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# Environmental impact of Recover cotton in textile industry

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ABSTRACT

A comparative evaluation of the life cycle assessment (LCA) of Recover cotton, obtained from recycled garments, and virgin one, cultivated from traditional and organic crops, has been made based on the quantification of environmental impact categories, such as abiotic depletion, global warming, water use, acidification and eutrophication potential. LCA data reported in the literature for the steps of cultivation, ginning/cutting, and dyeing were compared in order to clearly show the environmental advantages of moving from traditional practices, to organic cultivation and the use of Recover cotton, a novel procedure that involves the production of cotton yarns from coloured and well characterized recycled materials. Studies made evidenced that the use of organic cotton cultivation avoids the use of pesticides and chemicals, reducing environmental impacts, but maintaining those related to ginning and dyeing steps. However, the use of Recover cotton avoids the impact of both, cotton cultivation and dyeing steps, based on an appropriate selection of raw materials obtained from textile wastes, being only increased the energy costs of cutting/shredding processes as compared to ginning ones. In short, it can be concluded that the use of Recover cotton for the production of high quality textiles involves an added value of the products from an environmental point of view, being costs and electrical consumes also reduced and providing a second life for produced textiles.



## 1. Introduction

Cotton is the most consumed natural fibre in textile and clothing industry, with a worldwide production of 24.5 million tonnes in 2013. Cotton crops are distributed around the world principally in dry areas where other commodities grow on with difficulties. China (26.4%), India (20.5%), USA (13.9%), Pakistan (8.5%), Brazil (6.3%), Uzbekistan (4.1%), Australia (3.8%), and Turkey (3.3%) are the main producers of cotton lint (FAOSTAT, 2016). The environmental impacts associated to cotton production and yarn spinning are heterogeneous and complex, even in numerous cases there is no data available in the literature. Previous studies shown that water consumption, land occupation, emissions, and usage of chemicals are the most critical aspects to be evaluated during the cotton production step (PE International, 2014a; Baydar et al., 2015).

Cotton cultivation requires huge amounts of water, including green water, which arises from precipitation, but also blue water, from artificial irrigation, which is estimated as a 73% of the production. Actually, a 2.6% global water use is consumed in the production of cotton and it reduces freshwater reserves causing drought problems in the cultivation areas and a general damage of the water environment (Chapagain et al., 2006). The average fraction of total damage attributable to water consumption for cotton production is 17%; however, the irrigation requirements for cotton production significantly differ with the country, being from <1% for Brazil, to 77% for Egypt (Pfister et al., 2009)

The impacts of spinning and textile production, including weaving, cutting, and sewing, are noticeably elevated, considering the high amounts of electricity required, which considerably increases $CO_2$ emissions and acidification potential (GHK, 2006). However, the environmental impact of the aforementioned steps is relatively low as compared with cotton dyeing, one of the most contaminant parts in the whole textile process. It involves the use of big amounts of energy, water, steam, and assorted chemicals like bleaching agents, dyes, wetting agents, soap, softener, and salts, in order to obtain the required colour (Yuan et al., 2013; Roos et al., 2015). Moreover, high amounts of wastewater are generated in dyeing plants with deleterious effects to the environment (Roos et al., 2015), causing contamination of continental waters which is especially important concerning toxic dyes (Zhang et al., 2015).

In the last decades, several initiatives have been developed to reduce the negative impacts of cotton production. In such a frame, the cultivation following organic farming practices avoids the use of fertilizers, herbicides, and insecticides (PE International, 2014a).

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The total pesticide consumption involved in the cotton cultivation is estimated as an 11% of the world consumption, being around 50% in developing countries. So, the practice of organic agriculture strategies allows to drastically reduce the use of chemicals and the deleterious environmental impacts related to acidification and eutrophication potentials (Bevilacqua et al., 2014).

A novel Recover strategy has been recently developed for the production of cotton yarns from recycled materials (HIFESA, 2016). In this strategy, cotton growing is avoided, reducing the consumption of water, fertilizers and pesticides. Moreover, dyeing steps is neither required because the final colour of cotton fibre is related to the colour of the raw materials; thus, the use of water, dyes, wetting agents, softener, and any other related products is also avoided. The use of Recover technology avoids all the environmental impacts related to the cotton cultivation and dyeing of yarns, while as counterpart it involves the addition of a cutting/shredding step of recycled clothes previous to the spinning step, which have similarities with conventional ginning process. The ginning process of cotton consists of the separation of lint, seeds, and other plant residues, and it can be done by different ways, from manual to mechanised techniques which usually include high energetic steps, like drying, cleaning and pressing (Bajaj and Sharma, 2012).

Life-cycle assessment (LCA) is an useful methodology, regulated by the ISO 14040:1996 and ISO 14044:2006 (ISO, 1997, 2006), employed for the assessing of potential environmental impacts associated with a product by the evaluation of relevant inputs and outputs throughout it product life, from production and acquisition of raw materials, industrial treatment, and final disposal. LCA data are commonly provided by consultancy companies or research institutes, and there is little peer-reviewed literature available on this topic. An LCA study has been carried out for textiles made by different materials as polyester, nylon, acryl, and elastane, being cotton the fibre with a higher impact on the environment (van der Velden et al., 2014). The worldwide cultivation of cotton creates important troubles for a correct evaluation of LCA, because its cultivation is a complex system, due to the high dependence to environmental conditions at different regions, but also due to differences within a year, and from year to year. Thus, global impacts of cotton cultivation are difficult to be estimated due to the high variability of each specific cotton crop. Nevertheless, several studies have been published for the LCA of cotton from different perspectives, focused in a specific part of the whole process, such as: growing, spinning, weaving, dyeing, etc. Impact of cotton cultivation, under conventional and organic agriculture, has been exhaustively evaluated using LCA (Babu and Selvadass, 2013a; PE International, 2014a; Baydar et al., 2015), as well as different dyeing and finishing process (Babu and Selvadass, 2013b; Yuan et al., 2013). In spite of that, there are scarce LCA studies about the reuse/recycling of clothing waste (Woolridge et al., 2006; Morley et al., 2006), and in our knowledge, there are not reported LCA studies based on the use of recovered cotton for the industrial production of cotton yarn.

The main objective of this study has been the evaluation of the environmental impact of cotton yarn production from Recover cotton, being compared the obtained LCA data from a specific plant in Spain with those obtained from the published literature about the production of cotton yarn obtained from virgin cotton produced through conventional cultivation and organic agriculture.

## 2. Methods

### 2.1. Recover cotton procedure

As an example of cotton yarn production from recovered fibres, the process in use in a plant located in Spain was used to evaluate the LCA of this system and to compare the obtained data with those published in the literature for cotton yarn obtained from virgin cotton.

