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LIFE CYCLE ASSESSMENT OF TWO TEXTILE PRODUCTS

WOOL AND COTTON

ALBINO ANDRÉ MOREIRA CARDOSO

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President of the jury: Prof. Dr. Cidália Maria de Sousa Botelho
(Assistant Professor from the Department of Chemical Engineering from the Faculty of Engineering, Porto University, Portugal)

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Supervisor at the University: Prof. Dr. Belmira de Almeida Ferreira Neto
(Assistant Professor from the Department of Metallurgical and Materials Engineering from the Faculty of Engineering, Porto University, Portugal)

Supervisor at the hosting institution: Dr. Mireille Faist Emmenegger
(Director, operations, project manager of Quantis Switzerland/Germany. Formerly researcher at Empa)

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Abstract

The textiles represent the fourth largest manufacturing industry worldwide in terms of revenues and production. This sector leads to significant burdens in the environment due to the activities taking place during the yarn fibre manufacture including the raw fibre production (agriculture), spinning, dyeing and finishing processes. Therefore, it is very important to assess the impacts and find ways to reduce its impacts and improve the environmental performance of this industrial sector.

In the present study the life cycle stages associated with the processing wool and cotton are assessed based on real data obtained from some of the company (i.e. HUGO BOSS) suppliers' activity in 2011. It comprises the production of raw fibre (sheep farming and cotton cultivation), spinning, dyeing, dyeing & bleaching and scouring wool. The analysis was performed with the SimaPro software using ILCD impact assessment method and results are presented for the characterization step. The method allowed the quantification of potential environmental impacts at midpoint and the selected impact categories were: climate change, ozone depletion, human toxicity cancer effects, human toxicity non-cancer effects, eutrophication (freshwater and marine), freshwater ecotoxicity and water resource depletion.

The inventories were built using primary data made available by suppliers and secondary data was estimated based on existing models (mainly to model agriculture emissions) or taken from the ecoinvent databases. Results are analysed life cycle stage by life cycle stage for each material. Scenarios were created in order to assess the multiple combinations possible for the production of cotton and wool yarns based on the distinct processes taking part at each supplier. A worst and a best case scenarios are built that both materials can be compared in terms of impact.

Results show that in general, the field emissions in raw fibre production (more specifically the livestock emissions in sheep farming and the losses in the fertilizers to the environment in the cotton cultivation) show to contribute largely to the overall environmental impact categories studied. The production of fertilizers is another activity that shows a relevant pressure in the environment.

The results concerning the spinning processes show that the large electricity demand and electricity production leads to the major contribution in the cotton and the wool yarns manufacture. Water use, packaging and chemicals production (mainly in wool's spinning mills) also contribute significantly to environment problems. The dyeing (and bleaching) and scouring wool as a wet processes need considerable amounts of water and that is very much associated with the energy needed for heating and cooling baths and for drying yarns or fibres. Activities which are not directly associated to the company activity as the production of wire used for packaging and transoceanic transports emerge as important contributors in most of the categories for the scouring mill.

When the entire supply chain is analysed it is observed that the raw fibre production (named as sheep farming for wool and cotton cultivation for cotton) is the life cycle stage that is the main contributor to the impacts. In the worst case scenario, wool yarns have the largest impacts in the overall results except for freshwater eutrophication and water resource depletion. When a best case scenario is regarded, cotton has the largest burdens in categories as freshwater eutrophication, marine eutrophication, freshwater ecotoxicity and water resource depletion.

Keywords:
Life Cycle Assessment (LCA) | Textiles | Cotton | Wool | Sheep farming | Cotton cultivation | Scouring wool | Spinning | Dyeing | Bleaching

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Abbreviations	
BAT	Best Available Technologies
FAO	Food and Agriculture Organization of the United Nations
FU	Functional Unit
ILCD	Indicators from the International Reference Life Cycle Data System
PET	Polyethylene terephthalate
RSB	The Roundtable on Sustainable Biomaterials
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Units	
ha	hectare
kg	kilograms
kg DM	kilograms of dry matter
km	kilometre
kWh	kilowatt hour
L	litres
m^2	square meters
m^2.a	square meters year
Mt	mega tonne (1 000 000 tonne = 1 000 000 000 000 kg)
s.u.	stock units
t	tonne
tkm	tonne-kilometre (t*km)
Chemicals	
Heavy metals	
Cd	cadmium
Cr	chromium
Cu	copper
Hg	mercury
Ni	nickel
Pb	lead
Zn	zinc
Others	
AOX	halogenated organic compounds
BOD	biochemical oxygen demand / if BOD_5 (5 days of incubation at 20 °C)
CH_4	methane
CFC	chlorofluorocarbon
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
COD	chemical oxygen demand
H_2O_2	hydrogen peroxide
HCFC	hydrochlorofluorocarbon
VOC	volatile organic compounds
NaOH	sodium hidroxide
NOx	nitrogen oxides
N	nitrogen
N_2O	dinitrogen monoxide or nitrous oxide
NH_3	ammonia
P	phosphorus

1 INTRODUCTION

The textiles represent the fourth largest manufacturing industry worldwide in terms of revenues and production. The apparel sector is forming the most representative sector of this industry [1]. The textile industries are responsible for the production of yarn, fabric, and finished goods from natural or manmade fibers. Table 1 shows the different materials possible to produce from natural and man-made fibers.

Table 1 – Textile fibres [2]

Categories	Sub-Categories		Example of fibres
Natural Fibers	Organic	Vegetable fibers	Cotton Flax, Hemp Jute, Sisal, Broom
		Animal fibers	Wools Silk
	Inorganic	Mineral fibers	Basalt Asbestos
Manmade fibers	Organic regenerated natural fibers		Regenerated cellulose Viscose Cellulose acetate Cellulose triacetate
	Organic synthetic polymers		Polyester Polyamide Polyolefins Polyacrilic
	Inorganic fibers		Glass Carbon

The fiber production and consumption are increasing annually due to the population growth, the increasing fiber consumption with increasing per capita prosperity and the continual increasing of new applications for textiles

The clothing and textiles constitute about seven per cent of the world's exports in terms of sales. About one third of the sales were made in Western Europe, the same amount in North America and one quarter in Asia. In 2000 the industry employed 26.5 million people worldwide. More than 25 per cent of the world's production of clothing and textiles is made in China [3]. The volume of the world's fiber production, associated to the textile industry in 2012, was around 88.5 Mt, from which 56 Mt were manmade (40% polyester) and 32.5 Mt natural fibers (80% cotton) [4]. Summing up synthetic fibers does represent 64% of the overall amount of the production of textile fibers.

Cotton and wool are the world's most produced natural fibers. FAO in 2011 estimated a production of 26.1 Mt for cotton and 2.0 Mt for wool. China, United States and India are the three world level largest producers of cotton with productivity yields amounting respectively 6.58, 5.98 and 3.41 Mt. In the same year, the annual wool production is around 2.0 Mt. China has a share of 0.39 Mt, Australia 0.36 Mt and New Zealand 0.17 Mt [5, 6].

The World Bank estimates that 17 to 20 per cent of industrial water pollution comes from textile industry, mainly from the operations of dyeing and finishing. This sector is the second main contributor to clean water pollution. This is associated with the large amounts of water used, the energy needed to heat water and the large quantities of chemicals used in these processes[7].

The consumer's consciousness for textile products produced in more environmentally friendly way is increasing every time. At the same time its price is also an important criterion for purchasing. The pressure in this industry is promoted by markets which demand products with superior performance and quality as well as by regulations for sustainability and cleaner production. This is a strong motive for the textile companies to focus more and more on the production of sustainable products regarding its supply chain.

It is now clear that optimizations in the management performance of the supply chains turns it possible to achieve higher profits and improve the social and environmental performance of the business sector [8]. To improve this in a company or industry, it is necessary to understand how the supply chain system works, which symbiosis exists and where the opportunities to improve those relationships are. In an environmental point of view, life cycle assessment is an important tool used to evaluate the environmental burdens over the entire life-cycle of products and services. This tool analyses all the life cycle stages of products from raw material extraction to production process, distribution, use, and final disposal. It offers a holistic perspective of the supply chain performance and can help decision makers on identifying more efficient supply chains.

1.1 EcoLogText

The work presented is part of my internship tasks in the EcoLogTex project, at the Life Cycle Assessment and Modelling Group of EMPA (the Swiss Federal Laboratories for Materials Science and Technology) in collaboration with HUGO BOSS and IDSIA (Istituto Dalle Molle di Studi sull'Intelligenza Artificiale). Currently, due to a spin-off to the new branch of Quantis (Quantis Switzerland / Germany), the EMPA's group doesn't exist anymore and the project is now developed by the latter mentioned organization (Quantis).

The project EcoLogTex aims to deliver a new methodology and a tool (web-based software application) to evaluate alternatives for the textile supply chains taking into account the impact on the environment, while satisfying corporate social responsibility constraints. The results of this project will allow the textile companies to efficiently optimize their supply chains and suppliers to benchmark themselves. The integration of LCA in each step of the supply chain for the textile industry might add the environmental perspective when designing a more environmentally effective supply chain [9]. Questionnaires specific for the different life cycle stages of the supply chain for the two textile products in focus (cotton and wool) have been developed and sent to HUGO BOSS' suppliers and to other companies active in its supply chains (cotton growers, spinning mills, dyeing mills, finishing companies, assembly etc.), in order to obtain data used to assess the different processes from the life cycle of textile production.

The information is made available from the suppliers or estimated. The data considered includes specific data from companies as the consumption of energy, chemicals and water and production of waste as well as emissions in water and air and soil. The values were modelled into an inventory using the Ecoinvent database v2.2 for background data (www.ecoinvent.org).

During the internship at EMPA the data was analyzed and was used to model the environmental impacts by using SimaPro (LCA commercial software tool). The results obtained for the different suppliers from different parts of the supply chain for the two main fabrics in focus by EcoLogTex (i.e. cotton and wool) are presented in this study. Moreover, scenarios for the production of dyed wool and cotton are created, the worst and best case selected and the yarn production for both cases scenarios and materials are compared.

1.2 Thesis objective and goal

The main goal of this study is to assess the environmental burdens associated with the different life cycle stages from two textile products (cotton and wool) comprising: fibre production, spinning, dyeing, dyeing & bleaching and scouring wool. Scenarios for the production of the two yarns for each material (cotton and wool) were built based on the distinct processes reported by the suppliers for the different life cycle stages. This study compares the worst and the best scenarios in terms of environmental impacts for each material. Inventory data is collected from several suppliers and refer to 2011.

This study is elaborated following the scope of EcoLogTex project and its specifications. The environmental impacts are quantified using LCA and the guidelines reported in the ISO 14040:2002 [10]. In terms of the assessment of the impact categories this work performs LCIA until the characterization step and the methods used are taken from ILCD recommendations [11] due to the requirements of the above mentioned project. The main life cycle stages contributing to the impacts are identified. This is to say that the relevant emissions underlining each calculated impact categories (e.g. climate change induced by energy use due to greenhouse gas emissions from power plants). In the end scenarios are created in order to ascertain a comparison for the environmental performance of wool and cotton dyed yarns production. A comparative analysis among the best and the worst scenario is made.

1.3 Thesis outline

Chapter 1 overviews the main characteristics of the textile industry, including the annual average production and its environmental pressures. The role of the study in the EcoLogTex project is summarized and, at the end, the thesis's goals, objectives and structure are identified.

Chapter 2 presents and characterises the main processes of the textile industry supply chain for wool and cotton. A review of the main LCA studies in this sector and the main conclusions in terms of environmental problems are briefly presented.

Chapter 3 presents the LCA methodology and its application to the study. Following the ISO 14040:2002 [10] the main steps of LCA (goal and scope, inventory analysis, impact assessment and interpretation) are described while study data is presented. The study boundaries for each life cycle stage are drawn and the inventory data analysed.

Chapter 4 presents and discusses the LCA results for each life cycle stage of each material assessed (cotton and wool). The major contributors are identified and discussed.

In Chapter 5 combinations of several possible processes are presented resulting in the production of cotton and wool yarns. Subsequently two cases scenarios (worst and best) are identified and used to perform a comparative evaluation for each life cycle stage and for each textile product analysed. This is to understand which life cycle stages contribute mostly to the overall impact and to compare the environmental performance of the two textile products.

Chapter 6 draws and discusses the conclusions of the study. Recommendations for further works, based on the identified limitations, are listed.

2 CHARACTERIZATION OF THE LIFE CYCLE STAGES

Generally, all textile fibers are processed in a similar way: raw fibers are produced, collected and prepared to be spun by spinning mills. The produced yarn might pass through other pretreatments before being transformed into a knitted or woven fabric. After that, fabrics are cut and assembled into clothes which are ready to be transported to retailers, distributed to stores and sold to the final consumer, which will use them until its final destination. Between different stages the use of transportation is needed and the travelling distances might vary from short to medium and long (e.g. country, continent or transcontinental trips). This industry is identified has having one of the most complex industrial chains [12].

The present study focus on the production of wool and cotton dyed yarns. Having distinct natural origins (vegetal and animal), some processes are different for the two materials (cotton and wool). The cotton is harvested, dried and ginned while the greasy wool is scoured after the sheep shearing. Figure 2 and Figure 1 illustrate, respectively for cotton and wool, an example of the supply chain highlighting the main activities taking place on the production process (i.e. fibre to textile fabric).

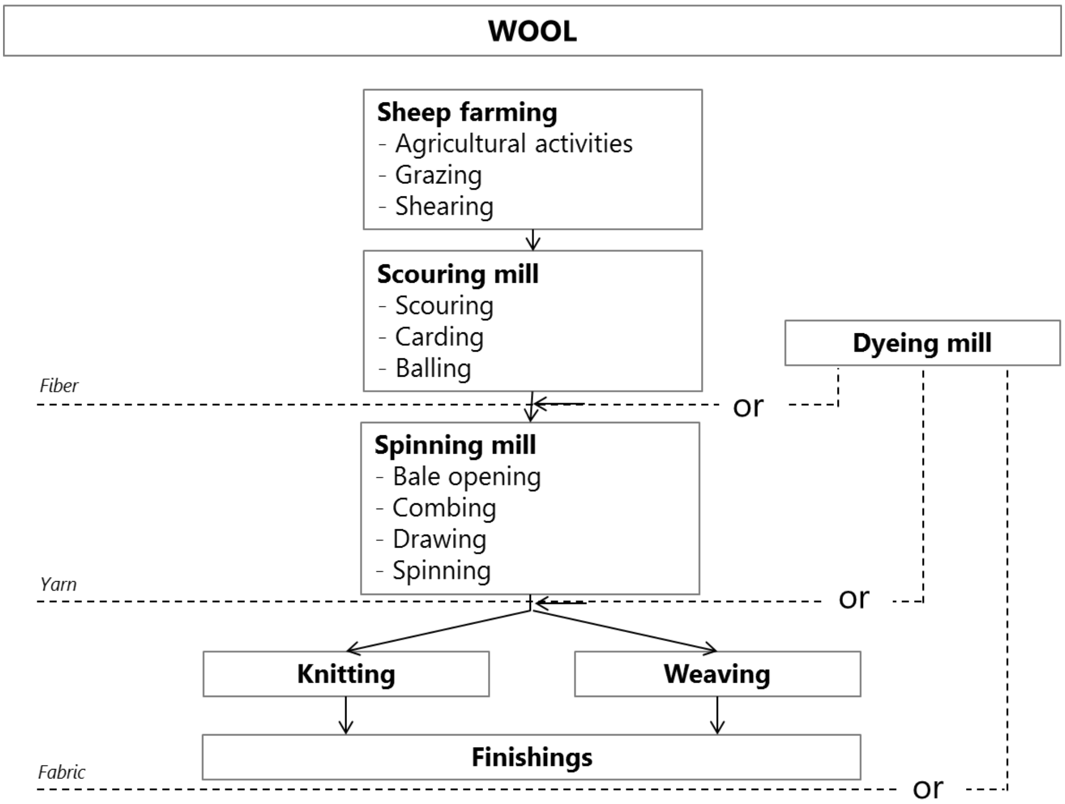

Figure 1 - Main life cycle stages of the supply chain for wool. The assembly, use phase and the final disposal is here disregarded. Transports link the presented stages

