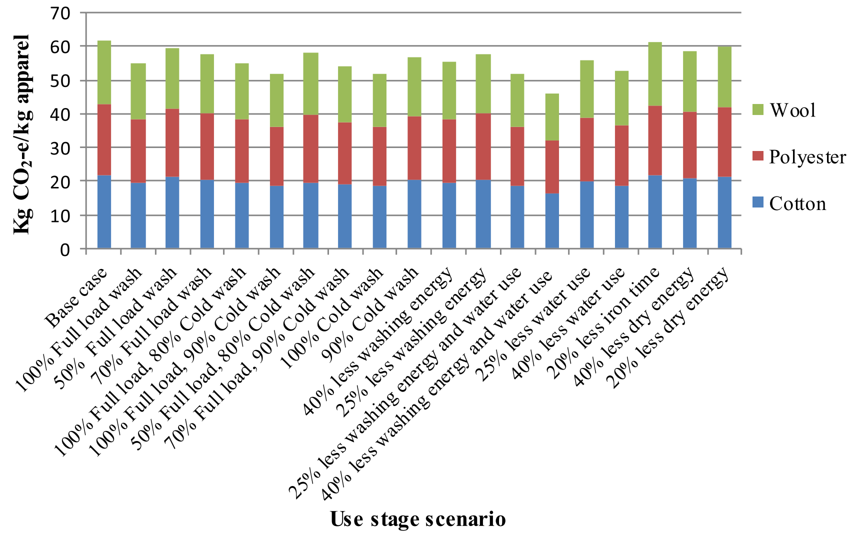

Figure 8. Sensitivity analysis of consumer use stage.

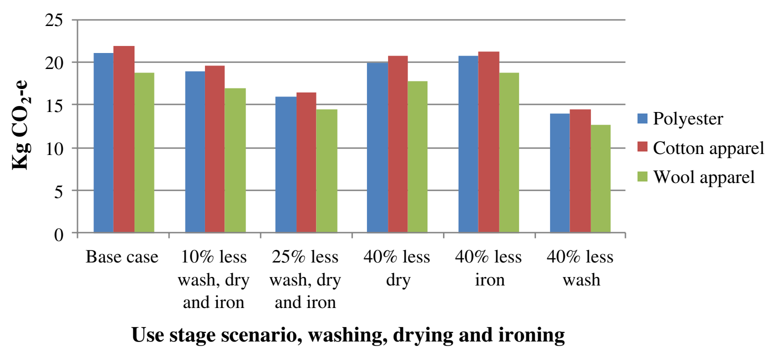

Figure 9. Sensitivity analysis of consumer washing, drying and ironing frequency.

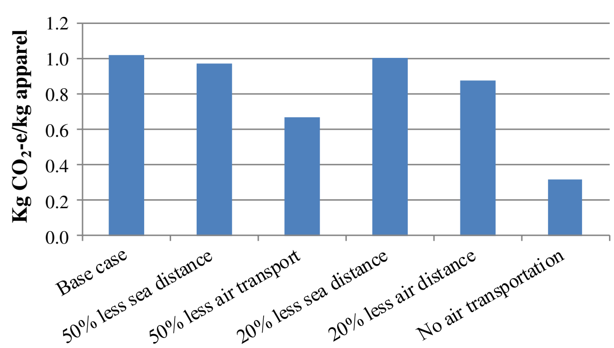

Figure 10. Sensitivity analysis of transport and distribution stages.

Change of transport mode

Sensitivity analysis of transportation of goods was presented using the parameters of transport distance for sea and air freight in Figure 10. Calculated impact 1.02 kg CO_2-e per kg apparel was based on the average transport distance. Impacts from transport and distribution stages are the same for all of the apparels. Baseline model of transport was done using 92% goods transportation by sea freight and 8% goods transportation by air freight. Environmental impact from air freight is relatively higher than sea freight. Around 30% impact from transport and distribution stages can be saved avoiding air transportation throughout the supply chain. The distance of the supplier to consumer country is an important factor in carbon reduction.

System expansion and avoided product

Integration of recycling in the product life cycle can reduce the environmental impact of CO_2-e emission. Most textiles that are disposed of can be used as carpet underlay, insulation material for building, industrial rag and wipers through open loop recycling. To identify the environmental benefit from recycling it is necessary to allocate the environmental impact in two product systems: product system A (primary life cycle, virgin textile products) and product system B (secondary life cycle, recycled products). In this study, we followed Weidema's approach (Weidema, 2000) to allocate the impact of recycling into two product systems by expanding the system with displaced or avoided process (e.g. production of paper wipes from the virgin material). According to Weidema's approach, environmental impacts of the used apparel (Product A) are ascribed associated with the production of apparel, transport distribution, use of apparel and landfill process. The outcome of the decision tree can be stated for used apparel. Environmental impacts of the recycled product (Product B) are ascribed associated with all intermediate process (e.g. discarded apparel collection, sorting, transport for recycling, local and overseas reuse), production of recycled wipes and credit from landfill process (Weidema, 2000). Sales growth of cleaning wipes in Australia is 6% in 2016 (Euromonitor International, 2016). It can be assumed that the market demand for cleaning wipes is high. If the quality of recycled cleaning wipes can match the paper wipes, paper wipes can be displaced by recycled wipes and the resultant environmental impact reduction can be credited. Energy credit from the displaced process of paper wipes is around 18.303 kWh/tonne discarded apparel (Woolridge, Ward, Phillips, Collins, & Gandy, 2006).

Conclusions

This study presented the application of life cycle assessment methodology to assess the environmental impact of textile supply chain from raw material extraction to end of life in terms of climate change impact category. A case study of three selected apparels consumed in Australia was carried out. This study focused on the relative comparison of the environmental impact of different apparel and different fibres with reduction scenarios. It revealed that the use stage of some specific apparels is a key contributor to the environmental impacts throughout the life cycle. From this study, it was demonstrated that the consumer use stage among the textile supply chain for cotton and polyester apparels is the main contributor of the environmental impact of climate change and the production stages contribute more impact than consumer use stage for wool apparel.

Overall, this LCA assessment suggests that significant improvement can be achieved by encouraging use stage activities with less environmental impact, such as, increasing apparel life time, reducing the frequency of wash, avoiding machine dry and use line dry, using full load machine wash and cold water when possible. Another activity related to consumer use stage is disposal option of used apparel. Great environmental savings can be achieved if consumers donate their used apparel for recycling and reuse as this may prevent or minimise the production of new apparels and other recycled products from the virgin raw material. Apparel manufacturing stages are another dominating contributor to environmental impact throughout the life cycle. Apparel manufacturing stages are characterised by large and complicated industrial chains which consist of fibre, yarn, fabric and apparel production and all of the stages involved with the use of different chemicals, auxiliaries, energy and water as well as agriculture for raw material production. Energy use is the main contributing factor for life cycle stages.

Apart from the baseline scenarios of each apparel, the sensitivity analysis was performed using different parameters on consumer use stage to identify the impact reduction scenario from the life cycle. From the scenario analysis, it can be stated that a reduction of washing machine energy and washing frequency can reduce the impact of CO_2-e emission around 10 and 33%, respectively. Reducing transport distance can save CO_2-e emission from transportation stage. Air freight contributes more emission in transportation stages. Further emission reduction can be achieved if supply chain involved only sea freight.

Disclosure statement

No potential conflict of interest was reported by the authors.

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