Hilaturas Ferre (Banyeres de Mariola, Spain) is a family business since 1914 dedicated to cover the entire production process from spinning to weaving at full industrial scale, with 24300 $m^2$ of facilities, and more than 140 employees (HIFESA, 2016). A new generation of Upcycled Textile System has been recently designed by Hilaturas Ferre for the production of high quality cotton yarn from recycled materials well classified by their colour. A summary with the main steps involved in the production of Recover cotton fibres is shown in Fig. 1. In this strategy, pre-consumer textile clips are mainly collected and carefully sorted according to their quality and colour as a raw material from different textile plants from all around the world. Small amounts of post-consumer garments

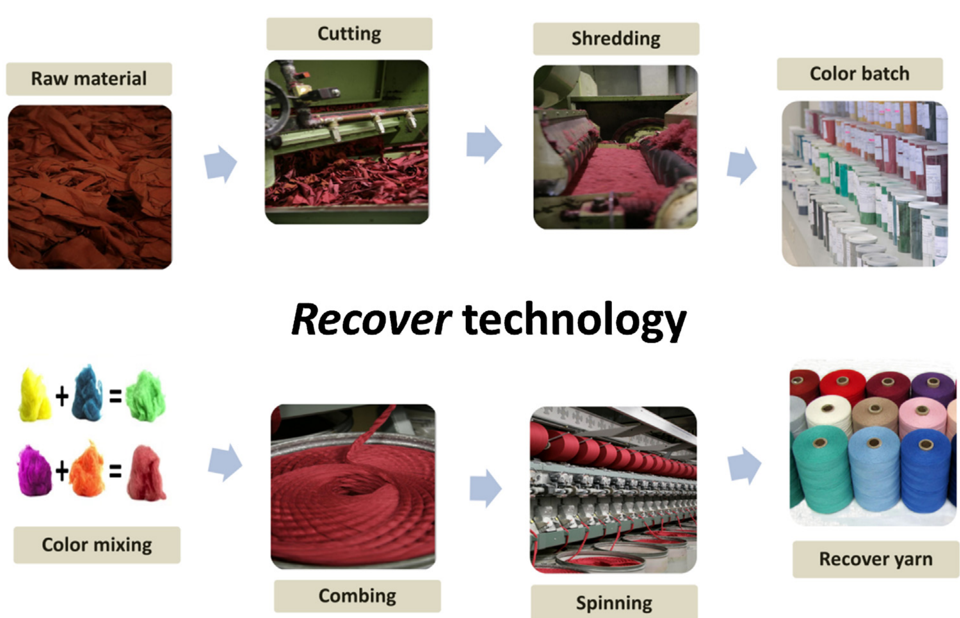


**Fig. 1.** Main steps involved in the production of Recover cotton fibres.

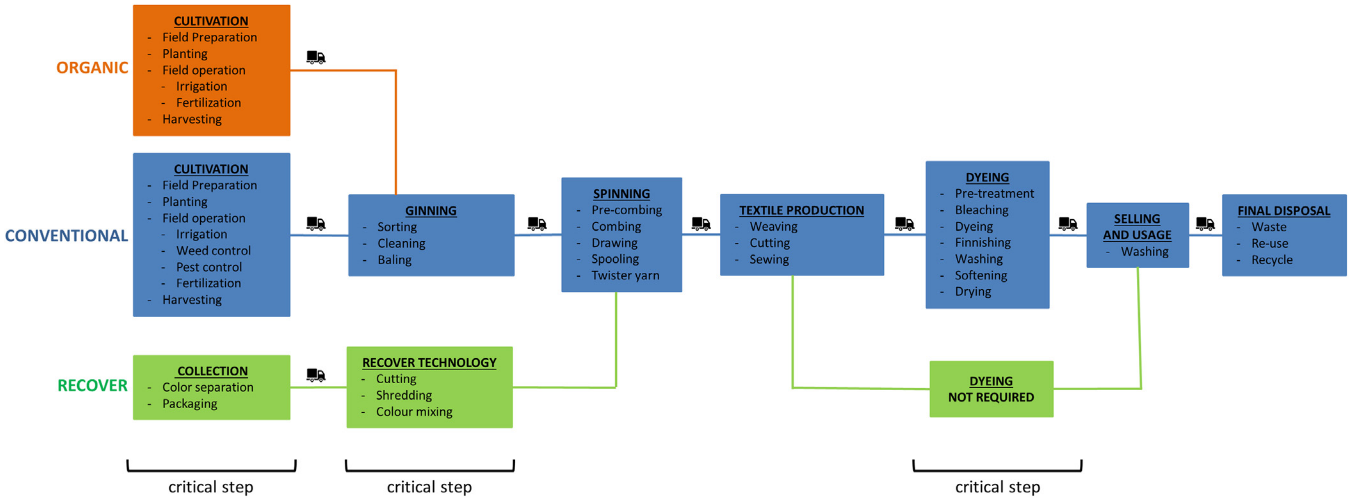


**Fig. 2.** Summary of the main steps involved in the production of textile clothes using conventional, organic, and Recover cotton.

can be also employed for the production of Recover cotton fibres. Then, textile wastes are cut into small pieces, shredded and gently opened back into fibres without damaging the fibre length. The obtained fibres have a length of 10–15 mm and accomplish high quality standards, concerning breaking strength (>8 Rkm), changes in mass Uster (<14%), colour fastness (3–4), washing colour fastness (3–5), and dry rubbing fastness (4). Finally, the use of open-end spinning technology allows a yarn production yield of 90%, and it can be mixed with synthetic fibres like polyester and acrylic for knitting, weft yarn and warp uses.

The process has similarities with ginning step involved in the production of conventional cotton. In this way, it can be created a coloured Recover cotton fibre, using different mixtures of coloured waste garments. Thus, following an appropriate selection of the raw recycled materials (colour matching) it can be created Recover cotton yarns in a full spectrum of colours, avoiding any dyeing process. So, Recover technology, evaluated through this study, allows a closed-loop and sustainable textile industry, avoiding all the environmental impacts related to the cotton cultivation and dyeing of yarns.

### 2.2. System boundary and declared unit

The main steps and differences in the production of cotton clothing by traditional and organic cotton cultivation, and Recover are depicted in Fig. 2. Three critical steps have been selected in order to highlight the differences between the evaluated strategies to obtain cotton yarn: cultivation/collection of cotton, ginning/cutting, and dyeing. Transportation of raw and produced materials for each production step was also considered and discussed. All the aspects related to the spinning of the yarn, textile production, selling and usage, and final disposal were not taken into account, considering that there are not differences in the process regardless of the type of cotton fibre employed (conventional, organic or Recover). The functional unit chosen is 1 kg of coloured cotton yarn. However, a T-shirt (0.3 kg) made with 100% cotton, was also employed as additional functional unit in discussion section.