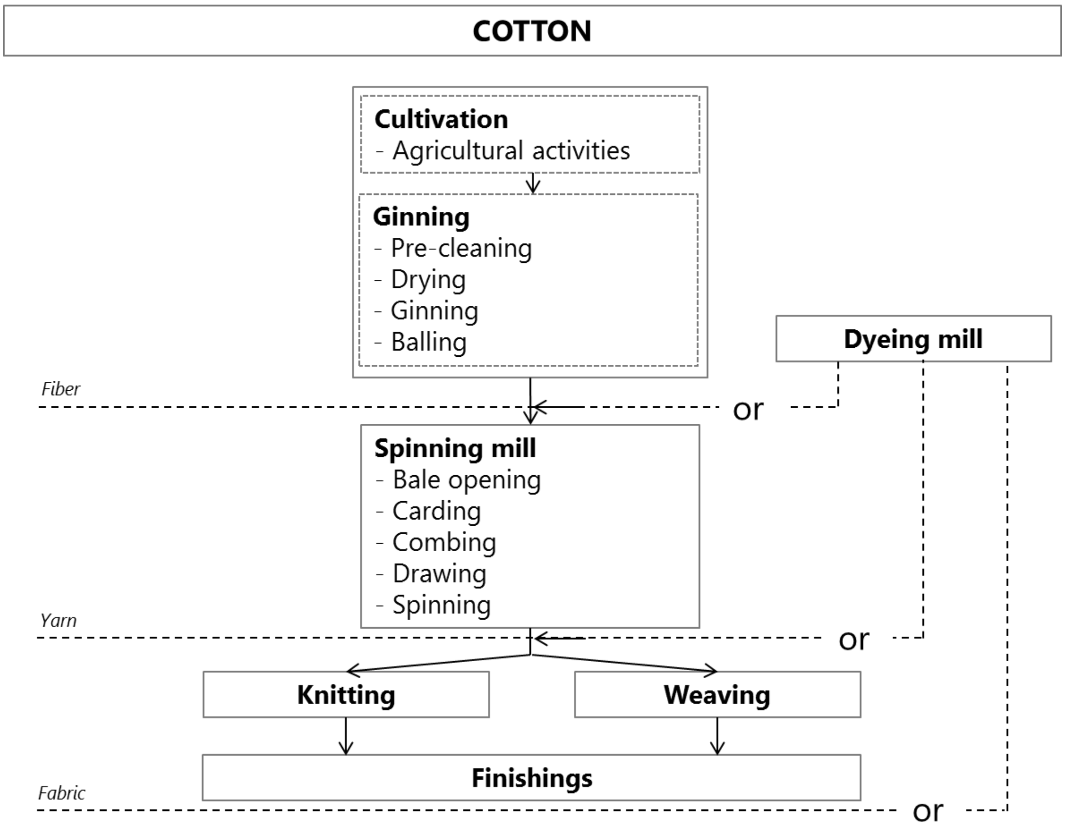

Figure 2- Main life cycle stages of the supply chain for cotton. The assembly, use phase and the final disposal is here disregarded. Transports link the presented stages

In the present section specifications for the life cycle stages of cotton and wool textiles are identified and described, its generic stages of mechanical and chemical processing for dyed yarns production are characterized and the main environmental concerns are summarized in the following.

The present study only comprises the life cycle stages which data was supplied during the internship. It includes the stages of sheep farming, scouring wool, cotton cultivation, ginning spinning (wool and cotton), dyeing (wool) and dyeing & bleaching (cotton). However, other finishing processes might occur throughout the supply chain of each material as presented in 2.3. These were, however, disregarded from this thesis scope.

2.1 Wool life cycle stages: sheep farming and scouring wool

Wools might be produced from sheep, goat, alpaca, camel and rabbit among other animals. Wool's production is mainly from sheep. In this case, the supply chain starts in grazing and shearing the ovine followed by the removal of impurities of the fleece. After this, wool is ready to be spun and dyed.

Sheep farming: the sheep is grazed on pasture and different cares are needed. Farmers have to ensure the correct nutritional requirements of animals (around 4L of water and 1kg of dry matter of food per day) as well as to prevent diseases (chemical or biological treatments). Sometime agricultural activities as fertilizers application or irrigation are developed on pastures in order to increase the meadow yield. The feedstuff as silage or grain may be imported or locally produced when the available grass is not enough. In fact, on average, one sheep produces about 4 to 5 kilograms of wool and around 40 to 60 kilogram of meat per year [13-15]. This animal has also an important role on greenhouse gases emissions due to its metabolic activity – enteric fermentation and manure left on pasture. In order to collect the fleece from the sheep there is the activity of *shearing*. It is usually made once a year in the springtime [14-16]. Most of the farmers worldwide shear sheep by hand and an experienced shearer can shear up to 200 sheep per day [17]. The fleece is kept in one piece and due to its content of natural grease it is named as greasy wool.

Scouring wool: it is a process similar to the scouring presented below (section 2.3) but in the case of wool it is always performed after shearing the sheep to remove impurities from the fleece. The main impurity is grease and suint and the goal of the process is to remove it using detergents. The extracted grease is turned into lanolin (byproduct with commercial value) [18]. Scouring facilities generates strongly alkaline effluents and significant loads of BOD_5 and COD [2]. Usually the scouring mills include processes of carding and combing and, in that case, the final product is named as wool top. This product is in a form ready for spinning. Wool tops are recombed in spinning mills in order to adjust the slivers weight and thickness as well as to realign fibers after dyeing and blending processes [19].

2.2 Cotton life cycle stages: cultivation and ginning

The life cycle stage of cotton textiles begins in the cultivation and it is followed by ginning. The fresh ginned cotton is ready to be spun or dyed in processes which are similar for both materials (cotton and wool).

Cultivation – cotton (*Gossypium* species) is a perennial shrub often cultivated as an annual crop for cotton-producing industries. Its propagation is usually made by seeds which are pre-treated with fungicides, insecticides and plant growth regulators to provide protection against diseases and pests (this pesticides are also applied to the crop during growing periods); plants can reach 1 to 2 meters high (sometimes more) [20] and the productivity rate equals a maximum annual average production ranging from 1 to 2 tonnes of seed cotton per hectare [21]. At this stage the raw fiber is named as seed cotton due to the presence of seeds mixed with lint (cotton fibers). Once the seed cotton is picked it is compacted into modules and is then transported to a cotton gin.

Ginning – this process is usually performed by cotton growers and it follows the harvest. The cotton seeds are stored in a natural capsule of the plant, surrounded by lint (makes up approximately 35% of the seed cotton) [22]. Ginning is a mechanical process used to separate the fibers (the more commercially interesting part of the plant) from the seeds. In order to reduce the moisture and improve the fiber quality, ginning is accompanied by drying processes that can be made by natural or artificial techniques [22]; these fibers are then compressed and baled. At this stage, the final product might be called as cotton lint or ginned cotton.

2.3 Mechanical and chemical processes for dyed yarn production (for wool and cotton)

Ginned cotton and scoured wool will follow the same life cycle stages. They will be spun and dyed in order to create a dyed yarn.

Spinning: is the process of transforming fibers into yarn; most of the mills encompasses processes as mixing (blending), cleaning, carding, combing, drawing and spinning fibers, followed by coning and packaging yarns.

- Carding is the process which separates the fibres and then assembles it into a loose strand, there is no preferential orientation of the fibres and a web-like fibre is formed using a carding machine consisting of rollers or drums which have pointed wires protruding from the surface. The wires pull the cotton fibre into line forming a sliver or a type of rope [22].
- Combing is the process that organizes fibres in a parallel orientation and removes some organic matter as straw or leafs remaining on the fibres. This activity is performed after carding and it offers a high quality of threads when compared with carded materials.
- The slivers are thinned out or thinned by using a process called drawing and drafting. This is completed by a series of rollers which make the fibres a consistent size in preparation for spinning [22].
- Spinning the yarn might be spun directly from the slivers (rotor spinning) or the fibre is twisted into thinner roving before being spun (ring spinning) [22].

Finishing: The "wet processes" also known as "finishing processes" (as presented in Figure 3) are the main activities of fabric preparation which might take place in different stages of the material production (fiber, yarn or fabric) depending on the required specifications of the final product. Examples of these activities are dyeing, bleaching, mercerizing, printing, desizing and washing [2, 12]. Every stage of production might include its finishing processes which allows the best fiber, yarn or fabric quality; in textile industry it is often applied after weaving or knitting the fabric in order to reach desirable fabric properties in terms of handle (softness and flexibility) and drape; the key goals are to remove surface hairs, increase fiber binding / cohesion and increase fiber friction according to the final product specifications [1]; finishing processes might comprise different processes according to the final desired product. Some examples of finishing or pretreatment processes are:

- *Dyeing*: process of adding color to fibers; batch, continuous or semi-continuous processes might be used depending on different factors as the stage of the material (fiber, yarn, fabric or garment), size of dye lots and quality requirements in the dyed fabric; the machinery must be resistant to attack by acids, bases, other auxiliary chemicals and dyes [23].

- *Printing*: Is the application of color to the surface of a fabric in a predetermined pattern using paste or ink; it may be considered as localized dyeing [1].
- *Bleaching*: is the process to make these products brighter or whiter; the most common bleaching reagent is hydrogen peroxide and may also be used reagents like sodium hypochlorite, sodium chlorite/chlorate and sulfur dioxide gas [2]; sometimes bleaching can be carried out in combination with other treatments: bleaching / scouring, bleaching / dyeing bleaching / scouring / desizing [12]. When the material has to be dyed in dark colors it can be directly dyed without requiring bleaching. On the contrary, bleaching is an obligatory step when the fiber has to be dyed in pastel colors or when it will need to be subsequently printed. In some cases, even with dark colors a pre-bleaching step may be needed [12].
- *Mercerizing* – consists of the pre-treatment of cotton fibers with caustic soda or liquid ammonia in order to improve tensile strength, dimensional stability and lustre [12]; this treatment increases the dye affinity of the materials, reducing the dyestuff consumption in the further process of dyeing; it can be done in two basis stages of material: yarn or fabric [2, 12]; usually post bleaching and pre-coloring process [24].
- *Scouring:* commonly scouring is the process that aims the removal of impurities as pectins, proteins, fat and waxes from raw fibers; the fibers go through a series of bowls and the scums are removed [12].
- *Desizing*: Sizing agents are introduced by the weaving firm in order to strength the fabric, but its excesses has to be removed by desizing processes using enzymes and other auxiliaries; as a result it has a high waste water production.[12].

After the yarn production (including its finishing processes) the fabric is created by knitting or weaving – at this stage we may also have a garment product (e.g. knitted wear).Knitting is the process responsible for the production of knitted fabrics. The material is produced by set of connected loops from series of yarns while weaving, similarly to knitting, originates woven fabrics by interlacing two types of threads [25]. After knitting or weaving, might be the life cycle stage of assembly in which the fabric is cut in a determined shape and assembled into a garment, usually using sewing processes. Sometimes trimmings are applied to the final clothing – it is the final stage of textile making.

2.4 Environmental aspects from the production of textiles

Environmental impacts occur at every stage of the life cycle of a product. More specifically and due to the growing need to lower the environmental impacts associated with the production of clothes. New patterns of production must be employed in such a way that the use of non-renewable resources, water, chemicals, fertilizers and land would be minimized throughout the supply chain. In summary, the textile fashion companies are focusing more and more on the production of sustainable products.

This industry is pointed as an intensive user for water, energy and chemicals. The air emissions, odours production and solid waste from processing fibres are also not negligible [12]. Figure 3 presents the relevant environmental effects per life cycle stage of a textile product.

	PRODUCTION OF RAW FIBRES		YARN PRODUCTION	GREY CLOTH PRODUCTION	TEXTILE FINISHING	MAKING UP
Process steps	Production of Natural fibres	Production of man-made fibres	Spinning, Twisting	Weaving Knitting	Pre-treatment Dyeing Printing Finishing	Cutting, Assembly, Finishing, Packing
Relevant environmental effects	Land use Pesticide Preservatives Water demand	Waste water pollution, Air emissions, poorly biode-gradable textile auxiliaries	Textile auxiliaries and chemicals use, Fibre waste, Noise pollution, Dust emissions	Textile auxiliaries and chemicals use, Noise pollution, Dust emissions, Waste, poorly biode-gradable sizing agents	Water demand , Waste water pollution, Textile auxiliaries and chemicals use, Air emissions, Energy demand	Energy demand Waste

Figure 3 - Main environmental aspects associated with the textile industry: from the raw fibre to the finished textile product [26].

The production and use phase of the natural fibres wool and cotton are identified as the main life cycle stages that contribute for the environmental impact of textiles [27].

The impacts on the environment of cotton production are related to cultivation practices and local conditions. The use of water for irrigation can salinize the soils, deplete the water resources and contribute to desertification. The large-scale explorations, mainly monocultures contribute to the losses in biodiversity. This crop is pointed as responsible for 8-10% of the global use of pesticides (around 50% of all pesticides are developed to be used in cotton cultures). Furthermore, large fractions of the amount of pesticides as well as fertilizers utilized to grow cotton are loose into the ground and can pollute the ground and surface water [28].

The production of wool requires a lot of land and the land on which sheep are grazed is generally less suitable for other agriculture. Depending on the original biodiversity and grazing techniques, grazing sheep may lead to a loss of biodiversity and erosion of the soil. Sheep contributes to the emission of methane and nitrous oxide, that are important greenhouse gases due to the fact that they have a significant contribution to climate change [28]. Some farmers utilize pesticides and fertilizers in order to improve pasture yields, even not being used in comparable scale as in the cotton cultivation, it is also an important issue as explained before. Wool is a more reactive and dirty raw fibre as it is called greasy wool after the shearing. Consequently, raw cotton is a much cleaner raw fiber than wool and initial operation (ginning) is mainly dry and simple against scouring wool that is complex and wet process (it is more intensive and with larger contributions to the environmental impacts).

In the following are described the main issues related to water and energy consumption, the mains pollutants emitted to air, water and soil as well as its source. Some benchmark values collected from the literature are listed as well.

2.4.1 Water consumption

The textile industry water-related impacts have origin in the use of dyes and chemicals in many different processes of textile manufacture [7, 12]. There is a need to encourage the use of less toxic dyes and chemicals as well as to recycle/re-use water within the supply chain. Most of the wastewater production is characteristically alkaline and with high BOD and COD loads and its discards might increase the streams temperature. The typical pollutants found in this emissions comprises suspended solids, mineral oils, surfactants, phenols and halogenated organics as well as heavy metals mainly from dyeing processes [2, 29]. A list of some water emissions that may be generated at different stages of textile processing are provided in Table 2 and the average consumption of water per life cycle stage considered as best available techniques (BAT) are listed in Table 3.

In addition, the wastewater resulting from natural fibre processing as wool and cotton might include pesticides residues, wax (grease and suint) and microbiological pollutants [2, 7, 29]. High water quantities are also used for irrigation during the growing of natural fibres, depending of course on the rainfall patterns and crop needs [12]. Varying with the amount and type of fertilizers, important emissions of nitrates and phosphates are released as well. In general, the water pollution in textile industry tends to be one of the most important problems caused to the environment, dominating in terms of environmental impacts, air emissions and solid waste production [24].

Table 2 - Specific water pollutants caused by the processing of textiles per process of the life cycle stages [29].