### 2.3. Data collection

Environmental impacts associated to the production of cotton yarn have been evaluated and compared in this study, using LCA data obtained from the published literature, being those consistent with ISO 14040 and 14044 guidelines (ISO, 1997, 2006). Life cycle inventory (LCI) has been mainly calculated using GaBi software (PE International 2014a; Baydar et al., 2015; Zhang et al., 2015). However, other tools like CROPWAT platform (Ullah et al., 2015), the Intergovernmental Panel on Climate Change (IPCC) method (IPPC, 2003), and Simapro LCA software (Babu and Selvadass, 2013a), have been also employed in the reviewed literature.

The required energy consumption and the generated emissions involved in the production of Recover fibres were calculated collecting LCA data for European electricity generation (Eurelectric, 2011) and from Hilaturas Ferre (Banyeres de Mariola, Spain) and their providers. Data were collected as an average of the last two years, from 2013 to 2015. The production plant evaluated is located in Spain, and the textile waste and pre/post-consumer garments are obtained from China (35%), Portugal (30%), Spain (20%), and South America (15%). Output of Recover cotton yarn is mainly commercialized in Europe (70%) and China (30%). Thus, environmental impacts associated to the transport of raw materials to be recycled and Recover fibres have been also discussed.

### 2.4. Impact assessment

The LCA environmental impact categories evaluated in this study were: abiotic depletion potential (ADP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), aquatic eutrophication potential (AEP), terrestrial eutrophication potential (TEP), human toxicity potential (HTP), fresh water aquatic ecotoxicity potential (FETP), terrestrial ecotoxicity potential (TETP), ozone layer depletion (ODP), fresh water sediment ecotox infinite (FWSE), water use (WU), photochemical oxidation (PO), photochemical ozone formation potential (POFP), land use (LU), ecotoxicity (ECP), human toxicity-cancer (HTPC), and human toxicity-non cancer (HTPNC), as they have been widely defined in the literature (Zhang et al., 2015; Ullah et al., 2015; Baydar et al., 2015).

### 2.5. Life cycle inventory

LCI was evaluated estimating input and outputs required for the three aforementioned critical production steps of cotton yarn production: cultivation of cotton, ginning, and dyeing. Energy consumption was divided by the respective of consumed energy, such as: electricity, fossil fuels, coal, natural gas, or uranium. The main material input was water consumption, but other specific inputs were also included, such as: fertilizers, pesticides, and compost for cultivation steps, and wetting agent, hydrogen peroxide, dyes, stabilizers, soap and softener for dyeing step. Outputs were estimated

**Table 1**
Summary of life cycle inventory data for cotton cultivation under conventional and organic agriculture (data normalized for 1 kg of coloured cotton yarn).

| Category | Sub-category | Conventional | | | Organic | | | | Recover |
|---|---|---|---|---|---|---|---|---|---|
| | | Finland[a] | Pakistan | India | India | India | Finland[a] | India, USA, China, Turkey, Tanzania | Spain |
| Energy (MJ) | Electricity | 12.1 | 1.75–2.04 | – | – | – | 13 | – | 0 |
| | Fossil fuel | 47.7 | – | – | – | – | 40.6 | – | 0 |
| | Natural gas | 19.25 | – | – | – | – | 7.7 | – | 0 |
| | Crude oil | 22.3 | – | – | – | – | 23.9 | – | 0 |
| | Coal | 12.4 | – | – | – | – | 14.3 | – | 0 |
| | Liquefied petroleum gas | 1.47 | – | – | – | – | 1.47 | – | 0 |
| | Hydro-power | 1.0 | – | – | – | – | 1.0 | – | 0 |
| | Natural uranium | 7.0 | – | – | – | – | 7.5 | – | 0 |
| | Diesel | – | – | – | – | – | – | 0.538 | 0 |
| Material (kg) | Fertilizers | 0.457 | 0.184–0.204 | 0.187 | 0.0602 | 0.0997 | – | 0.0305 | 0 |
| | Pesticides | 0.016 | 0.0043–0.00506 | 0.00637 | 0 | 0 | – | – | 0 |
| | Water | 22200 | 4823–5947 | 2617 | 2793 | 1570 | 24000 | 127270 | 0 |
| | $H_2SO_4$ | – | 0.00092–0.00166 | – | – | – | – | – | 0 |
| | Compost | – | – | – | – | – | – | 0.473 | 0 |
| | Farm yard manure | – | – | 0.03433 | 0 | 5.866 | – | 4.25 | 0 |
| Air emissions (Kg) | $CO_2$ | 4.265 | 3.05–3.42 | – | – | – | 3.913 | – | 0 |
| | $CH_4$ | 0.0076 | – | – | – | – | 0.0061 | – | 0 |
| | $SO_2$ | 0.004 | – | – | – | – | 0.004 | – | 0 |
| | $NO_X$ | 0.0227 | 0.00282–0.00315 | – | – | – | 0.0227 | – | 0 |
| | HC | 0.005 | – | – | – | – | 0.005 | – | 0 |
| | CO | 0.0161 | – | – | – | – | 0.0172 | – | 0 |
| | $NH_3$ | – | 0.0179–0.0200 | – | – | – | – | – | 0 |
| | $NO_3$ | – | 0.202–0.223 | – | – | – | – | – | 0 |
| | $PO_4$ | – | 0.018–0.030 | – | – | – | – | – | 0 |
| Tillage (Ha) | | – | 0.00046–0.00050 | 0.000533 | 0.000742 | 0.000533 | – | – | 0 |
| References | | Kalliala and Nousiainen (1999) | Ullah et al. (2015) | Babu and Selvadass (2013a) | Babu and Selvadass (2013a) | Jackson (2005) | Kalliala and Nousiainen (1999) | PE International (2014a) | This study |

[a] This study was performed in Finland; however, the cotton source was not identified.

**Table 2**
Summary of life cycle inventory data for cotton dyeing (data normalized for 1 kg of coloured cotton yarn).

| Category | Sub-category | Bleaching | Dyeing | Green dyeing | Stone dyeing | Blue dyeing | Red dyeing | Continuous pad-dyeing | Dyeing | Recover |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy (MJ) | Electricity | 3.04 | 3.86 | 2.24 | 0.33 | 0.63 | 0.64 | 2.92 | 1.3–12.1 | 0 |
| | Coal | – | 69.12 | – | – | – | – | 4.47 | – | 0 |
| | Steam | 26.74 | 3.16 | 15.82 | – | – | – | 126 | 3.78–5.04 | 0 |
| | Hardwood logs | – | – | – | 17.73 | 22.16 | 5.697 | – | – | 0 |
| | Fuel oil | – | – | – | – | – | – | 0.0333 | – | 0 |
| | Crude oil | – | – | – | – | – | – | 0.0100 | – | 0 |
| | Diesel | – | – | – | – | – | – | 0.0459 | – | 0 |
| | Coke oven gas | – | – | – | – | – | – | 0.0612 | – | 0 |
| | Natural gas | – | – | – | – | – | – | 0.0006 | 28.8–33.8 | 0 |
| | Gasoline | – | – | – | – | – | – | 1.4 | – | 0 |
| Material (kg) | Water | 177 | 186 | 106 | 46 | 60 | 23 | 112 | 80–104 | 0 |
| | Dyes | 0.049 | 0.050 | 0.049 | 0.0018 | 0.021 | 0.019 | 0.088 | – | 0 |
| | Auxiliaries | – | 1.346 | – | – | – | – | – | – | 0 |
| | Water vapor | – | 77.78 | – | – | – | – | – | – | 0 |
| | Wetting agent | 0.01182 | – | 0.01182 | 0.0035 | 0.0035 | 0.0004 | – | – | 0 |
| | Enzymes | 0.00354 | – | 0.00354 | – | – | – | 0.0483 | – | 0 |
| | Acetic acid | 0.04728 | – | 0.03546 | 0.0035 | 0.0035 | 0.00131 | 0.0055 | – | 0 |
| | Sequestering agent | 0.02364 | – | 0.01182 | – | – | – | 0.01 | – | 0 |
| | Salt | 0.8274 | – | 0.8274 | – | – | – | 0.425 | – | 0 |
| | Soda ash | 0.2364 | – | 0.2364 | – | – | – | 0.216 | – | 0 |
| | Soap | 0.01182 | – | 0.01182 | 0.014 | 0.028 | 0.0105 | 0.010 | – | 0 |
| | Softener | 0.02364 | – | 0.02364 | – | – | – | 0.160 | – | 0 |
| | Silicon | 0.01182 | – | 0.01182 | – | – | – | – | – | 0 |
| | NaOH | 0.02955 | – | 0 | 0 | 0 | 2.8 | – | – | 0 |
| | Hydrogen peroxide | 0.02955 | – | 0 | – | – | – | 0.0429 | – | 0 |
| | Stabilizer | 0.00591 | – | 0 | 0.014 | 0.014 | 0.0016 | 0.0459 | – | 0 |
| | Sodyum thiosulphate | 0.01182 | – | 0 | – | – | – | – | – | 0 |
| | Lubricant agent | – | – | – | 0.007 | 0.007 | 0 | – | – | 0 |
| | Sodium sulfate | – | – | – | 0.210 | 0.560 | 0 | – | – | 0 |
| | Sodium carbonate | – | – | – | 0.035 | 0.140 | 0.016 | 0.08 | – | 0 |
| Air emissions (kg) | $NO_X$ | – | 0.095 | – | – | – | – | 0.00429 | – | 0 |
| | $CO_2$ | – | 7.843 | – | – | – | – | 12.33 | – | 0 |
| | Fly ash | – | 0.044 | – | – | – | – | – | – | 0 |
| | $SO_2$ | – | 0.0078 | – | – | – | – | 0.0135 | – | 0 |
| | CO | – | – | – | – | – | – | 0.00204 | – | 0 |
| | $CH_4$ | – | – | – | – | – | – | 0.0576 | – | 0 |
| | $N_2O$ | – | – | – | – | – | – | 0.0000665 | – | 0 |
| | Dust | – | – | – | – | – | – | 0.00700 | – | 0 |
| | $NH_3$ | – | – | – | – | – | – | 0 | – | 0 |
| Water emissions (kg) | Wastewater | 175.8 | 84.3 | 104.9 | 41.9 | 55.9 | 21.7 | 101.1 | – | 0 |
| | Phosphorus | – | 0.0000588 | – | – | – | – | – | – | 0 |
| | Hydrocarbons | – | 0.0000588 | – | – | – | – | – | – | 0 |
| | Solids (dissolved) | – | 0.0045752 | – | – | – | – | – | – | 0 |
| | Total nitrogen | – | 0.0058824 | – | – | – | – | – | – | 0 |
| | COD | 0.2303 | 0.0065359 | 0.1937 | – | – | – | 0.115315 | – | 0 |
| | VOC | – | – | – | – | – | – | 0.000265 | – | 0 |
| References | | Baydar et al. (2015) | Zhang et al. (2015) | Baydar et al. (2015) | Babu and Selvadass (2013b) | Babu and Selvadass (2013b) | Babu and Selvadass (2013b) | Yuan et al. (2013) | van der Velden et al. (2014) | This study |

**Table 3**
Environmental impacts categories, electricity consumption, and production yield for cotton ginning and cutting/shredding (data normalized for 1 kg of coloured cotton yarn).

| Category | Ginning | | | | | | Cutting/shredding |
|---|---|---|---|---|---|---|---|
| | India, USA, China, Turkey, Tanzania | Australia | Africa | India | Australia | Turkey | Spain |
| GWP (kg $CO_2$ eq) | 0.173 | – | 0.128 | – | – | – | 0.214 |
| AP (kg $SO_2$ eq) | 0.0016 | – | 0.0014 | – | – | – | 0.0025 |
| AP ($m^2$ UES) | – | – | – | – | – | 1.4 | – |
| EP (kg $PO_4^{3-}$ eq) | 0 | – | 0.000061 | – | – | – | 0.00021 |
| Energy consumption (MJ) | 2.48 | 0.20–0.26 | – | – | – | 0.63–0.95 | 1.31 |
| Production yield (%) | | | | | | | |
| Lint | 35.7 | – | 42.0–43.5 | 32.2–38.1 | 40.2–41.1 | – | 96.0 |
| Seed | 53.6 | – | – | – | – | – | – |
| Waste | 10.7 | – | – | – | – | – | 4.0 |
| References | PE International (2014a) | Ismail et al. (2011) | PE International (2014b) | Bajaj and Sharma (2012) | van der Sluijs (2015) | Baydar et al. (2015) | This study |

as air emissions of main gases like $CO_2$, CO, $CH_4$, $SO_2$, and $NO_X$. In the case of dyeing, emissions to water were also quantified considering their high incidence in the contamination of aquifers by dyes.