Life cycle stage	Compounds
Desizing	Sizes as enzymes and starch, waxes, ammonia
Scouring	NaOH, surfactants, soaps, fats, waxes, pectin, oils, sizes, anti-static agents, spent solvents, enzymes, insecticides and pesticides.
Bleaching	H_2O_2, AOX, sodium silicate or organic stabilizer, high pH
Mercerizing	High pH, NaOH
Dyeing	Colour, metals, salts, surfactants, organic processing assistants, sulphide, acidity/alkalinity, formaldehyde
Printing	Urea, solvents, colour, metals
Finishing	Resins, waxes, chlorinated compounds, acetate, stearate, spent, solvent, softeners

2.4.2 Energy consumption

The requirements for fossil fuels used in the production of electricity used in the industrial machinery, heating processes, transportation and agricultural machinery causes a large contribution to the climate change and resources depletion. The uses of water and energy are often related in the textile industry since the main use of energy is to heat up the process baths [12] and drying operations occurring after the wet processes [2]. In a scenario where the stage of "garments use" is accounted, laundry operation the electricity consumption has a large contribution summing up about 65% of the overall life cycle of a textile product [3]. Table 3 presents some benchmarks values taken from BAT [12] for different life cycle stages.

Table 3 - Benchmarks values for electricity, heat and water consumption taken from BAT for wool and cotton[12].

Life cycle stage	Electricity, kWh/kg	Heat, MJ/kg	Water, L/kg
Wool scouring [a)]	0.3	3.5	2-6
Yarn finishing	-	-	70-120
Yarn dyeing	0.8-1.1	13-16	15-50
Fibre dyeing	0.1-0.4	4-14	4-20
Knitted fabric finishing	1-6	10-60	70-120
Woven fabric finishing	0.5-1.5	30-70	50-100
Dyed woven fabric finishing	-	-	<200
Spinning [b)]	1-3	1.1 – 4.7	-

a) Values from Barber *et al*. (2006) for average production of wool top (scouring + carding + combing) in New Zealand.

b) Average values reported in YST (2006) [30] and not in BAT.

2.4.3 Air Emissions

Activities as agriculture, grazing sheep, and all the energy consumption processes are the main contributors to air emissions. However, some of the air emissions are not produced in the exploration place but in the power plants where the electricity is generated. About 14% of the overall 2004 global greenhouse gases emissions were release from agriculture [31]. Examples of its sources are the management of agricultural soils, livestock, rice production, and biomass burning. The most dominant greenhouse gases emitted from agriculture are CH_4 and N_2O, which contribute, respectively, to 21 and 310 times to the global warming potential of CO_2. The agricultural activities, such as the application of fertilisers are the primary source of N_2O emissions [31]. At the end, the livestock production results in CH_4 emission from enteric fermentation and both CH_4 and N_2O emissions from livestock manure management [32].

Significant sources of direct air emissions in fiber, yarn and fabric processing have origin in finishing, dyeing, printing, drying and cleaning fiber operations [2]. A list of air emissions that may be generated at different stages of textile processing are provided in Table 4.

Table 4 - Sources of air emissions in textile industry.[2]

Life cycle stage	Pollutant	Origin
Sheep Farming Cotton Cultivation	CH_4, N_2O, NOx and NH_3	Livestock emissions and fertilizers application
Spinning	Dust	Natural fiber processing as bale breaker and automatic feeders
Dyeing Printing Finishing	VOC's: ammonia, formaldehyde, alcohols, esters, aliphatic hydrocarbons Odours	Use of oils, solvent, formaldehyde, sulphur compounds and ammonia
Boilers and electricity generation	CO_2, CO, NO_x, SO_2	Exhaust gases

2.4.4 Soil emissions

These emissions are mainly allocated to activities of raw materials production, due to agriculture works as fertilizers and pesticides application. A list of soil emissions that may be generated at agricultures stages of textiles are provided in Table 5.Table 6

Table 5 - Major sources of soil emissions in the textile industry [33, 34].

Life cycle stage	Pollutant	Origin
Sheep farming Cotton cultivation	Heavy metals: Cd, Cu, Zn, Pb, Ni, Cr and Hg	Fertilizers losses
	acetamide-anillides, benzimidazole, diazine, diazole, dinitroanilines, pyrethroids, among others	Pesticides losses

2.4.5 Solid waste production

The production of solid waste within the supply chain has a big diversity of chemical compositions and origins, most of the residual material are non-hazardous as, for example, scraps of fabric or yarn and packaging material. Obviously, it is possible to say that the more efficient use of materials induces a lower waste production [2, 24]. A list of solig waste emissions that may be generated in different life cycle stages of textiles are provided in Table 6.

Table 6 – Sources of solid waste generation in the textile industry [35].

Life cycle stage	Solid Waste
Fiber preparation	Fiber waste; packaging waste; hard waste.
Yarn spinning	Packaging waste; sized yarn; fiber waste; cleaning and processing waste.
Scouring	Little or no residual waste generated.
Bleaching	Little or no residual waste generated.
Dyeing	Little or no residual waste generated.

2.3 Overview of LCA studies for textile products: cotton and wool

There are some studies concerning LCA for the textile industry. Most of the studies are based on the indirect collection of data (i.e. data is provided by suppliers of the supply chain) and focused t-shirts as the textile sector product. Cotton is dominating the production of natural fibers; therefore LCA studies for this material are more complete. Thus, the available literature for wool only regards fiber production and cleaning. This means that the downstream processes as spinning, dyeing finishing, assembly and use phase are missing. Some of the case studies found in literature are LCI studies and, consequently, no environmental impacts are assessed. Table 7 presents an overview of the LCAs studies for the textile industry focusing mainly in cotton ([36] [37] [38]) but also in wool ([13] [18]) and one study where both are compared among other fibers [27].

The study named as "Environmental Improvement Potential of Textiles" from the European Commission presents a comparison between production systems using different types of fibers (as Viscose, Flax, Silk, Wool, Cotton, Polyester, PA6, Acrylic and Polypropylene) [27] The functional unit is the production of 1 kg of finished woven fabric (i.e. a t-shirt). It is concluded that the production of raw materials (comprising the raw fiber production and its first treatments as ginning cotton or scouring wool) is the main contributor to the overall results in each environmental impact category assessed (climate change, human toxicity, freshwater ecotoxicity, ecosystem diversity and resource availability). The second main contributor is the finishing processes. However, when cotton and wool are compared, cotton has the largest impacts in all the assessed categories (except in human toxicity). If it is concerned only the life cycle stages related to the production of a dyed yarn: wool processing has the main contribution on climate change, human toxicity and resource availability the overall results (mainly due to the production of raw fiber); while cotton processing has the largest impacts in the categories of freshwater ecotoxicity and ecosystem diversity.

The study from Cotton Incorporated and PE International compiles a robust and current LCI dataset for global cotton fibre production and textile manufacturing based on the LCA of 1,000 kg of cotton fibre, 1,000 kg of knit fabric (shirt), and 1,000 kg of woven fabric (pant) [36] With the purpose of being more representative of the global situation, data from cotton growers in U.S., China and India as well as fabric producers in Turkey, India, China, and Latin America (where the main producers are settled) were collected. Looking into the knit fabric production impacts, spinning is the major contributor followed by dyeing and finishing. In the other hand, the potential impacts of wove fabric production are strongly affected by spinning and secondly by finishing, dyeing and weaving. The main impacts from agriculture are identified as irrigation, post-harvest (transport to ginning facility and ginning), field emissions (estimated loss of fertilizer and pesticides to the air, water or soil), fertilizer and fuel use. The main causes of the overall results are energy and water use along the processing stages of the fibre. When agriculture is considered it has a contribution up to 20% to the final results, while in the category of water consumption it reaches almost 80%.

The assembly, use and disposal contribute with more than 80% to the ozone depletion potential.

The cotton LCI study' of Blackburn and Payne focus on energy consumption. It concludes that 76% are used in the use phase, 19% in stages of fiber processing and 4% during the agriculture [37] The authors compare the energy (heat and electricity) and water consumption during the production phase concluding that dyeing and spinning are the high input processes, being spinning the largest consumer of energy followed by dyeing (that is the biggest consumer of water).

The carbon dioxide and sulphur dioxide emissions from energy consumption in each life cycle stage analysed are accounted in the production of four different t-shirts in the study from Steinberger *et al.* [38]. In this LCI study the production stages of spinning and dying are also the largest contributors for these emissions in which both are responsible for about 50% of the total air emissions.

The study from Biswas *et al.* (2010) [13] studied the life cycle global warming potential of wheat, meat and wool in three different pasture systems and identified that the activities in the farm stage (seeding, spraying, harvesting, topdressing, sheep shearing, fertilizer, and pesticide use and emissions from pastures and crop fields) contributed to the most significant portion of total GHG emissions. Emissions of methane resulting from the enteric production and from the decomposition of manure accounted for a significant part of the total emissions (40 to 90% depending on the type of pasture and farming activities developed).

In summary, it is possible to conclude that due to the use of heat and electricity, spinning is reported as one of the crucial stages of cotton fabric production. This stage is followed by the dyeing and finishing processes that use significant amounts of water, chemicals and energy. However, there is no results identifying individually the contribution of all the production processes and only a few are reporting more than one impact category. There are also only a few studies available related with LCA of wool. This limits the number of data available associated with the environmental impacts categories.

Table 7 - Set of selected studies regarding LCA and LCIA of cotton and wool.

Study	Environmental Improvement Potential of Textiles – IMPRO-textiles	Life Cycle Assessment of Cotton Fiber & Fabric	LCA of cotton towels	A spatially explicit life cycle inventory of the global textile chain	Global warming contributions from wheat, sheep meat and wool production	Merino Wool Total Energy Use and Carbon Dioxide Emissions
Reference	Beton et al. (2006)[27]	Cotton Incorporated and PE International (2012)[36]	Blackburn and Payne (2004)[37]	Steinberger *et al.*(2009)[38]	Biswas, Graham, Kelly and John (2010)[13]	Andrew Barber and Glenys Pellow (2006)[18]
Location	EU-27	Cotton growers: U.S., China and India; fabric production: Turkey, India, China, and Latin America;	U.S.	-	Australia	New Zealand
Goals	Comparison of different fibre types (Viscose, Flax, Silk, Wool, Cotton, Polyester, PA6, Acrylic and Polypropylene)	Compile a robust and current LCI dataset for global cotton fiber production and textile manufacturing.	Ascertain the impact of domestic laundering on the life cycle of cotton articles and whether techniques to provide an overall greener life cycle.	Establishing a country level, spatially explicit life cycle inventory (LCI)	Comparison of the life cycle global warming potential of wheat, meat and wool in different pasture systems	Develop LCI for New Zealand merino farms, offering benchmark figures to this industry based on a LCA perspective.
FU	1 kg of finished woven fabric (t-shirt)	1000 kg of cotton fiber, 1000 kg of knit fabric, and 1000 kg of woven fabric	dyed 600g of a 100% cotton towel	1 t-shirt (110g)	1 kg of wheat, sheep meat and wool produced	Tonne of dry wool top; tonne of greasy wool
Life cycle stages	Raw material production, cleaning, desizing, spinning, printing and dyeing, weaving and finishing	Cotton production, ginning and knit and woven fabric manufacturing (spinning, dyeing, knitting/weaving and finishing).	Growing cotton fibre; towel making (ginning, spinning, weaving, dyeing and finishing and assembly); consumer use and disposal.	Agriculture, Production (spinning, knitting, dyeing, apparel, transport); Use (washing, drying and disposal)	Agricultural machinery; fertilizer and pesticide (use, production and transportation) and emissions from pastures and crop fields.	Production and use of fertilizers and pesticides; wool processing (farming, shearing, scouring, combing) and shipping wool top to China.
Method	ReCiPe	USEtox™	-	-	-	-
Impact categories	Midponts: climate change, human toxicity and freshwater ecotoxicity. Endpoints: human health, ecosystem diversity and resource availability.	Acidification, eutrophication, global warming, ozone depletion, smog creation, energy demand, water use and water consumption	Energy consumption	The carbon dioxide and sulphur dioxide emissions from energy consumption in each life cycle stage	Global warming potential	-
Hot spots	Finishing and raw material production are the biggest contributors. Finishing assumes an important role in cotton fabric's LCA while raw material production is the main cause in wool product's impacts.	Agriculture: field emissions and fertilizer use; Knitted fabric: mainly spinning, secondly dyeing and finishing; Woven fabric: mainly spinning, secondly finishing, dyeing and weaving.	76% use phase 19% towel making 4% growing cotton	CO_2 emissions: Agriculture (15%); Spinning (7%); Dyeing (7%); Use phase (65%). SO_2 emissions: Agriculture (30%); Spinning (17); Dyeing (13%); Use phase (25%).	CH_4 emissions from enteric methane production and from the decomposition of manure accounted for a significant portion of the total emissions.	On-farm activities have a contribution of 67% while processing 30% on the overall results.
Conclusions	Raw material production and finishing are the main contributors in the overall results. Cotton as the highest impacts in all the assessed categories when compared with wool.	Energy and water use are the significant causes to the overall results. Agriculture has a contribution up to 20% in the final results while in water consumption its contributions are around 80%.	Within towel making processes, dyeing and spinning are the high input processes.	In this LCI study the production stages of spinning and dying are also the largest contributors for these emissions in which both are responsible for about 50% of the total scores	The life cycle GHG emissions of 1 kg of wool is significantly higher than that of wheat and sheep meat.	Wool processing accounts for 47% of total energy use, of which almost 90% occurs during wool scouring.
Limitations	Based on high amount of literature data. Cotton is better modelled than the other fibres due to the amount of data available.	Data not collected directly in the suppliers facilities.	Focus on use phase	LCI and only for emissions from energy consumption	Specific for the local, only global warming assessed and downstream processes missing.	This study only evaluates one impact category (energy use). Processing energy use was based on a German wool scouring and top making plant

3 THE LIFE CYCLE ASSESSMENT METHODOLOGY

In the present study LCA is performed according to the principles of the International Organization for Standardization (ISO) both 14040 and 14044 series of standards for Life Cycle Assessment [10, 39]. Another methodological guideline for this study was *The Hitch Hiker's Guide to LCA* [40]. The measurement of the potential environmental impacts is performed using the commercial software SimaPro (version 7.3.3, 2011).

3.1 LCA methodological phases

Life Cycle Assessment is an environmental tool that allows to assess the environmental impacts of the product, process or activity (including the entire life cycle), encompassing stages as: extraction and processing of raw materials, manufacturing, transport, distribution, use and final disposal – accounting for water, air and soil emissions, energy and material consumption and waste disposal. LCA usually analysis a diversity of environmental impacts such as climate change, human toxicity, resources depletion, land use among others. According to the ISO standards, a LCA is carried out in four distinct phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation (as shown in Figure 4).

The **Goal and Scope Definition** is the first phase of LCA, which states the context of the study and the purposes of its results. Technical aspects and the level of detail considered are here defined by aspects as functional unit (FU)[1], system boundaries, assumption and limitations, allocation methods and impact categories chosen. ISO standards require that the goal and scope of an LCA has to be clearly defined and consistent.

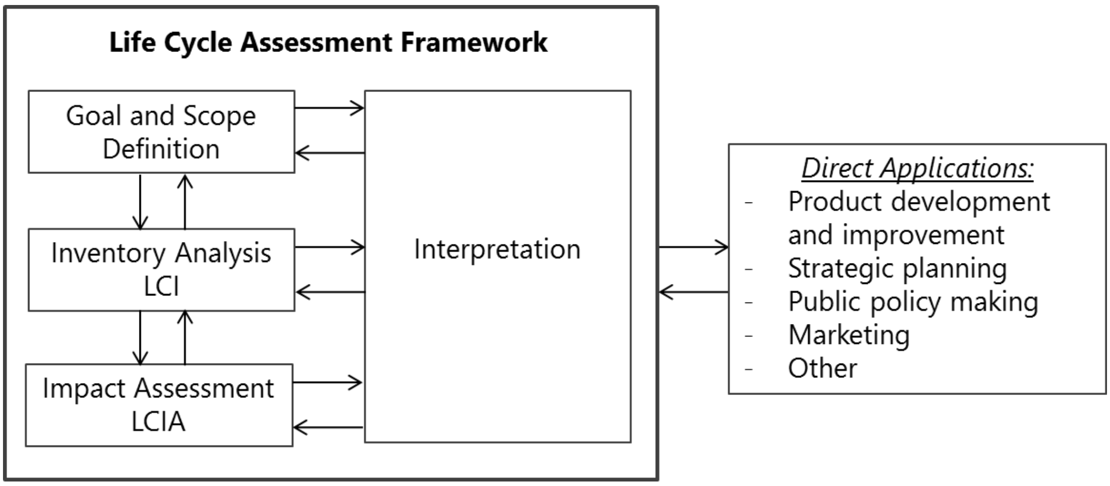

Figure 4 - Phases of a LCA study [10].

[1] The FU defines exactly the object being studied, providing a reference to which the inputs and outputs can be related. It makes all the inputs and outputs of the studied product comparable.

The **Inventory Analysis** takes place after defining the goal and scope of the study, a fundamental component of LCA is the creation of the LCI, a complete list compiling the relevant inputs (energy and materials) and outputs (environmental releases or emissions) related to the functional unit defined.

The **Impact Assessment (LCIA)** is when the quantified LCI flows are linked to its potential environmental impacts using a selected method. The method comprises selected categories of environmental impacts and characterization, normalization or weighting factors. This step is done using a systematic procedure based on a sequence of steps stated by the ISO standards (some of these steps are compulsory whilst others are optional):

- Classification (compulsory): respecting the selected method, the inventory flows are classified according to the type of environmental impact they cause (e.g. CH_4 emission are associated with climate change).
- Characterization (compulsory): after classified, the substance flow must be characterized; each means that all the flows causing the same environmental impact are converted to the same representative unit (e.g. conversion of CH_4 to $CO_{2\text{-eq}}$).
- Normalization (optional): this step offers a reference situation (country, region or world) of pressure on environment for each environmental impact category analysed [41].
- Grouping (optional): consists of sorting and possibly ranking the impact categories.
- Weighting (optional): is a subjective result where the impact categories are weighted relative to each other so that it can be possible to generate a single final score.

The **Interpretation** is made throughout all the phases with the purpose to summarize and discuss the results achieved systematically and to verify if the results are in accordance with the defined goal and scope. Changes and recommendations are proposed and the final conclusions of the study are drawn.

3.2 Goal and Scope of the study

The main goal of this study is to assess the environmental burdens associated to different life cycle stages of dyed yarns (cotton and wool) comprising: fibre production, spinning, dyeing, dyeing & bleaching and scouring wool; while ascertain about the environmental performance of wool and cotton dyed yarn production concerning the possible scenarios for its manufacture and the suppliers assessed for each material. The inventory data collected from several producers is from 2011. The different producers located worldwide may have distinct technologies within the same life cycle stage. The wool and cotton processes studied as its production yields are summarized in Table 8 for each company that supplied the inventory data. This table also identifies the functional unit (FU) utilized to report the data collected according to the final product of each life cycle stages.

All the case studies are named with a code as listed in the table: as an example, three case studies supplying the greasy wool from sheep faming were used in the analysis and they are designated as F1, F2 and F3 (the same procedure was used in spinning, dyeing and dyeing & bleaching); cotton growers are distinguished by its mode of cultivation (conventional and organic) and; as only one scouring mill is assessed no code was defined.

Table 8 – Data provided from suppliers for wool and cotton productions for 2011.

Life cycle stage	Case studies	Location	Annual average production, t	Functional Unit (FU)
		WOOL		
Sheep farming	F1	New Zealand	70	1 kg of greasy wool
	F2	Australia	50	
	F3	Australia	30	
Scouring wool		Italy	6000	1 kg of wool top
Spinning	S3	China	400	1 kg of wool yarn
	S4[1)]	Italy	4000	
	S5	Italy	1200	
	S6	Italy	250	
Dyeing	D1[1)]	Italy	4000	1 kg of dyed wool
	D2	Italy	650	
	D3	China	5500	
		COTTON		
Cotton cultivation	Conventional	Tajikistan	2.2 t/ha	1 kg of ginned cotton
	Organic	Tajikistan	2.5 t/ha	
Spinning	S1	China	12500	1 kg of cotton yarn
	S2	Switzerland	3500	
Dyeing & Bleaching	D&B 2	Italy	100	1 kg of dyed and bleached cotton
	D&B 3	China	30	

1) S4 and D1 are developed under the same facility roof. It explains the equal amount of product produced.

3.2.1 System boundaries

The LCA perspective adopted is cradle-to-gate for the case studies considered. The boundaries of the processes encompass the production of chemicals and auxiliaries needed for the supplier activities including raw materials, manufacture of intermediate materials and manufacture of the product being studied.

Two main groups are identified for the two products, namely activities from the agricultural sector (cotton cultivation and sheep farming) and mechanical and chemical processes comprehending the scouring wool, spinning, dyeing and dyeing & bleaching.

For all systems it was excluded the transportation and storage of materials as chemicals, auxiliaries, fertilizers, pesticides, feedstuff and packaging as well as activities that were not directly related to the production system as such the administrative, labs and other services operations.

Figure 5 identifies the stages considered in the analysis by detailing the processes, input and output products concerned for the production of ginned cotton and greasy wool. Similarly, the Figure 6 illustrates the activities regarded to model the textile products (wool and cotton).

Sheep farming and Cotton cultivation

Regarding the main activities of these life cycle stages inputs and outputs from on-farm and pre-farm origin are included. In Figure 5 are illustrated the stages considered within the system boundaries. The modelling of these agricultural systems comprises:

- The production of cotton seeds, fertilizers (organic or inorganic), pesticides (insecticides, fungicides and plant growth regulators), chemicals for seed[2] and sheep[3] treatments and sheep feed;
- Machinery use in field works based on its consumption (e.g. harrowing, sowing and pesticides application);
- Water consumed by the plants (cotton and pastures) and sheep;
- Energy production from grid or own;
- Emissions to air (NH_3, N_2O and NO_x), water (NO_3^- and PO_4^{3-}) and soil (heavy metals and pesticides);
- Emission from livestock (CH_4, NH_3 and N_2O);
- The process of ginning after harvesting cotton.

[2] It refers to the application of fungicide, insecticide or a combination of both in order to disinfect and protect the seeds from seed-borne or soil-borne pathogenic organisms and storage insects.

[3] Sheep lice and blowflies, among other parasites' threats cause major economic loss to the wool industry [42]. Some farmers are using chemicals to prevent the contamination of its ovine. Most of these products comprises as active ingredient pesticides.

From this analysis are excluded:

- The carbon dioxide equivalent uptake was not considered because:
  - Following the study of Eady et *al*. (2011), biogenic carbon that is part of the annual carbon cycle was assumed to be in equilibrium thus changes in soil and vegetation carbon in farm products were not included in the system boundary [15]; thus, in extensive pasture the majority of the vegetable materials are retained on site and it is assumed that CO_2 will be released with time respecting the carbon cycle.
  - Cotton and wool fibre stores carbon but it is then released at end of life;
  - Soil carbon sequestration is not considered to be significant during periods ranging from 6 to 12 months according to Biswas *et al.* (2012) [13]
- The production and use of bio controllers and natural pesticides due to the lack of background information and datasets to model it. For the same reasons, cow manure production is not considered within the system boundaries (but its emissions are modelled).
- Emissions from the application of chemical treatments in sheep are not accounted. It is considered an output which will be released from wool and carried out in downstream processes (e.g. wastewater emissions from scouring wool).
- Transports of fertilizers, pesticides and chemicals are not included as they are assumed to be transported from local retailers to farm and thus not relatively significant for the overall analysis.

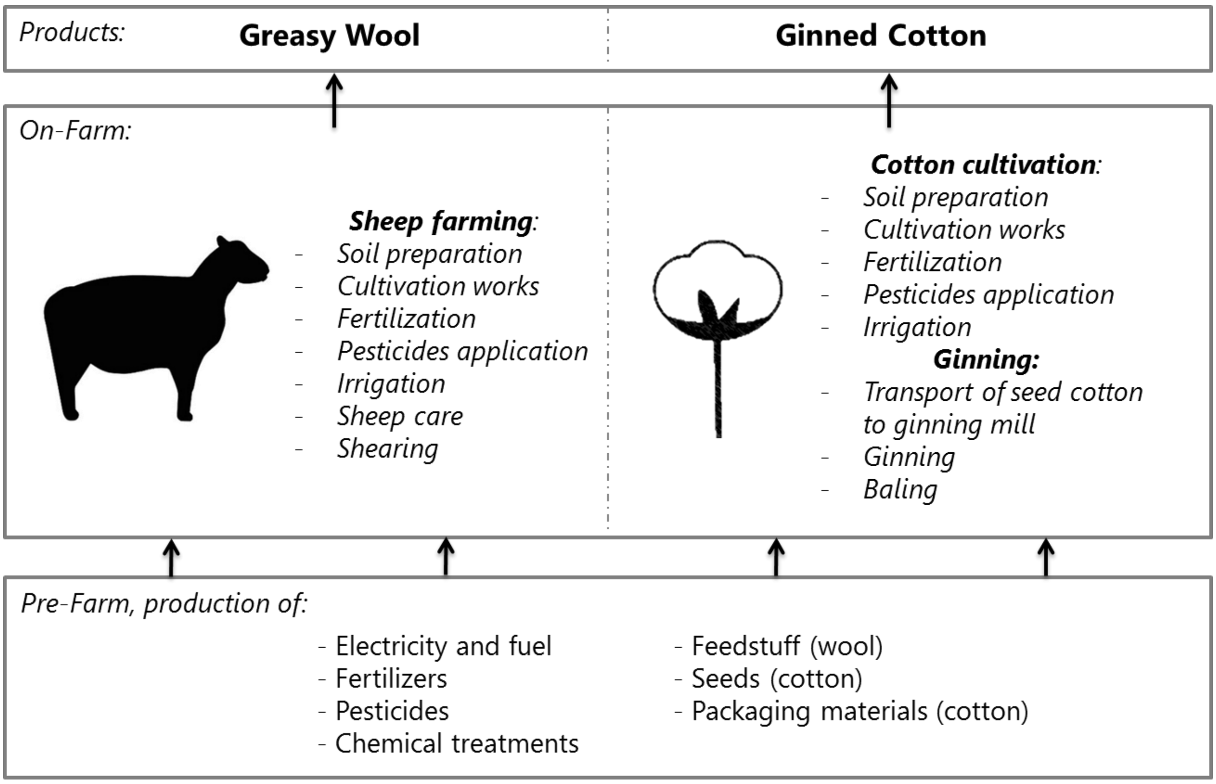

Figure 5 - Life cycle stages processes associated to the production of seed cotton and greasy wool.

Mechanical and chemical processes for dyed yarn production

Regarding the main activities of these life cycle stages inputs and outputs from on-company and pre-company origin are included. In Figure 6 are illustrated the stages considered within the system boundaries. The modelling of these industrial systems comprises:

- Chemicals, auxiliaries and packaging material production;
- Energy (electricity, heat or cogeneration) production from grid or own production;
- Water used (e.g. tap water, underground water and industrial water);
- Wastewater and solid waste final treatment;
- Air emissions;
- The modes of raw material (textile products) transportation from the previous step of the supply chain to the company and correspondent impacts are accounted.

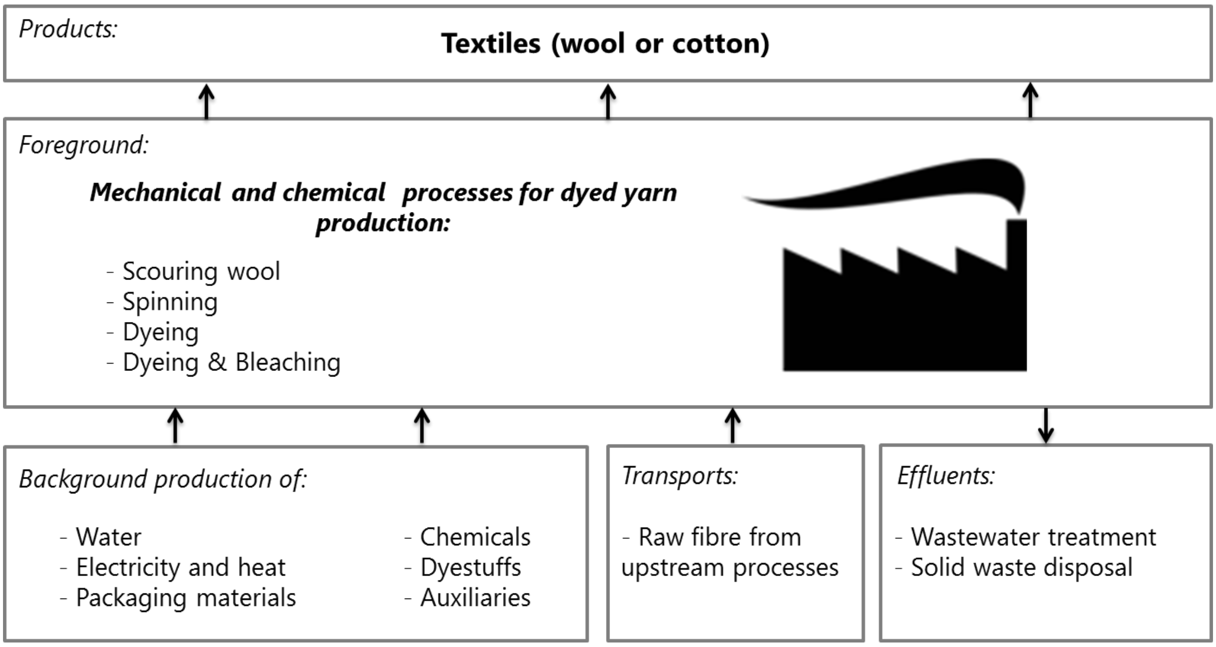

Figure 6 – Life cycle stages processes associated to the mechanical and chemical processes for dyed yarn production (activities occurring after ginned cotton and greasy wool production).

From the analysis are excluded:

- Solid wastes which are recycled are not assessed as it is assumed as a raw material of other processes outside the system boundaries.
- Transports of chemicals, auxiliaries and packaging materials are not included as they are assumed to be transported from local retailers to the suppliers and considered that low amount of fuel would be used. Following the same consideration, solid waste transports to its final disposal is not accounted.

3.2.2 Allocation process

The case companies that supplied the inventory data produced a number of products and sub products. The data supplied reports to the production of all the set of products and sub-products. In order to report the specific values referring the products under study the amount of inputs and outputs (materials and energy) flows were split among the different products or by-products. Allocation is defined as partitioning the input or output flows of a process to the product system under study [10, 40]. Economic allocation was used as preferential due to the fact that in ISO 14044 [39] this allocation is suggested where physical relationship (i.e. kg, L, m^2, m^3, among others) cannot be established. It is assumed that economical partitioning reflects the relationships between products and by-products production. Table 9 presents the allocation factors used.

Table 9 - Products (underlined) and by-products produced by the suppliers and the allocation factors used.

Life cycle stage	Case studies	Products	Allocation Factor			Type
WOOL						
Sheep Farming	F1 | F2 | F3		F1	F2	F3	Economical
		Greasy wool	0.30	0.62	0.81	
		Carcases	0.70	0.23	0.13	
		Live Units	a)	0.15	0.06	
Scouring		Wool top	0.85			Economical
		Lanolin	0.15			
Spinning	S3	Wool yarn	1			none
	S4	Wool yarn	0.96			Economical
		Wool noil	0.04			
	S5 | S6	Wool yarn	1			none
Dyeing	D1| D2 | D3	Wool	1			none
COTTON						
Cotton Cultivation	Conventional Organic	Ginned cotton	0.60			Economical
		Seeds	0.37			
		Neps	0.03			
Spinning	S1 | S2		S1	S2		Economical
		Cotton yarn	0.80	0.83		
		Cotton comber	0.20	0.17		
Dyeing & Bleaching	D&B 2 |D&B 3	Cotton	1			none

a) The supplier F1 is not selling live unit.

3.3 Inventory analysis

The inventories were built using primary data made available by suppliers, secondary data was estimated based on existing models or taken from the ecoinvent databases.