The LCI data concerning virgin cotton cultivation, following conventional and organic strategies, were obtained from different studies as can be seen in Table 1. The corresponding LCI data related to dyeing procedures is also summarized in Table 2. All these records were obtained from heterogeneous sources; so, data was normalized for 1 kg of coloured cotton yarn.

The use of Recover fibres as substitute of virgin cotton (conventional or organic), avoids all the costs and impacts related to the cultivation and dyeing of cotton. Nevertheless, a cutting/shredding step is required that involves the use of electricity. Therefore, Table 3 shows the electricity consumption and cotton production yield for cutting/shredding procedures, and also those required for standard ginning processes. Finally, environmental impacts coming from transport expenses will be discussed later in Section 3.4.

## 3. Results

### 3.1. Cotton cultivation

Some studies have quantified the environmental impact associated to the production of virgin cotton from a global point of view; thus, the data summarized through this study could be considered as an estimation of the average impact. Environmental impacts were obtained from different countries like China (Zhang et al., 2015), Pakistan (Ullah et al., 2015), Turkey (Baydar et al., 2015), India (Babu and Selvadass, 2013a), Africa (PE International, 2014b), and a pool of data concerning USA production together with that of other countries (PE International 2014a; Bevilacqua et al., 2014; CI, 2012) for the production of traditional cotton. These values were compared with those obtained for cotton cultivation following organic guidelines in Turkey (Baydar et al., 2015), India (Babu and Selvadass, 2013a; Jackson, 2005), and a pool of countries (PE International, 2014a). Environmental impact categories involved in cotton cultivation are related to the processes under conventional and organic agriculture are slightly different, as it can be seen in Table 4. GWP impact for conventional cotton is slightly higher (0.62–5.5 kg $CO_2$ eq) than that reported for organic cotton (0.98–2.40 kg $CO_2$ eq), but they can be considered similar taking into account the high variability within the same kind of cultivation, most likely due to the differences in the use of human labour, tractor and other farm machinery in every cotton crop. Similar WU data have been also observed, in the range of 0.177–14.74 and 0.106–2.79 $m^3$ $H_2O$ for conventional and organic crops, respectively. The most relevant differences are observed for those categories where the use of fertilizers and pesticides are involved: AP with values ranging from 0.0108 to 0.058 kg $SO_2$ eq for conventional crops, and from 0.0050 to 0.0068 kg $SO_2$ eq for organic; and also for EP that ranges from 0.003 to 0.070 kg $PO_4^{3-}$ eq, and from 0.0014 to 0.0028 kg $PO_4^{3-}$ eq for conventional and organic crops, respectively.

LCI data concerning to conventional and organic cotton were obtained from different studies (see Table 2). However, not enough data were found to estimate changes in the consumed energy, and then generated air emissions are quite similar. Nevertheless, great changes can be observed in material inputs. The use of fertilizers is strongly reduced in organic crops by one order of magnitude (from 0.184–0.457 to 0.0305–0.997 kg), while pesticide consumption is completely avoided.

It must be taken into account that most of the data found for cultivation, which are shown in Tables 1 and 4, also comprise ginning operations. However, the energy consumption, inputs and outputs of ginning procedure have a minimal contribution when compared to those of cotton cultivation.

### 3.2. Ginning vs cutting/shredding

The most employed automatized ginning technologies are basically: saw ginning (55%), double roller ginning (35%), rotary knife roller gin (5%), and single roller (5%) (Bajaj and Sharma 2012). These methods comprise the use of electricity with consumption reported values ranging from 0.20 to 0.95 MJ $kg^{-1}$ with lint yields from 32 to 43% (see Table 3). Scarce LCA data has been obtained from the literature regarding ginning operations, mainly due to the common inclusion of ginning impacts inside the general frame of cotton cultivation. The impacts of ginning have been quantified as GWP from 0.128 to 0.173 kg $CO_2$ eq, AP from 0.0014 to 0.0016 kg $SO_2$ eq, and the unique value found for EP was 0.0000612 kg $PO_4^{3-}$ eq. Thus, environmental impacts caused by ginning appear minimal when they are compared to those obtained for cotton cultivation. Moreover, these operations are the same, independently of the kind of cultivation practices, whether organic or not, employed for the production of virgin cotton.

In the case of Recover fibres, no ginning of cotton is required, but a cutting and shredding of recycled clothes must be performed previous to the spinning step. Thus, this cutting/shredding process has been compared to ginning one in terms of environmental impacts. LCA data for cutting/shredding step is also summarized in Table 3. Energy consumption was estimated in 1.31 MJ $kg^{-1}$ of

**Table 4**
Environmental impacts categories involved in cotton cultivation processes under conventional and organic agriculture (data normalized for 1 kg of coloured cotton yarn).

| Categories | Units | Conventional | | | | | | | | Organic | | | | Recover |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | China | Pakistan | Turkey | Egypt, China, India, USA | India, USA, China, Turkey, Tanzania | Africa | India | Global | Turkey | India, USA, China, Turkey, Tanzania | India | India | Spain |
| ADP | kg Sb eq | 0.0000182 | 0.020 | – | – | – | – | 0.0120 | – | – | – | 0.00933 | 0.00609 | 0 |
| GWP | kg $CO_2$ eq | 2.37 | 3.15 | 5.5 | 0.62–0.89 | 1.808 | 0.871 | 1.32 | 1.54 | 1.5–2.4 | 0.978 | 1.08 | – | 0 |
| AP | kg $SO_2$ eq | 0.0584 | 0.051 | – | – | 0.0187 | 0.0108 | 0.0115 | 0.0187 | – | 0.0057 | 0.00678 | 0.005012 | |
| | $m^2$ UES | – | – | 0.52 | – | – | – | – | – | 0.17–0.30 | – | – | – | 0 |
| EP | kg $PO_4^{3-}$ eq | 0.0113 | 0.056 | – | 0.04–0.07 | 0.0038 | 0.0202 | 0.00289 | 0.0038 | – | 0.0028 | 0.00195 | 0.00138 | 0 |
| AEP | kg $NO_3^-$ eq | – | – | 0.22 | 0.03–0.05 | – | – | – | – | 0.010–0.015 | – | – | – | 0 |
| TEP | kg $NO_3^-$ eq | – | – | 1.50 | – | – | – | – | – | 0.38–0.83 | – | – | – | 0 |
| HTP | kg 1,4-DB eq | – | 2.78 | – | – | – | – | 1.11 | – | – | – | 0.932 | 0.670 | 0 |
| FETP | kg 1,4-DB eq | – | 5.44 | – | – | – | – | 0.479 | – | – | – | 0.384 | 0.245 | 0 |
| TETP | kg 1,4-DB eq | – | 1.01 | – | – | – | – | 0.0103 | – | – | – | 0.009473 | 0.00623 | 0 |
| ODP | kg CFC-11 eq | – | – | – | – | – | – | 8.9E-08 | 7.6E-09 | – | – | 5.8E-08 | 4.8E-08 | 0 |
| | kg ethene-eq | 0.00142 | – | – | – | – | – | – | – | – | – | – | | |
| FWSE | | – | – | – | – | – | – | 1.02 | – | – | – | 0.825 | 0.527 | 0 |
| WU | $m^3$ $H_2O$ | 9.13 | 5.16 | 0.177 | 3.88–14.74 | 2.12 | 3.40 | 2.61 | 2.74 | 0.106 | 0.182 | 2.79 | 1.57 | 0 |
| PO | | – | – | – | – | – | – | 0.000536 | – | – | – | 0.000333 | 0.000229 | 0 |
| POFP | $m^2$ UES*ppm*h | – | – | 45 | – | – | – | – | – | 28-60 | – | – | – | 0 |
| LO | $m^2$ | – | – | – | – | – | – | 0.147 | – | – | – | 0.147 | 0.104 | 0 |
| ECP | CTUeco | 76.73 | – | – | – | – | – | – | – | – | – | – | – | 0 |
| HTPC | CTUh | 1.61E-07 | – | – | – | – | – | – | – | – | – | – | – | 0 |
| HTPNC | CTUh | 1.72E-06 | – | – | – | – | – | – | – | – | – | – | – | 0 |
| References | | Zhang et al. (2015) | Ullah et al. (2015) | Baydar et al. (2015) | Bevilacqua et al. (2014) | PE International (2014a) | PE International (2014b) | Babu and Selvadass (2013a) | CI (2012) | Baydar et al. (2015) | PE International (2014a) | Babu and Selvadass (2013a) | Jackson (2005) | This study |

cotton treated, which doubles those values obtained for ginning procedures, due to the intensity of the process. As it can be seen, GWP (0.214 kg $CO_2$) eq and EP (0.00021 kg $PO_4^{3-}$ eq) categories were slightly increased, by moving from ginning of virgin cotton, to cutting and shredding of the recovered one. Nevertheless, a high efficiency of the method was obtained with a production yield of 96% fibres. Wastes have been characterized as short fibres with a potential utility for the production of building isolation materials, thus providing a new life for these residues.

### 3.3. Dyeing

There are different procedures for the dyeing of clothes or yarns, being the desired colour an important factor to be considered due to different chemical consumption related to each colour. It must be also taken into consideration that dyeing can be performed over the finished clothes, but also directly to the yarns before weaving. Table 5 shows the environmental impacts categories involved in different dyeing studies. GWP data ranges from 7.0 to 17.3 kg $CO_2$ eq, which are almost one order of magnitude higher than those obtained in cultivation steps. The other impacts evaluated show a low variability and they are in the same order than those found for cultivation of cotton with values ranging from 0.037 to 0.997 kg $SO_2$ eq for AP, from 0.010 to 0.017 kg $NO^{3-}$ eq for AEP, from 0.47 to 0.60 kg $NO^{3-}$ eq for TEP, and from 0.00083 to 0.00870 kg $PO_4^{3-}$ eq or from 0.010 to 0.018 kg $NO^{3-}$ eq for EP. LCI data for cotton dyeing procedures founded in the literature (see Table 2) shows that energy consumption ranges from 0.3 to 12.1 MJ of electricity, and from 3.2 to 126.0 MJ of steam. Water use in dyeing technologies are in the 23–186 kg range, while chemical consumption data are highly heterogeneous ranging from 0.0018 to 0.0880 kg for dyes, from 0.0004 to 0.0118 kg for wetting agents, from 0.010 to 0.028 kg for soaps, and from 0.024 to 0.216 kg for softeners. The generated air emissions were in the range of 7.84–12.33 kg for $CO_2$, 0.004–0.095 kg for $NO_X$, and 0.0078–0.0135 kg for $SO_2$. Water emissions can be really problematic, considering the high toxicity of dye residues, with a wastewater production in the 21.7–175.8 kg range.

The use of both, conventional and organic cotton, comprises a dyeing step to obtain the desired colour. However, in the case of Recover technology, the appropriate selection of coloured cutting scarps defines the final colour of the fibre to be obtained. Thus, there is no need to any dyeing step and consequently all impacts related to this process can be reduced to nil. This factor added to those given by the absence of cotton cultivation make relevant the production of Recover cotton as an environmentally friendly alternative to standard textile production procedures. In addition, the use of industrial wastes moves from a disposal or incineration raw material to an added value starting point of the production of a new generation of cotton yarn with extremely reduced environmental impacts as compared with those processes which start from virgin cotton.

### 3.4. Transport

It exist a high heterogeneity and variability in the location and distance between the production of raw materials and the cotton spinning plants around the world. Thus, the environmental impacts associated to freight transportation must be adapted plant by plant, and they are easy to calculate for specific cases, but very difficult for a global estimation due to the high diversity of every situation. The global freight transportation in textile sector is distributed as a 4% by air, 21% marine transport, and the rest by truck, being the average shipping distance 410 km for truck, 1408 km by air, and 5337 km for water (Borken-Kleefeld and Weidema, 2013).

In the case of Recover cotton, we have employed data provided from Hilaturas Ferre (HIFESA, 2016), which obtain the raw mate-

**Table 5**
Environmental impacts categories involved in textile dyeing (data normalized for 1 kg of coloured cotton yarn).