The suppliers reported the consumption of energy and materials used and outputs as products, by-products, solid waste and emissions (water and air) from their production system. Some of the emissions were estimated. Models are used in the cases where measures require scientific knowledge, technology difficulty of measurement or costs (e.g. quantity of nitrate or phosphate emissions to water from fertilizers use on cotton cultivation). The ecoinvent database is used to complete and simplify the assessment, for instance, if the supplier is using 1 kg of cardboard the correspondent dataset comprises the environmental impacts associated to its production (background data).

Activities such as the production of energy (electricity and heat), fertilizers, pesticides, feedstuff, chemicals and auxiliaries or the use of transports and agricultural machinery are included in the analysis through the use of ecoinvent databases. The impact is assessed by generalist databases.

Models from the literature are developed to describe sheep farming and cotton cultivation emissions from applied fertilizers and pesticides as well as from livestock metabolic processes. These models are created aiming to quantify flows while being valid to different regions worldwide, and thus applicable to different kind of soils and climate regions.

3.3.1 Inventory for sheep farming

Table 10 lists the main characteristics of the three assessed farms in terms of stock units (s.u.)[4], wool production and land used. These producers use extensive models of grazing sheep in a way that its stock rate is equal or lower than 12 s.u./ha [33]. It is also visible that similar rates of greasy wool yield are obtained. These vary from 4.4 kg/s.u. (for F3) and 4.6 kg/s.u. (for F1).

Table 10 – Profile of the assessed farms

Farms	F1	F2	F3
Sheep			
Stock units [a)], s.u.	14 500	10 500	6 500
Stock rate, s.u./ha	1.2	12	0.1
Wool production			
Greasy wool, kg	67 000	47 500	28 500
Yield, kg/s.u.	4.6	4.5	4.4
Land			
Location	New Zealand	Australia	Australia
Grazing area, ha	12 400	900	64 000
Soil type [43]	Histosol	Vertisol	Vertisol
Average slope	0.01	0.01	0.01

a) The farmers are calculating the stock units using standard and official values for their countries.

[4] Stock unit's value represents the number of sheep equivalent and it has different conversion factors according to the metabolic system of the animals (breed and age) and country or region environment.

Table 11 and Table 12 summarize, respectively, the inputs and the output flows from greasy wool production. Table 11 lists land use, energy consumption, transports, machinery, water, fertilizers, pesticides, feed and chemicals for sheep's treatment. Table 12 lists emissions to air, water and soil. All the values are reported according to the functional unit used in this stage – 1kg of greasy wool.

Table 11 – Inventory of inputs for the life cycle stage of sheep farming. Values related to the FU of 1 kg of greasy wool produced.

Farms	F1	F2	F3
Electricity			
Electricity from grid 1), kWh	-	6.82E-02	1.10E+00
Electricity from own production 2), MJ	1.80E-01	6.70E-01	1.07E+01
Machinery			
Sowing3), ha	1.97E-04	-	-
Fertilizers application 3), ha	8.39E-05	3.71E-03	-
Pesticides application 3), ha	5.05E-05	1.23E-04	-
Harvest 3), ha	6.65E-05	-	-
Tractor 4), tkm	1.15E+00	-	2.81E+00
Water			
Irrigation 5), m^3	5.71E-03	-	-
Sheep 6), m^3	9.43E-02	2.00E-01	2.71E-01
Electricity from grid 1), kWh	-	1.24E+00	1.10E-02
Electricity from own production 2), MJ	-		1.07E-1
Feed 7), kg			
Silage	2.69E-02	-	-
Maize grain	-	6.48E-01	-
Hay	-	6.48E-01	-
Fertilizers7), kg			-
Urea ammonium nitrate 8)	2.60E-02	4.20E-02	-
Single superphosphate 8)	2.66E-01	-	-
Monoammonium phosphate 8)	-	9.09E-02	-
Poultry - broilers manure, solid 8)	-	1.46E+01	-
Pesticides, kg 9)			
Paraquat	-	7.00E-04	-
Glyphosate	-	3.78E-03	-
Chemical treatments, kg 9)			
Chlorpyrifos	6.12E-04	-	-
Cryomazine	-	2.49E-04	-
Dicyclanil	-	6.22E-05	-
Abamectin	-	2.59E-06	-
Albendazole Oxide	-	4.66E-06	-

Levamasole Hydrochloride	-	1.07E-05	-
Spinosad	-	1.62E-06	-
Vacines [10)]	-	2.36E-06	-

Note: cells with hyphen (-) means that the input is inexistent for the respective supplier.

1) Electricity consumption reported by the suppliers for activities related to sheep (pumping water, shearing, and illumination).
2) Values calculated in MJ according to the farmer's litres of diesel consumed for electricity production and its calorific power of 43 MJ/kg (with the density of 0.832 L/kg). It is assume that the electricity is produced in a diesel generator set.
3) Litres of diesel consumed per agricultural work are reported by the farmers and are converted to hectares according to the rate of fuel consumption (L/ha) of the dataset utilized [33].
4) Litres of diesel consumed for transports are reported by the farmers and are converted to tonne-kilometre according to the rate of fuel consumption (L/tkm) of the dataset utilized [33]. Transports of persons and animals are considered.
5) Value reported by the supplier. For F1 the supplies is not reporting the electricity used for irrigation, thus a dataset from ecoinvent concerning the energy use for this activity was utilized.
6) Drinking water for sheep is estimated based on bibliographic references due to the inexistence of specific data from farmers.
7) Value reported by the supplier.
8) Class of fertilizers selected according to the properties of the commercial products utilized by the companies.
9) Values reported according to the active principle content of the commercial products
10) A low generic content of 2 mL of active principle per vaccine is adopted according to the values reported in Walter (2009).

The suppliers F2 and F3 are consuming electricity from Australian grid. The 2011 mix of the country is published in *2012 Australian Energy Update* and utilized in order to model the electricity generation using datasets from ecoinvent. For that year, the electricity mix was: 38% coal, 35% oil, 22% gas and 5% renewables [45].

Farmers report on questionnaires the litres of fuel consumed for each one of the machinery works presented. These values are converted from litres to hectares or from litres to tonne-kilometre depending on the FU required while respecting the rates of fuel consumption reported by the ecoinvent database [33]. The conversion factors and correspondent datasets are specific for each type of machinery used and are presented in Table B.6 in Appendix B.

Water is one of the basic needs of any system and its consumption must be accounted. Drinking water for sheep is estimated based on its nutritional values and on bibliographic references due to the inexistence of specific data from farmers. The value is based on an average of 4 litres of water per sheep and day [46].

The selection of datasets to model the fertilizers production was based on the active nutrient of the fertilizers and its content reported by farmers. Most of the fertilizers applied have the same composition of as the modelled ones.

Suppliers are reporting the quantities of active ingredient presented in the pesticides applied on field. Attending to the chemical classes of the pesticides, datasets have been selected. Data for certain pesticides is not available, therefore surrogate figures have been used based on the active ingredients, i.e., generic dataset as for instance unspecified insecticides, fungicides or pesticides, growth regulators and chemicals organic was considered in the analysis. The same assumption is made for the chemical treatments of sheep that uses pesticide compounds. Furthermore data from two studies (Van Cleemput *et al*., 1998, and West, 2002) indicate that there are not large differences in energy requirements and carbon emissions between herbicides, insecticides and fungicides, so representative compounds were used.

Table 12 – Inventory of emissions to air, water and soil from sheep farming. Values related to the FU: 1kg of pollutant per 1 kg of greasy wool produced.

Compartment	Emissions	F1	F2	F3
Air	CH_4 1)	5.17E-01	1.09E+00	1.49E+00
	N_2O 2)	2.91E-02	5.64E-02	7.43E-02
	NO_x 3)	1.13E-05	7.27E-03	1.56E-02
	NH_3 4)	2.37E-01	3.47E-01	4.43E-01
Water	Nitrate 5)	-	-	5.96E-04
	Phosphorus 6)	1.26E-04	3.05E-04	1.79E-04
	Phosphate 6)	4.75E-04	1.00E-03	5.87E-04
Soil	From fertilizers 7)			
	Cd	4.45E-05	8.74E-06	-
	Cu	8.27E-05	2.20E-04	-
	Zn	4.20E-04	1.96E-03	-
	Pb	4.88E-04	1.92E-05	-
	Hg		1.16E-06	-
	From pesticides 8)			
	Glyphosate	-	3.78E-03	-
	Paraquat	-	7.00E-04	-

Note: cells with hyphen (-) means that the output is inexistent for the respective supplier due to a result on the calculation (nitrates), lack of information for the fertilizer utilized (Hg) or not use of pesticides.

1) Grazing sheep emissions of CH_4 from livestock estimated using emission factors from the IPCC (2007) of 8 kg CH_4/stock unit [32] reported per country and year by FAO.
2) Grazing sheep emissions of N_2O from livestock estimated using emission factors from the IPCC (2007) of 0.5 (New Zealand) and 0.4 (Australia) kg N_2O/stock unit [32] reported per country and year by FAO. Emissions from the application of fertilizers are estimated according to the formula in Nemecek and Kägi (2007)[35] and adopts the IPCC (2006) guidelines[49]
3) Emissions are calculated based on the formula in Nemecek and Kägi [35] and the dinitrogen oxides releases: $NO_x = 0.21 * N_2O$.
4) Livestock emissions are estimated according to the emission factor of 1.4 kg NH_3/stock unit reported by EMEP (2006) [50] . Emissions from agriculture activities are calculated based on the Agrammon Group (2009) models.
5) The nitrate emissions from agricultural nitrogen inputs are modeled according to the models developed by Faist et *al.* (2009) in the Sustainability Quick Check for Biofuels [51].

6) Phosphate emissions are calculated using the models described in [52], [53] and [54]
7) Heavy metal emissions in soil are estimated using the same model as the one used in the ecoinvent report *Life Cycle Inventories of Bioenergy* [55]
8) The emissions of the specific pesticides are equal to the inputs of pesticides [55].

Ammonia releases to air are quantified using two models according to the use of mineral fertilizer or organic fertilizer both based on the nitrogen emissions in form of NH_3 (NH_3-N):

- In case of mineral fertilizers the procedure is based on the nitrogen emissions in form of NH_3 (NH_3-N) from fertilizers use and then NH_3-N is converted to NH_3. Using the conversion factor of 17/14;
- The Agrammon methods [56] are used to model emissions from organic fertilizers use and the NH_3-N emissions are calculated considering the parameters: TAN (total ammoniacal nitrogen) and standard emission rates for specific manure.

Water emission as nitrate and phosphates are estimated by considering different parameters. Nitrate emissions are accounted regarding the amount of nitrogen inputs, nitrogen uptake by vegetation, amount of nitrogen in soil organic matter, precipitation, clay content on soil and root depth.

Phosphorus losses are estimated in the shape of dissolved ions (phosphate). Its models follows several studies based on average availability of phosphorus, erosivity and slope factors, use of fertilizers and its application technics and run-off [52-54].

Heavy metals are emitted to the soil when fertilizers are applied. These emissions were estimated based on the SALCA for identifying emission factors from fertilisers and uptakes from wool [35]. Following the studies of Kazemeini *et al.* (2010), Nemecek *et al.* (2004), Patkowska-Sokola *et al*. (2009) and Smith *et al*. (2010) to estimate the metal-uptakes by wool which uptake figures are listed in the Table H.1 and Table H.2 in Apendix H.

The pesticides emissions were estimated by using a simplified model following the one presented in the ecoinvent report *Life Cycle Inventories for Bioenergy* [55] where it is assumed that all inputs of pesticides are emitted in the nature. Therefore it is considered that the emissions to the soil of the specific pesticides are equal to the amounts used.

3.3.2 Inventory for cotton cultivation

The cotton growers' production is made in Tajikistan and the two case studies have distinct modes of agriculture production: while one is using conventional, the other is adopting organic production. Both growers fields have an average slope of 0.015 and the soil type is characterized as gelisol according to USDA standards [43]. On average the growing period of the cotton plant is around 6.5 months and seed cotton is harvest by hand for both farms.

Table 13 summarizes the inputs as land use, energy consumption, transports, machinery, water, fertilizers, pesticides and chemicals for seeds' treatment and in Table 14 are listed the output flows from cotton cultivation as emissions to air, water and soil.

Table 13 - Inventory of inputs for the life cycle stage of cotton cultivation. Values related to the FU of 1 kg of ginned cotton]

Cotton producer	Conventional	Organic
Land occupation, m^2a	4.48E+00	3.94+00
Irrigation		
Rain 3), m^3	1.03E+00	9.09E-01
River 1), m^3	5.18E+00	4.83E+00
Groundwater 1), m^3	1.73E+00	1.52E+00
Electricity 4), kWh	4.13E-01	3.64E-01
Machinery 5), ha		
Soil preparations	6.65E-04	1.67E-06
Harrowing	6.25E-03	1.57E-05
Sowing	1.82E-03	4.57E-06
Fertilizers application	-	3.30E-06
Cleaning	2.02E-03	5.08E-06
Fertilizers, kg 6)		
Ammonium nitrate, as N	2.07E-01	-
Potassium chloride, as K_2O	8.26E-02	-
Ammonium nitrate phosphate, as P_2O_5	1.65E-01	-
Compost	-	7.27E-01
Poultry manure	-	7.27E-01
Ginning 1)		
Electricity, kWh	8.86E-02	8.86E-02
Packaging, kg		
Cotton cloths	6.29E-04	6.29E-04
Metal rings	4.09E-03	4.09E-03
Transports, tkm 7)	1.24E-02	1.24E-02
Pesticides, kg 81)		
Lambda-cyhalothrin	2.48E-04	-
Prometryn	1.03E-03	-
Diquat	2.08E-03	-
Seeds, kg		
Seeds bought 1)	8.26E-02	6.23E-02
Seed treatments 9)		
Bronopol	5.79E-04	-
Carboxin 10)	7.02E-05	-
Thiram 10)	7.02E-05	-

Note: cells with hyphen (-) means that the particular input does not exist in the respective supplier's activity

1) Quantity reported by the suppliers.
2) Area of land occupied per growing period. The area is allocated to the 6.5 months of cultivation.
3) This value was calculated based on the rainfall stress and farmer's reliability as well as the quantity of rainwater needed to grow cotton without irrigation.
4) Electricity consumption reported by the suppliers for pumping water.
5) Litres of diesel consumed per agricultural work are reported by the farmers and are converted to hectares according to the rate of fuel consumption (L/ha) of the dataset utilized [33].
6) Class of fertilizers selected according to the properties of the commercial products utilized by the companies.
7) Average distance between cultivation fields and ginning mill is used and multiplied by the quantity processed in order to have tonne-kilometre units.
8) Values reported according to the active principle content of the commercial products.
9) Values reported according to the active principle content of the commercial products.
10) Carboxin and thiram are the active ingredients of the commercial product utilized by the farmers (Vitavals 200FF) both compounds have a concentration of 200 g/L.

According to UNESCO (2005) [58] the minimum amount of rainfall needed for cotton plant growth without artificial irrigation is around 500 mm per year. This value is used as reference due to the lack of average precipitation values in some countries and regions as well as the variability verified in mountain areas (climate might drastically change depending on the side of the mountain where the farmers are located). This figure is than corrected according to the level of reliability of the cotton growers on the effective rainfall. In these study cases the Tajik farmers are not relying on the rain water and are using irrigation systems. It is assumed that 25% of the UNESCO's value is consumed by the plants. Extra amounts of water are extracted from river or underground reservoirs for irrigation purposes and are reported by the suppliers.

The electricity produced from standard grid is modelled according to the mix of the country published in PSIA Energy Tajikistan (2011) [59]. The energetic mix reported is from 2008 production as no recent data are available. For that year, the electricity mix was: 56% hydropower, 22% oil, 18% gas and 4% coal.

The suppliers are not reporting direct data for ginning as most of the times this process is performed by cotton growers itself. For model ginning it is used the data reported from cotton growers' outsourced company.

Pesticides applied as well as seed treatments are modelled regarding the same considerations made for grazing sheep models for pesticides and sheep' chemical treatments (3.3.1). In this case, the farmer is reporting its consumption based on the commercial names of the products and datasets are selected according to the chemical class of the products used.