| Categories | Units | Bleaching | Dyeing | Green dyeing | Stone dyeing | Blue dyeing | Red dyeing | Recover |
|---|---|---|---|---|---|---|---|---|
| ADP | kg Sb eq | – | 3.69E-05 | – | – | – | – | 0 |
| GWP | kg $CO_2$ eq | 12.5 | 13.7 | 9.0 | 12.7 | 17.3 | 7.0 | 0 |
| AP | kg $SO_2$ eq | – | 0.997 | – | 0.0618 | 0.0851 | 0.0374 | 0 |
| | $m^2$ UES | 0.43 | – | 0.34 | – | – | – | |
| AEP | kg $NO_3^-$ eq | 0.017 | – | 0.010 | – | – | – | 0 |
| TEP | kg $NO_3^-$ eq | 0.60 | – | 0.47 | – | – | – | 0 |
| EP | kg $PO_4^{3-}$ eq | – | 0.00872 | – | 0.00125 | 0.00174 | 0.000831 | 0 |
| | kg $NO^{3-}$ eq | 0.018 | – | 0.010 | – | – | – | |
| FETP | kg TEG water | – | – | – | 729 | 934 | 355 | 0 |
| TETP | kg TEG soil | – | – | – | 234 | 297 | 109 | 0 |
| ODP | kg CFC-11 eq | – | – | – | 5.23E-07 | 6.63E-07 | 3.03E-07 | 0 |
| | kg ethene-eq | – | 0.00661 | – | – | – | – | |
| WU | $m^3$ $H_2O$ | – | 0.809 | – | – | – | – | 0 |
| POFP | $m^2$ UES*ppm*h | 51 | – | 40 | – | – | – | 0 |
| LO | $m^2$ | – | – | – | 0.360 | 0.456 | 0.162 | 0 |
| ECP | CTUeco | – | 5.37 | – | – | – | – | 0 |
| HTPC | CTUh | – | 1.185E-06 | – | – | – | – | 0 |
| HTPNC | CTUh | – | 1.119E-06 | – | – | – | – | 0 |
| References | | Baydar et al. (2015) | Zhang et al. (2015) | Baydar et al. (2015) | Babu and Selvadass (2013b) | Babu and Selvadass (2013b) | Babu and Selvadass (2013b) | This study |

rial from Portugal (30%) and Spain (20%) traders by truck, and from China (35%) and South America (15%) using overseas transport. The average transport has been estimated as 568 km by truck and 14355 km by container ship. Overseas transport has also an average additional transportation by road of 105 km. The environmental impacts related to the employed freight transport normalized for 1 kg and 1 km distance are: $CO_2$ emission from 4.2 $10^{-5}$ to 1.7 $10^{-4}$ kg for road and from 1.2 $10^{-6}$ to 4.3 $10^{-6}$ kg for ship transport; NOx emission of 0.4–2.2 $10^{-6}$ kg for road and 0.9–1.2 $10^{-7}$ kg for ship; and particles emission from 4.0 $10^{-9}$ to 93.3 $10^{-9}$ kg for road and from 6.0 $10^{-7}$ to 1.1 $10^{-5}$ kg for ship (Eriksson et al., 1996; Facanha and Horvath, 2006; Mötzl, 2009; Gernez, 2011). Consequently, it can be seen that sea transport of freight reduces air emissions one order of magnitude as compared with road transport. So, in spite of the long distances for the overseas transport of the raw materials required in the production of Recover cotton, their environmental impact incidence can be considered minimal when compared to the steps involved in conventional cotton production. Other studies support this theory, considering that the use of energy for transportation of textile products is minimal, and shifting location of production does not reduce significantly environmental impacts (Allwood et al., 2006).

## 4. Discussion

Considering the average range values for each evaluated LCA category per functional unit, the environmental saving provided by the use of organic farming strategies can be estimated as: 0.53 kg $CO_2$ eq for GWP (26%), 0.022 kg $SO_2$ eq for AP (79%), 0.028 kg $PO_4^{3-}$ eq for EP (93%), and 4332 kg water for WU (79%). So, it can be concluded that on moving from traditional cultivation of cotton to organic farming, a considerable reduction of AP, EP and WU impacts is provided, while GWP impact is slightly reduced. In the same way, all environmental impacts are drastically reduced using Recover technology, because of cultivation, ginning, and dyeing steps are replaced by a high efficacy cutting/shredding step. Thus, the environmental savings are 13.98 kg $CO_2$ eq for GWP, 0.32 kg $SO_2$ eq for AP, 0.033 kg $PO_4^{3-}$ eq for EP, and 5594 kg water for WU impact category.

The main environmental impacts (GWP, AP, EP and WU) have been compared in Fig. 3 for conventionally growth, organic farm-

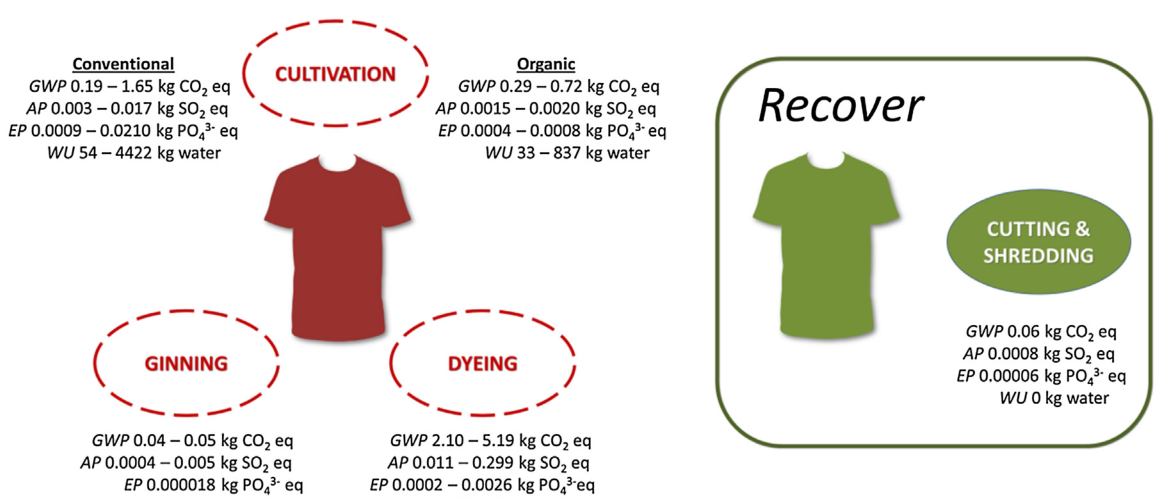


**Fig. 3.** Environmental impacts of a cotton T-shirt (0.3 kg) as a function of the steps involved in traditional and organic-cotton based plants and those employing Recover technology (Note: Impacts related to yarn spinning, textile production, selling and usage, final disposal, and transport were no considered).

ing, and Recover cotton. In this case, the selected functional unit was a standard T-shirt as example of textile product, a widely use functional unit to evaluate different scenarios (Allwood et al., 2006; Roos and Peters, 2015). As it can be seen, the production of a T-shirt using Recover cotton considerably reduces main environmental side effects compared to the use of virgin cotton.

## 5. Conclusions and future trends

Data reported in this study show the advantages to move from traditional cotton cultivation to organic farming in order to greening the production step. However, the use of organic cotton also requires a dyeing process, which is far to be considered as a sustainable practice and has deleterious effects on the environment preservation. On the contrary, the introduction of Recover technology, based on the use of upcycled raw materials and a smart selection of coloured fibres, avoids both, cotton cultivation and dyeing environmental side effects and replaces the impacts of ginning to those of a cutting/shredding step. Furthermore, the recycling of industrial cotton wastes offers a second life for the product, thus reducing the deleterious effects and cost of disposal and/or incineration.