Table 14 - Inventory of emissions to air, water and soil from cotton cultivation. Values related to the FU: 1kg of pollutant per 1 kg of ginned cotton produced.

Compartment	Emissions	Conventional	Organic
Air	N_2O 1)	1.36E-03	3.26E-04
	NO_x 2)	2.87E-04	6.85E-05
	NH_3 3)	1.82E-03	4.95E-04
Water	Nitrate 4)	1.84E-01	-
	Phosphorus 5)	2.04E-03	1.79E-03
	Phosphate 6)	1.77E-04	1.56E-04
Soil	From fertilizers 7)		
	Cd	1.67E-05	1.17E-07
	Cu	5.12E-06	3.45E-05
	Zn	5.81E-05	4.69E-04
	Pb	1.36E-06	1.98E-06
	Ni	2.83E-06	7.32E-06
	Cr	8.48E-05	5.54E-06
	Hg	-	2.01E-07
	From pesticides 8)		
	Diquat	2.08E-03	-
	Lambda-cyhalothrin	2.48E-04	-
	Prometryn	1.03E-03	-
	From seed treatments		
	Bronopol	5.79E-04	-
	Carbonix	7.02E-05	-
	Thiran	7.02E-05	-

Note: cells with hyphen (-) means that the output is inexistent for the respective supplier due to a result on the calculation (nitrates), lack of information for the fertilizer utilized (Hg) or not use of pesticides and seed treatments.

1) Emissions estimated according to the formula in Nemecek and Kägi (2007)[35] and adopts the IPCC (2006) guidelines[49]
2) Emissions are calculated based on the formula in Nemecek and Kägi [35] and the dinitrogen oxides releases: $NO_x = 0.21 * N_2O$.
3) Emissions are calculated based on the Agrammon Group (2009) model and Flish et al (2009).
4) The nitrate emissions from agricultural nitrogen inputs are modeled according to the models developed by Faist et *al.* (2009) in the Sustainability Quick Check for Biofuels [51].
5) Phosphate emissions are calculated using the models described in [52], [53] and [54]
6) Heavy metal emissions in soil are estimated using the same model as the one used in the ecoinvent report Life Cycle Inventories of Bioenergy [55]
7) The emissions of the specific pesticides are equal to the inputs of pesticides [55].

To model these emissions the same models as in 3.3.1 for sheep farming have been used. Of course that livestock releases are not accounted in this subsection as no animal is grazed on the crop fields during the growing periods.

Heavy metals are emitted to the soil when fertilizers are applied. These emissions were estimated based on the SALCA for identifying emission factors from fertilisers and uptakes from cotton. Emission and uptake factors used are presented in Table H.3, H.4 and H5 in Appendix H.

The pesticides emissions were estimated by using a simplified model following the one used in the ecoinvent report *Life Cycle Inventories for Bioenergy* [55] as in 3.3.1 for sheep farming. In cotton cultivation this model is not only followed for pesticides applied on cotton crop but also for the pesticides used as seeds treatment. Following the same lines it is assumed that all inputs of pesticides are emitted in the nature (in soil from agriculture).

3.3.3 Inventory of mechanical and chemical processes for dyed yarn production

Scouring wool, spinning, dyeing and dyeing & bleaching are modelled using similar methods. All are wet processes with the exception of spinning which generation of wastewater is pointed as small and with low content of pollutants. The input flows of these life cycle stages are presented Table 15.

Table 15 - Life cycle stage inputs for scouring, dyeing, dyeing & bleaching and spinning.

	Scouring Wool	Dyeing Wool			D&B [1] Cotton		Spinning Cotton		Spinning Wool			
		D1	D2	D3	D&B 2	D&B 3	S1	S2	S3	S4	S5	S6
Energy [2], MJ	1.72E+01	5.90E+01	1.67E+01	1.21E+01	1.67E+01	1.21E+01	9.46E+00	1.32E+01	1.26E+01	3.37E+01	3.69E+00	3.57E+01
Electricity, kWh:												
Standard grid	6.92E-02	1.31E+00	1.66E+00	7.49E-01	1.66E+00	7.49E-01	2.19E+00	3.56E+00	2.85E+00	3.01E+00	9.70E-01	8.24E+00
Own production[3]	7.84E-01[a]	3.94E-01[b]	-	-	-	-	-	-	-	9.34E-01[b]	-	-
Heat [4], *MJ*	1.41E+01[a]	5.28E+01[a]	1.07E+01[a]	9.36E+00[b]	1.07E+01[a]	9.36E+00[b]	1.57E+00[a]	3.59E-01[c]	2.32E+00[a]	1.95E+01[a]	1.96E-01[a]	6.00E+00[a]
Water, m^3	4.23E-02	2.81E-01	3.67E-01	8.50E-02	3.67E-01	8.50E-02	6.90E-02	5.77E-03	1.33E-03	2.07E-02	7.32E-04	2.43E-02
Wastewater, m^3	4.23E-02	2.70E-01	3.67E-01	8.50E-02	3.67E-01	8.50E-02	8.11E-02	5.77E-03	1.33E-03	1.73E-02	7.32E-04	6.41E-03
Transports [5], tkm	2.20E+01	1.53E+01	6.13E+00	4.34E+00	3.22E-01	2.80E-02	3.48E+00	6.50E+00	5.62E+00	1.53E+01	4.30E+00	5.30E+00
Sea	2.16E+01	1.51E+01	6.08E+00	4.22E+00	2.91E-01	-	1.14E-01	5.79E+00	4.73E+00	1.51E+01	4.20E+00	5.18E+00
Road	3.99E-01	1.62E-01	4.58E-02	1.19E-01	3.13E-02	2.80E-02	1.68E+00	7.09E-01	8.92E-01	1.62E-01	9.83E-02	1.18E-01
Rail	-	-	-	-	-	-	1.68E+00	-	-	-	-	-
Packaging, kg	*1.07E-02*	*5.98E-02*	*7.94E-02*	*2.24E-02*	*7.94E-02*	*2.24E-02*	*2.13E-02*	*8.83E-03*	*4.17E-02*	*2.31E-04*	*1.35E-01*	*2.39E-01*
Cardboard	-	2.50E-02	5.30E-02	1.53E-02	5.30E-02	1.53E-02	1.92E-02	8.83E-03	-	2.31E-04	1.28E-01	1.20E-01
Paper	-	5.01E-04	-	2.34E-04	-	2.34E-04	-	-	-	-	-	-
PET	3.29E-03	4.26E-03	2.65E-02	2.86E-03	2.65E-02	2.86E-03	-	-	-	-	6.45E-03	-
Polyester	-	-	-	-	-	-	2.12E-03	-	-	-	-	-
Polyethylene HD	-	1.50E-02	-	4.03E-03	-	4.03E-03	-	-	-	-	-	1.20E-01
Polypropylene	-	6.26E-03	-	-	-	-	-	-	4.17E-02	-	-	-
Steel	7.41E-03	8.76E-03	-	-	-	-	-	-	-	-	-	-
Chemicals, kg	9.45E-02	1.35E-01	4.03E-02	1.08E-04	1.50E-01	9.18E-05	8.00E-04	7.07E-04	2.36E-04	8.41E-03	1.10E-01	2.27E-03
Dyestuffs	-	1.10E-01	2.11E-02	3.23E-02	2.97E-02	3.79E-02	-	-	-	-	-	-
Bleach	-	-	-	1.58E-05	4.64E-02	-	-	-	-	-	-	-
Paraffin waxes	-	-	-	-	-	-	8.00E-04	7.07E-04	-	3.00E-03	2.00E-02	2.27E-03
Lubricants	4.34E-03	-	-	-	-	-	-	-	2.36E-04	8.04E-04	7.00E-02	-
Other auxiliaries	9.02E-02	2.42E-02	1.91E-02	9.18E-05	7.36E-02	9.18E-05	-	-	-	4.62E-03	2.00E-02	-
Note: cells with hyphen (-) means that the particular input does not exist in the respective supplier's activity.												

1) D&B = Dyeing and Bleaching
2) Energy corresponds to the sum of electricity and thermal energy consumed by the supplier in MJ. The conversion is made from kWh to MJ using the factor of 3.6 MJ/kWh.
3) The suppliers are using as source of energy: ***a)*** hydropower and; ***b)*** cogeneration using natural gas as fuel.
4) The suppliers are using different sources of heat energy and reporting it in distinct units: ***a)*** natural gas - conversion from m^3 to MJ using its calorific power of 36.3 MJ/m^3 [60]; ***b)*** diesel - conversion from kg to MJ using its calorific power of 42.8 MJ/kg [60]; ***c)*** district heat (wood chips) – its figure is reported as MJ consumed.
5) These values are the result of the multiplication of the distance between suppliers (km) with the quantity transported (t). Sea distances are calculated based on the FSI (2013) where port-to-port or door-to-door transit time and distances are calculated based on the statistical data, provided by shipping lines. Road and rail distances are estimated using the Google (2013).

The suppliers D3 and S1 (both located in China) do report the energy mix utilized on the production of the electricity consumed in their facilities. D3's energy mix is composed by 81% coal, 18% solar and 1% nuclear, while S1's mix uses 65% coal, 30% hydro and 5% solar. All the others suppliers presented are modelled regarding its country's standard grid in ecoinvent. Electricity imports are also accounted for.

Heat production is modelled according to the datasets available in the ecoinvent. The model selected refers to the boiler capacity and burner type utilized in the case studies. In the case where district heating is used the generic dataset selected according the energy source utilized (wood chips).

The suppliers describe the origins of its fibres or yarns (raw materials to be processed in their facilities) as well as the type of transportation used from the previous life cycle stage to the company. The modes of transports used are sea, road and rail and distances are estimated based on tools available online.

Chemicals and auxiliaries productions are modelled according to the datasets existing in the database utilized. Some assumptions are made when specific ingredients are not modelled in the databases. That way, some alternatives are adopted taking into account its similarity with other compounds or their chemical class. This is done for organic, inorganic or a mixture of both.

Water emissions are listed in Table 16. The composition for the effluents is only reported by the scouring mill and dyeing mil D1 as these have internal treatment of polluted water coming from its processes. All other suppliers are releasing its wastewater for external treatment plants. For these cases, wastewater impacts are modelled using datasets for wastewater treatment plant.

Table 16 – Water emissions from wet processes of scouring and dyeing wool reported as kilogram of compound per FU (wool top and dyed product, respectively).

Compounds	Scouring wool	Dyeing wool (D1)
Ammonium, NH_4-N	4.86E-03	1.23E-04
BOD_5	8.97E-03	7.26E-05
Chlorides, Cl^-	3.80E-02	4.88E-04
Chromium, Cr	-	2.90E-07
COD	3.09E-02	2.18E-04
Copper, Cu	-	1.45E-07
Iron, Fe	-	7.12E-06
Lead, Pb	-	1.45E-07
Mercury, Hg	-	1.45E-08
Nickel, Ni	-	1.45E-07
Nitrate, NO_{3-N}	4.00E-04	3.33E-03
Nitrite, NO_{2-N}	2.76E-05	-

Organic nitrogen, N_{-org}	3.28E-04	-
Sulfates, SO_4	-	2.71E-03
Suspended solids	1.06E-04	-
Total phosphorus, P	7.18E-05	2.90E-06
Zinc, Zn	-	7.26E-07

Note: cells with hyphen (-) means that the particular compound is not analysed in the internal treatment plant. That way, no value is available.

Conversion factors used to convert the amount of substance reported in the inventory to the amount of substance in ecoinvent (example: ammonium-N into ammonium). These factors and datasets are listed in the Table D.3 in Appendix D.

Table 17 shows the amount of solid waste generated and its final end of life option.

Table 17 –Inventory of solid waste production per type of final disposal

Suppliers	Scouring wool	D&B Cotton	Dyeing wool		Spinning cotton		Spinning wool		
		D3	D1	D3	S1	S2	S4	S5	S6
kg of solid waste disposed									
Landfill	1.75E-02	-	3.65E-02	-	1.60E-03	-	2.06E-03	6.02E-03	-
Incineration	-	7.81E-04	-	7.81E-04	2.53E-03	1.24E-02	-	-	-
Incineration of hazardous waste	-	9.76E-06	-	9.76E-06	4.49E-04	-	-	-	1.69E-03

Note: cells with hyphen (-) correspond to end of life options which are not utilised for disposal of the solid waste generated according to the suppliers' data.

Solid waste is regarded according to its final treatment and modelled by generic dataset. Solid wastes which are recycled are not assessed as it is assumed as a raw material of other processes outside of the system boundaries.

Only the supplier S2 is reporting its emissions to air resulting from the spinning processes. These emissions are listed in Table 18. Air emissions are generally collected and emitted in mixture with other air emissions from other processes, as for example the exhaustion of combustion gases from boilers. Thus, it is not easily reported the allocation of the emissions of specific processes as for instance, dyeing, spinning or scouring. As only one supplier is reporting emissions form its specific processes and only two compounds are analysed, these values are not concerned in the LCA. It is assumed that the most important emissions emerge from processes of heat and electricity production as well as transports.

Table 18 – Air emissions from the spinning mill S2. Values reported to the functional unit of 1 kg of cotton yarn

Compounds	**Spinning mill S2**
Chlorine and inorganic compounds, HCl	1.30E-03
Dust	4.34E-04

3.3.4 Datasets from ecoinvent

Secondary data from ecoinvent used to model the life cycle stages presented are listed in the Appendix A to G. Table 19 summarizes the datasets included in the listed Appendixes.

Table 19 – Location of the datasets utilized in the appendixes.

Category	Sub-category	Appendix	Table
Energy production	Electricity	A	A.1
	Heat		A.2
Agriculture	Machinery	B	B.1
	Feedstuff		B.2
	Fertilizers		B.3
	Pesticides		B.4
	Chemical treatments (sheep and seeds)		B.5
	Emissions		B.6
Packaging material	-	C	C.1
Water	Sources of consumed water	D	D.1
	Wastewater treatment		D.2
	Water emissions		D.3
Chemicals, dyestuffs and auxiliaries	-	E	E.1
Transports	-	F	F.1
Solid waste disposal	-	G	G.1

3.4 Impact assessment

Environmental impacts are quantified using the LCA tool and respecting the guidelines reported in the ISO 14040:2002 [10]. This work performs LCIA until characterization step and following the EcoLogTex the methods used are from taken from ILCD recommendations [11]. This method was chosen because it is a result of a project for the European Commission that analysed several life cycle impact assessments (LCIA) methodologies to reach and recommend a consensual methodology [11]. Thus, the potential environmental impact categories assessed were:

- **Climate change:** Global Warming Potential calculating the radiative forcing over a time horizon of 100 years. | IPCC 2007.
- **Ozone depletion:** Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years. | World Meteorological Organization (WMO) 1999.
- **Human toxicity, (cancer effects and non-cancer effects):** Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogramme). | USEtox.

- **Acidification:** Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. | Seppälä et al. 2006 and Posch et al. 2008.
- **Freshwater eutrophication:** Expression of the degree to which the emitted nutrients reaches the freshwater end compartment (phosphorus considered as limiting factor in freshwater). | ReCiPe version 1.05.
- **Marine eutrophication:** Expression of the degree to which the emitted nutrients reaches the marine end compartment (nitrogen considered as limiting factor in marine water). | ReCiPe version 1.05.
- **Freshwater ecotoxicity:** Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg). | USEtox.
- **Water resource depletion:** Freshwater scarcity: Scarcity-adjusted amount of water used. | Swiss Ecoscarcity 2006.

4 RESULTS AND DISCUSSION

Here the results for the different life cycle stages are presented and discussed for each textile product. Moreover, the results obtained for each supplier for the same life cycle stage are compared, the burdens are identified and the opportunities of improvements suggested.

The presentation of the results is divided in two phases according to the materials assessed. At first the results for wool yarns production (including sheep farming, scouring, spinning and dyeing) are presented. These are followed by the results for cotton yarn manufacture (including cotton cultivation, spinning and dyeing & bleaching).

4.1 LCA of Wool Yarns

4.1.1 Sheep farming

The contribution to the total impact of greasy wool production from each farm is shown in Table 20 for F1, F2 and F3. In order to highlight the representativeness of each supplier for each environmental impact category assessed it is calculated the relative contribution. This is done by dividing the contribution of each supplier by the maximum value calculated for each impact category as show in the table.

Table 20 – Results from sheep farming (case study: F1, F2, F3) for the production of 1 kg of greasy wool and its relative contribution to the maximum value calculated for each category.

Impact Category	F1	F2	F3	Relative contribution, %		
				F1	F2	F2
Climate change, kg CO_2 eq	2.11E+01	4.39E+01	5.76E+01	37[a)]	76	100
Ozone depletion, kg CFC-11 eq	9.51E-08	3.34E-07	2.55E-07	28	100	76
Human toxicity (CE) [b)], CTUh	6.01E-08	4.31E-08	1.19E-09	100	72	2
Human toxicity (NCE) [b)], CTUh	3.81E-05	9.07E-05	2.62E-06	42	100	3
Acidification, molc H^+ eq	5.39E-01	1.09E+00	8.21E-01	50	100	76
Freshwater eutrophication, kg P eq	5.84E-04	2.08E-03	2.21E-04	28	100	11
Marine eutrophication, kg N eq	1.82E-02	5.55E-02	3.89E-02	33	100	70
Freshwater ecotoxicity, CTUe	1.23E+01	5.12E+01	1.55E+00	24	100	3
Water resource depletion, m^3 water eq	1.68E-02	3.40E-02	4.42E-02	38	77	100

a) Example of the procedure performed for the calculation of the relative contribution of each supplier in all the categories: for F1 in the climate change category = 2.11E+01 / 5.76E+01 * 100.

b) CE = cancer effects; NCE = non-cancer effects

The sheep farmer F2 has the largest impacts for six categories out of 9 calculated, namely for the ozone depletion, human toxicity (non-cancer effects), acidification, eutrophication (freshwater and marine) and freshwater ecotoxicity. This supplier has the second largest contribution in the other categories (climate change, human toxicity (cancer effects) and water resource depletion). F2's has a larger input of fertilizers, pesticides and chemical treatments to sheep. This activity has also a substantial use of machinery and electricity.

No fertilizers, chemicals nor pesticides and chemicals are utilized by F3 but it reports a high consumption of energy and use of tractor on its activities. These reflect its large results in categories such as climate change, ozone depletion, acidification and marine eutrophication while having low contribution in human toxicity (cancer and non-cancer), freshwater eutrophication and freshwater ecotoxicity categories. As a big area is used by this supplier the use of tractor to cover all the fields is higher.

F1's burdens are mostly in between F2 and F3 in the overall results. Exceptions are made for climate change, ozone and water resource depletion in which it has the lowest potential impacts and in human toxicity (cancer effects) where this supplier has the highest contribution.

The relative contribution of each activity to the total impact on cotton fibre production is illustrated in Figure 7.

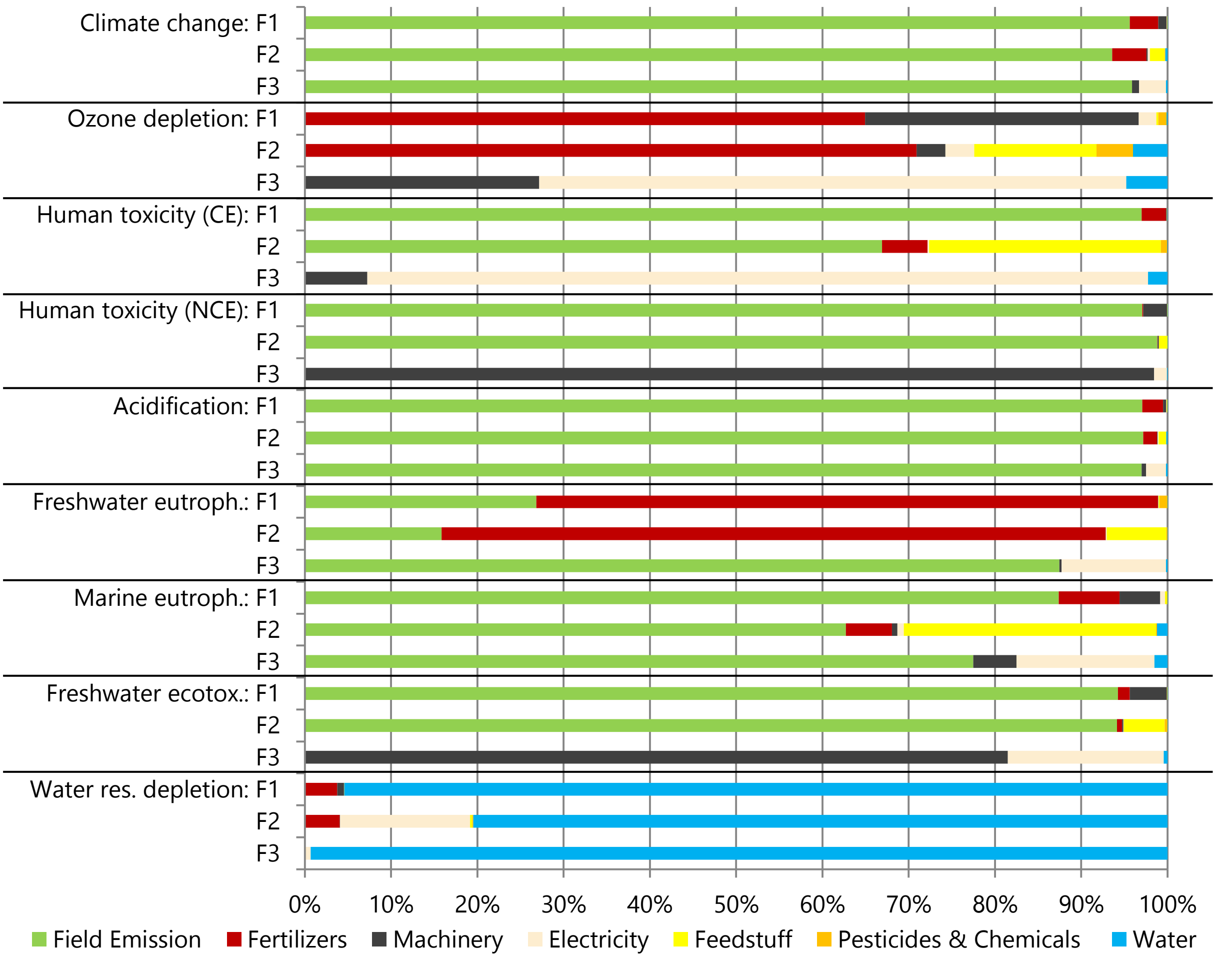

Figure 7 - Relative contribution of each activity to the overall impact for F1, F2 and F3 for the production of 1kg of greasy wool.

Sheep farming processes were evaluated and its contribution for the environmental impacts is presented per kilogram of greasy wool at farm. Burdens have been grouped as listed:

- **Field Emissions:** estimated releases of fertilizer and pesticides as well as livestock emissions to the air, water or soil.
- **Feedstuff:** production of seeds and chemicals utilized for their treatments.
- **Pesticide & Chemicals:** it includes the production of the pesticides utilized as well as the chemicals used for sheep treatment (which include also pesticides).
- **Fertilizers:** it includes the production of the fertilizers used.
- **Machinery:** this group comprises the machinery used on pasture activities as sowing, fertilizer and pesticide application as well as the utilization of a tractor on transports through the farm of people, assets and flock movements; including its consumption of diesel and emissions.
- **Electricity:** generation of electricity in power plant and generation set for farming activities as shearing, lightning, workshop and other activities related to sheep farming.
- **Water:** water used for irrigation and sheep watering as well as energy associated with its application.

Field emissions to the air, water or soil comprising the releases of fertilizer and pesticides and livestock emissions are identified to be a major contributor in most of the potential impact categories for all the farms. Its relative contributions are larger than 60% for impact categories such as climate change, human toxicity, acidification, marine eutrophication and freshwater ecotoxicity. These results are lower in F3 for the categories of human toxicity and freshwater ecotoxicity as this supplier has no inputs of pesticides.

Another important contributor was fertilizer manufacture which showed up a high impact (around 70%) on ozone depletion and freshwater eutrophication in the suppliers F1 and F2. In the other hand machinery and electricity have significant weight in categories as human toxicity and freshwater ecotoxicity in F3. Feedstuff has significant contributions in F2 in ozone depletion, human toxicity (cancer effects) and freshwater ecotoxicity.

The major impact associated with the water resource depletion is from water used in the sheep farming activities as drinking water for sheep (major contribution) or irrigation.

Emissions from livestock of CH_4 and N_2O show up as the major contributors on climate change in the three case studies. Although the emissions per FU are differing between farms, the emissions and yield of wool production per livestock unit are similar. The results are almost proportional to the allocation factor (economical) of each production. In studies from Biswas *et al* (2010)[13] and Eady *et al.* (2012) [15] it is calculated a similar allocation factors to the one used in F1. These studies are reporting values of CO_2-eq per kilogram of greasy wool around 16 and 29, respectively – similar to the results of F1 (21 kg CO_2 eq). This fact leads to conclude that greenhouse gases emissions from sheep farming are in line with the literature values.

Since most ozone depleting chemicals (mostly refrigerants) were phased out after the Montreal Protocol [36], ozone depletion emissions today are usually minimal and related to electricity production. Fertilizers production is the main contributor to Ozone Depletion due to releases of halons, HCFC's and CFC's in electricity production in their upstream life cycles stages. Other important contributions are coming from machinery operations which are consuming diesel and the electricity consumption in farms (both are main contributors in the supplier F3 as no fertilizers are utilized).

The major inputs of heavy metals (mainly lead, cadmium, zinc and mercury) into agricultural systems are from fertilizers use. It increases the toxicity and has a large contribution in the categories of human toxicity and freshwater ecotoxicity. The origins of these inputs are, of course the fertilizers utilized in pastures but also the one used to grow feed crops. Emissions of glyphosate to soil from pesticide application in the supplier F2 also contributes to its impacts on freshwater ecotoxicity. As neither fertilizers nor pesticides are utilized in F3's activities his contributions to the rise of toxicity potential in these categories are on the use of tractor which is emitting heavy metals to soil, air and water and upstream activities of electricity production (e.g. burning hard coal and disposal its ashes).

Acidification potential is contributed mainly by the emissions of ammonia and nitrous oxides from livestock emissions to air. These gases might originate nitric acid formed during lightning storms by the reaction of nitrogen and oxygen. NO reacts with oxygen originating N_2O which will react with water forming the acid which contributes to the phenomenon of acidification [63].

The enrichment of phosphorus and phosphates (dissolved phosphorus) nutrient in water are the main contributors to freshwater eutrophication. There are two main sources identified in the present study: the fertilizers production (mainly in F1 and F2) and field emissions (mainly in F3). The marine Eutrophication main source is also in field emissions by the releases of ammonia and nitrous oxide to air. Most of these emissions are realized from livestock but also from agricultural processing in feedstuff production (mainly in the supplier F2).

Field emissions are a major contributor to several environmental impact categories: climate change influenced by livestock emissions; human toxicity and freshwater ecotoxicity due to the use of fertilizers and pesticides; eutrophication due to ammonia, nitrous oxide and phosphorus emissions and; acidification influenced by ammonia and nitrous oxides. The enteric methane from sheep emerges as the hotspot for the climate change contribution. According to the Biswas et al (2010)[13] a correct management of sheep diets might reduce emissions or, in the future, the selection which genetic breeds may produce wool with the desired wool properties while producing less methane. Precision management of fertilizer is might also be concerned.

4.1.2 Scouring wool

The LCA results for the scouring mill analysed is shown in Table 21 and the relative contribution of each activity to the overall impact of the scoured wool production in each environmental impact category is illustrated in Figure 8.

Table 21 - Results from the scouring mill reported to 1 kg of wool top produced.

Impact category	Scouring
Climate change, kg CO_2 eq	1.48E+00
Ozone depletion	4.06E-09
Human toxicity, cancer effects, CTUh	1.91E-08
Human toxicity, non-cancer effects, CTUh	8.52E-03
Acidification, molc H^+eq	8.15E-05
Freshwater eutrophication, kg P eq	5.83E-03
Marine eutrophication, kg N eq	1.26E-01
Freshwater ecotoxicity, CTUe	6.97E-03
Water resource depletion, m^3 water eq	4.06E-09

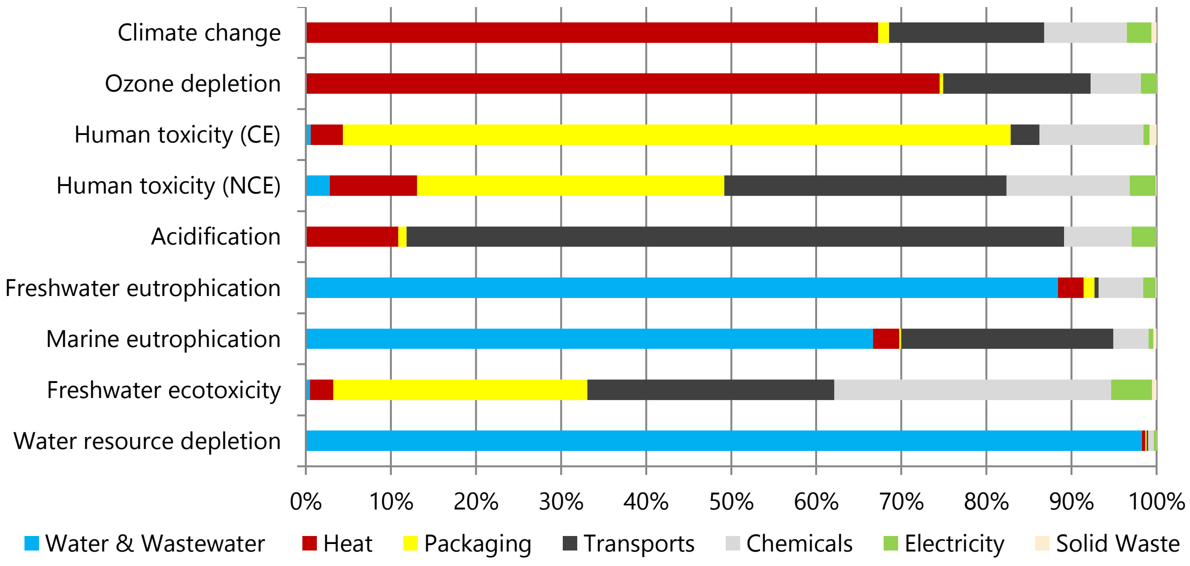

Figure 8 - Relative contribution of each activity to the overall impact for scouring wool reported to 1 kg of wool top produced..

Scouring mill activities were evaluated and its contribution for the environmental impacts is presented per kilogram of scoured wool at company gate. Burdens have been grouped by its origins or main activities as listed:

- **Water & Wastewater:** consumption of water from aqueduct and well, water emissions from internal treatment and wastewater treatment of untreated water in a municipal plant.
- **Chemicals:** production of chemicals and auxiliaries utilized.
- **Packaging:** manufacture of packaging materials used to pack the products.
- **Electricity:** generation of electricity in power plant as well as from own production (hydro).
- **Heat:** production of calorific energy within the facilities.
- **Transports:** transport of fibres to be scoured from sheep farmers to the scouring mill.
- **Solid waste:** waste disposal.

Climate change and ozone depletion are characterized by the large contribution of heat.

Human toxicity (cancer and non-cancer effects) main contributor is the production of steel used in packaging (contribution up to 80%). Transports are sharing a burden of 30% in the category of human toxicity non-cancer effects.

Acidification potential is increased by the activities of transportation by sea of raw materials with origins in different continents - contribution around 70%. This activity also has significant impacts in climate change, ozone depletion human toxicity (non-cancer effects), marine eutrophication and freshwater ecotoxicity (contributions up to 30%).