However, as it has been indicated through this study, we are in a starting point of the use of recycled cotton fibres as raw materials. Additionally, extensive studies must be required to fully validate the real impact of this technology and to provide further data on the LCA evaluating the use of disposal as raw materials, which has not been quantified in our study, and the environmental costs of transportation for which deep calculation it will be necessary the cooperation of producers all around the world.

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## References

Allwood, J.M., Laursen, S.E., Malvido de Rodríguez, C., Bocken, N.M.P., 2006. Well Dressed. University of Cambridge, Cambridge, UK, ISBN 1-902546-52-0.

Babu, K.M., Selvadass, M., 2013a. Life cycle assessment for cultivation of conventional and organic seed cotton fibres. Int. J. Res. Environ. Sci. Technol. 3, 39–45.

Babu, K.M., Selvadass, M., 2013b. Life cycle assessment for the dyeing and finishing process of organic cotton knitted fabrics. J. Text. Apparel Technol. Manag. 8, 1–16.

Bajaj, L., Sharma, M.K., 2012. Future Trends in Cotton Ginning and Pressing Technologies. Bajaj Steel Industries Limited, Nagpur, India http://www.bajajngp.com/images/technical/5th.pdf.

Baydar, G., Ciliz, N., Mammadov, A., 2015. Life cycle assessment of cotton textile products in Turkey. Res. Conserv. Recy 104, 213–223.

Bevilacqua, M., Ciarapica, F.E., Mazzuto, G., Paciarotti, C., 2014. Environmental analysis of a cotton yarn supply chain. J. Clean Prod. 82, 154–165.

Borken-Kleefeld, J., Weidema, B.P., 2013. Global default data for freight transport per product group. Int. J. Life Cycle Assess., ecoinvent report No. 1.

CI, Cotton incorporated, 2012. Life Cycle Assessment of Cotton Fiber & Fabric. Cotton incorporated, Cary, NC, USA.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., Gautam, R., 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol. Econ. 60, 168–203.

Eriksson, E., Blinge, M., Lövgren, G., 1996. Life cycle assessment of the road transport sector. Sci. Total Environ. 189–190, 69–76.

Eurelectric, Union of the Electricity Industry, 2011. Life Cycle Assessment of Electricity Generation. Eurelectric, Brussels, Belgium.

FAOSTAT, 2016. Food and Agriculture Organization of the United Nations – Statistics Division. http://faostat3.fao.org (accessed 1.07.16.).

Facanha, C., Horvath, A., 2006. Environmental assessment of freight transportation in the U.S. Int. J. LCA 11, 229–239.

GHK, 2006. A study to examine the benefits of the End of Life Vehicles Directive and the costs and benefits of a revision of the 2015 targets for recycling, re-use and recovery under the ELV Directive. http://ec.europa.eu/environment/waste/pdf/study/final_report.pdf.

Gernez, E., 2011. An Assessment of the Environmental Impact of Cargo Transport by Road and Sea in Iceland. University of Akureyri, Akureyri, Islandia http://hdl.handle.net/1946/9332.

HIFESA, 2016. Hilaturas Ferre. http://www.hifesa.com/ (accessed 01.07.16.).

IPPC, Integrated Pollution Prevention and Control, 2003. Reference Document on Best Available Techniques for the Textiles Industry. European Commission.

ISO, International Organization for Standardization, 1997. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, ISO 1404:1997.

ISO, International Organization for Standardization, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, ISO 1404:2006.

Ismail, S.A., Chen, G., Baillie, C., Symes, T., 2011. Energy uses for cotton ginning in Australia. Biosyst. Eng. 109, 140–147.

Jackson, G.J., 2005. Organic Cotton Farming In Kutch. Agrocel, Gujarat, India.

Kalliala, E.M., Nousiainen, P., 1999. Life cycle assessment – Environmental profile of cotton and polyester-cotton fabrics. AUTEX Res. J. 1, 1.

Mötzl, H., 2009. Life Cycle Assessment of Means of Transport for Goods Traffic. www.umweltbundesamt.at.

Morley, N., Slater, S., Russell, S., Tipper, M., Ward, G.D., 2006. Recycling of Low Grade Clothing Waste. Oakdene Hollins Ltd, Salvation Army Trading Company Ltd. http://www.oakdenehollins.co.uk/pdf/defr01_058_low_grade_clothing-public_v2.pdf.

PE International, 2014a. Life Cycle Assessment (LCA) of Organic Cotton, A Global Average. PE International AG 11 http://farmhub.textileexchange.org/upload/library/Farm%20reports/LCA_of_Organic_Cotton%20Fiber-Summary_of%20Findings.pdf.

PE International, 2014b. Life Cycle Assessment (LCA) of Cotton Made in Africa (CmiA). PE International AG 11 http://www.cottonmadeinafrica.org/fr/deutsch-docs/cmia-standard/wirkungsmessung/61-cmia-life-cycle-assessment-2014/file.

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43, 4098–4104.

Roos, S., Peters, G.M., 2015. Three methods for strategic product toxicity assessment—the case of the cotton T-shirt. Int. J. Life Cycle Assess. 20, 903–912.

Roos, S., Posner, S., Jönsson, C., Peters, G.M., 2015. Is unbleached cotton better than bleached? exploring the limits of life-Cycle assessment in the textile sector. Cloth. Tex. Res. J. 33, 231–247.

Ullah, A., Perret, S.R., Gheewala, S.H., Soni, P., 2015. Eco-efficiency of cotton-cropping systems in Pakistan: an integrated approach of life cycle assessment and data envelopment analysis. J. Clean. Prod., Available online.

van der Sluijs, M.H.J., 2015. Impact of the ginning method on fiber quality and textile processing performance of Long Staple Upland cotton. Text. Res. J. 85, 1579–1589.

van der Velden, N.M., Patel, M.K., Vogtländer, J.G., 2014. LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane. Int. J. Life Cycle Assess. 19, 331–356.

Woolridge, A.C., Ward, G.D., Phillips, P.S., Collins, M., 2006. Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: an UK energy saving perspective. Res. Conserv. Recy. 46, 94–103.

Yuan, Z.W., Zhu, Y.N., Shi, J.K., Liu, X., Huang, L., 2013. Life-cycle assessment of continuous pad-dyeing technology for cotton fabrics. Int. J. Life Cycle Assess. 18, 659–672.

Zhang, Y., Liu, X., Xiao, R., Yuan, Z., 2015. Life cycle assessment of cotton T-shirts in China. Int. J. Life Cycle Assess. 20, 994–1004.