Packaging materials production, mainly of the wire utilized to tie the scoured wool, has the largest burden in the category of human toxicity (cancer effects) and has significant contributions in the categories of human toxicity (non-cancer effects) and freshwater ecotoxicity.

Both, transports, packaging and chemicals are sharing a burden around 30% in freshwater ecotoxicity.

Electricity production has small impacts in the overall results as 95% of the energy is produced by the company (hydroelectric power). The remaining 5% are imported from the Italian standard grid. Solid waste accounts for not more than 4% of the impacts in all categories.

Most of the climate change contributors are exhaust gases (mainly CO_2, CH_4 and N_2O) released from fossil fuel combustion in heat production and transports. The same drivers have a similar share in Ozone Depletion due to the emission of halons and CFC's in upstream activities of natural gas and diesel production.

The production of metallic wire used to tie the scoured wool packaging, use of transports and heat generation are responsible for the emission of heavy metals such as chromium, mercury, lead and zinc to air and water which contributes most to human toxicity and freshwater ecotoxicity. The origins of these emissions are in the production of wire, combustion of fossil fuels and disposal of mining residues in upstream processes of electricity generation. Chemicals production also has a significant burden in the freshwater ecotoxicity due to upstream processes of energy production.

Air emissions of SO_2 and NOx which are released in exhaust gases coming from the combustion of fossil fuels in transports, heat and electricity production are the main cause for acidification potential category. These gases might originate nitric and sulphuric acid, respectively

Freshwater eutrophication is mainly caused by phosphate, while marine eutrophication by ammonia, nitrate and nitrite in its water emissions. The latter category is also a result of emissions of NOx to air from transports.

Scouring wool is a wet process, in such a way that large quantities of water are consumed and consequently big amounts of wastewater are generated. It has negative repercussions in environmental impact categories of eutrophication (freshwater and marine) and water resource depletion (contributions larger than 65%). Since the use of water and energy are often related in the textile industry as the main use of energy is to heat up the process baths and drying fibres. Heat is the biggest contributor in the potential impact categories of climate change and ozone depletion with contributions larger than 65%. A positive aspect which has to be highlighted is the electricity production mix based mostly on a hydropower source. It results on a small share in the overall results.

The scouring mill is located in Italy and its suppliers are producing wool in New Zealand, Australia and South Africa. It means that large distances are travelled in order to produce 1 kilogram of wool top and strong impacts are emerging from transoceanic transports in all the categories assessed (exceptions are considered in freshwater eutrophication and water resource depletion.

The production of the wire used to tie the packages has important role on the toxicity categories. A substitution of this material or the reduction of its inputs might increase the environmental performance of the company.

In the study from Barber *et al*. (2006) [18] the average quantities of electricity is 0.2 kWh while heat consumption is around 15 MJ for the production of one kilogram of wool top. These values are quite similar to the ones reported by the supplier.

In the other hand, comparing the consumption of energy and water of the presented scouring mill with those referenced values by BAT, possible improvements might be achieved using different processing technologies or management. Regarding to the average values reported in BAT the case study is producing 2.5 to 6 times more wastewater, 4 times more energy and 3 times more electricity. The establishment of a roadmap fixing targets and procedures to reduce its consumption shall provide opportunities to improve the overall results.

4.1.3 Spinning

The contribution of each activity to the total impact in the spinning mills assessed is presented in Table 1Table 22. In order to compare the relative contribution of each mill, the relative contribution of the suppliers per environmental impact category is calculated dividing its contribution by the maximum value calculated for each category (example of the calculus provided in the table).

Table 22 - Results of spinning activity of each case study for the production of 1kg of yarn and its relative contribution to the maximum value calculated for each category.

Impact category	S3	S4	S5	S6	Relative contribution, %			
					S3	S4	S5	S6
Climate change, kg CO_2 eq	2.27E+00	3.86E+00	1.02E+00	6.02E+00	38[a)]	64	17	100
Ozone depletion, kg CFC-11 eq	2.17E-07	4.36E-07	9.21E-08	5.39E-07	40	81	17	100
Human toxicity, cancer effects, CTUh	2.27E-09	4.12E-09	2.15E-09	6.28E-09	36	66	34	100
Human toxicity, non-cancer effects, CTUh	3.56E-08	6.75E-08	4.64E-08	1.12E-07	32	60	41	100
Acidification, molc H^+ eq	1.34E-02	1.74E-02	6.16E-03	3.28E-02	41	53	19	100
Freshwater eutrophication, kg P eq	5.17E-05	7.22E-05	2.47E-05	1.52E-04	34	47	16	100
Marine eutrophication,	2.38E-03	3.20E-03	1.16E-03	4.91E-03	49	65	24	100

kg N eq								
Freshwater ecotoxicity, CTUe	3.50E-01	4.02E-01	4.03E-01	1.06E+00	33	38	38	100
Water resource depletion, m^3 water eq	1.22E-03	4.44E-03	9.09E-04	7.11E-03	17	62	13	100

a) Example of the procedure performed for the calculation of the relative contribution of each supplier in all the categories is: for S3 in the climate change category = 2.27E+00 / 6.02E+00 * 100.

The supplier S6 has the largest impacts in the overall results. This company is consuming more energy (electricity and heat), water and packaging materials to produce 1 kg of yarn when compared among the other suppliers. In general, the supplier S5 has the lowest burdens in the total results.

The relative contribution of each activity to the total impact on spinning mills activity is illustrated in Figure 9.

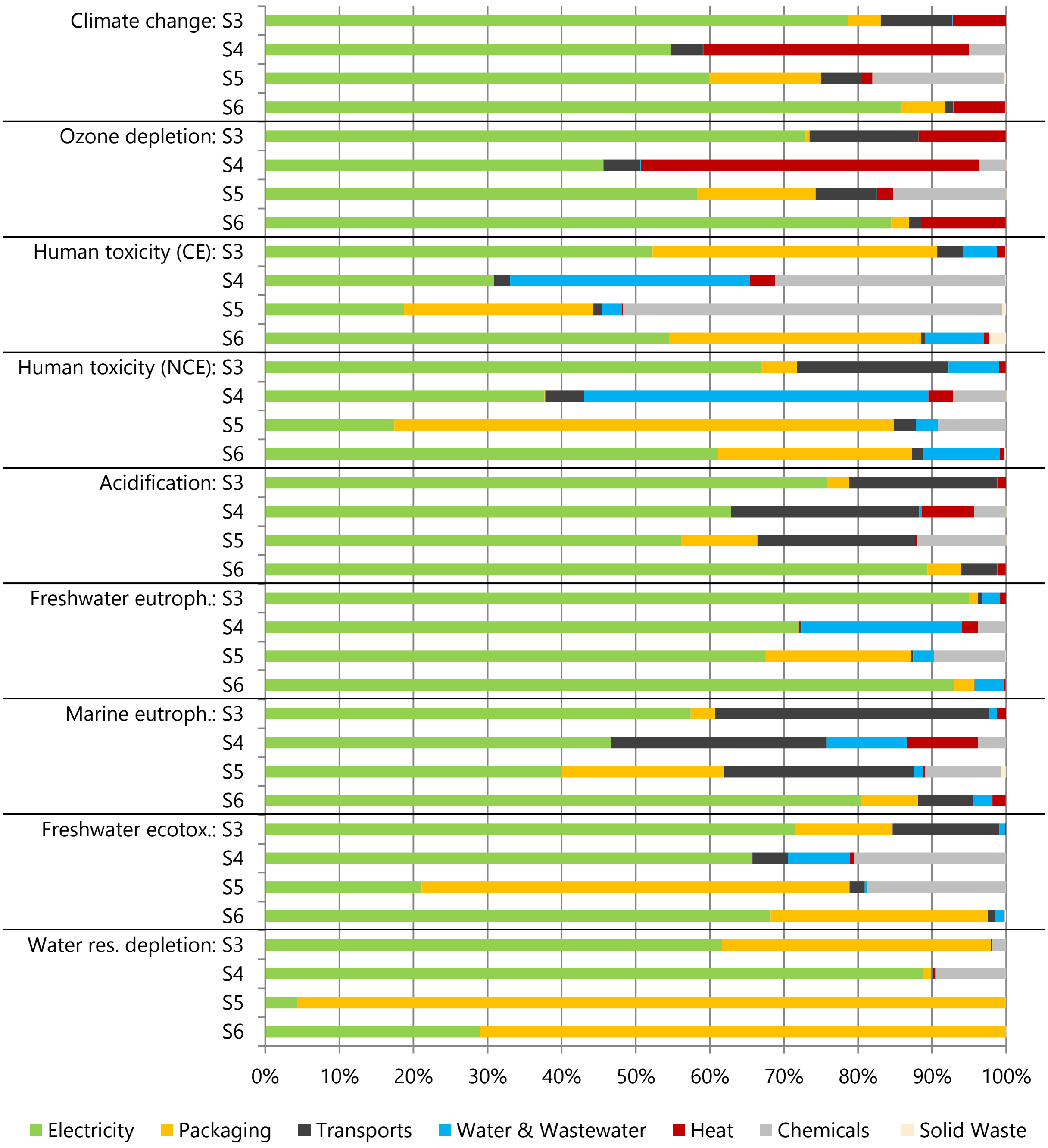

Figure 9 - Relative contribution of each activity to the overall impact for spinning mills for the production of 1 kg of yarn.

Spinning mill activities were evaluated and its contribution for the environmental impacts is presented per kilogram of spun wool or wool yarn at spinning mill gate. Burdens have been grouped by its origins as listed:

- **Water & Wastewater:** consumption of water from aqueduct or well and wastewater treatment in a municipal plant.
- **Chemicals:** production of chemicals and auxiliaries utilized.

- **Packaging:** manufacture of packaging materials used to pack the products as well as plastic or cardboard cones utilized to give shape or support the yarns.
- **Electricity:** generation of electricity in power plant or own facilities.
- **Heat:** production of heat from natural gas in boilers to be used in the spinning.
- **Transports:** transport of fibres to be spun from scouring mills to spinning mills.
- **Solid waste:** disposal of the solid waste generated.

The main contributor in climate change and ozone depletion is electricity production. It emerges as the major origin of its impacts in most of the suppliers (up to 85%) while heat production is the larger hotspot in the supplier S4. Activities as packaging and chemicals production are a significant contribution (around 15%) in the spinning mill S3.

Human toxicity categories have different key origins for its burdens in each supplier but electricity is always sharing significant contributions (ranging from 20% in S5 to 50% in S3 and S6). Human toxicity (cancer effects) is mainly originated by contributions around 35% in S3 and S6 and 25% in S4 from packaging production but also contributions from chemicals production in the supplier S4 and S5 (30% and 50% respectively). Water and wastewater have an important share in S4 around 30%. In the environmental impact category of human toxicity (non-cancer effects) electricity keeps being the largest contributor for the suppliers S3 and S6 (around 60%), while the major contributors in S4 and S5 are water & wastewater (45%) and packaging materials production (65%).

The environmental impact of electricity generation is the key contributor in the category of acidification. It shows up contributions larger than 55% in all the spinning mills assessed, Transports also have important shares (up to 25%). A similar pattern of contributions is verified in marine eutrophication where electricity has smaller impacts and transports' contribution is now up to 35%.

Freshwater eutrophication is mainly originated by electricity production as well. 20% of its contribution in this category is coming from water & wastewater in the supplier S4 and packaging in the supplier S5.

Freshwater ecotoxicity has a similar pattern as the one verified for the category of human toxicity (non-cancer effects).

In the category of water resource depletion the major contributors are electricity production for S3 and S4 and packaging production for S5 and S6. Packaging also has an important contribution in the environmental performance of S3 (up to 30%).

The use of fossil fuels in power plants, boilers as well as in engines of transports is responsible for several negative impacts in the environment mainly due to the release of greenhouse gases and heavy metals. Examples of exhaust gases coming from its combustion and correspondent impacts are CO_2, CH_4 and N_2O emissions which contributes most to the climate change and SO_2 and NOx that have important burdens on acidification due to the potential formation of sulphuric and nitric acid.

The consumption of these fuels is also associated to the emissions of heavy metals from burning coal and light fuels processes as well as from the generation of mining spoils from its extraction. Example of these toxic compounds which are released to air, water and soil are chromium, mercury, lead and zinc which contributes most to the categories of human toxicity and freshwater ecotoxicity.

As mentioned before ozone depletion emissions today are usually minimal and related to electricity production. In the present case it is systematic burden with origin on the processing of natural gas and the main actors are halons, HCFC's and CFC's.

Other important shares of electricity on environmental impact are in eutrophication: while mining activities also generates the emissions of nutrients as phosphates which contributes most to freshwater eutrophication, NOx and ammonia from exhaust gases increases the potential impact of marine eutrophication.

Chemicals and packaging material have important impacts on ozone depletion in the supplier S5 as in its production energy is consumed but also direct releases of ozone depletion contributors.

Emissions of heavy metals and losses of pesticides and fertilizers from agricultural processes in upstream activities of the cardboard production are the mains origins of its contributions.

The major contributor for the overall results is electricity. Packaging emerges as a significant contributor in categories as human toxicity, freshwater eutrophication and water resource depletion (mainly in the supplier S5 but also in S6). Transports have important contributions (up to 30%) in ozone depletion, acidification and marine eutrophication. Chemicals production has impact in the overall results of S4 and S5. The spinning mill S4 is producing more heat and wastewater than the others, that way it is a hotspot in the categories of climate change, ozone depletion and water resource depletion for the latter driver. Solid waste accounts for not more than 3% of the impacts in all indicators.

The spinning activity has very low direct impacts, as direct emissions from this activity are almost none. The main drivers for the environmental impacts of spinning mills are activities which happen in upstream processes like e.g. electricity production. Therefore, possible improvements are mainly depending on the supplier management.

The S3 and S5 companies, which are having relative impacts, are reporting consumption levels of electricity and heat as the ones reported as an average in literature: 1 to 3 kWh/kg of electricity and 1 to 5 MJ/kg of thermal energy. The heat used in S5 is 10 times lower than the minimum reported while in S4 it is almost 3 times higher. Regarding the LCI of this energetic consumption values, higher improvements might be needed in S4 in terms of heat and in S6 in terms of electricity consumption. That way, improvements in the overall results may be achieved.

4.1.4 Dyeing

The contribution of each driver to the total impact in the three dyeing mills is shown in Table 1Table 23. Similarly to the previous results, in order to compare the relative contribution of each mill the relative contribution of the suppliers per environmental impact category is calculated dividing its contribution by the maximum value calculated for each category (example of the calculus provided in the table).

Table 23 - Results of dyeing mills activity for the production of 1 kg of dyed yarn and its relative contribution to the maximum value calculated for each category.

Impact category	D1	D2	D3	Relative Contribution		
				D1	D2	D3
Climate change, kg CO_2 eq	5.36E+00	2.15E+00	1.84E+00	100	40	34
Ozone depletion, kg CFC-11 eq	7.01E-07	2.50E-07	1.40E-07	100	36	20
Human toxicity (CE), CTUh	1.92E-08	3.11E-08	1.04E-08	62	100	34
Human toxicity (NCE), CTUh	2.75E-07	7.00E-07	1.91E-07	39	100	27
Acidification, molc H^+ eq	1.53E-02	1.06E-02	1.41E-02	100	69	92
Freshwater eutrophication, kg P eq	1.68E-04	3.73E-04	1.09E-04	45	100	29
Marine eutrophication, kg N eq	6.26E-03	8.88E-03	3.38E-03	71	100	38
Freshwater ecotoxicity, CTUe	6.09E-01	1.02E+00	3.25E-01	59	100	32
Water resource depletion, m^3 water eq	4.63E-02	6.53E-02	1.61E-02	71	100	25

a) Example of the procedure performed for the calculation of the relative contribution of each supplier in all the categories is: for D3 in the climate change category = 1.84E+00 / 5.36E+00 * 100.

The supplier D2 has the highest impacts in most of the categories and is the second largest contributor in climate change and ozone depletion after the suppliers D1 and has the lowest share in the category of acidification where D1 is the main contributor. D3 is the dyeing mill which has the lowest shares in most of categories.

Dyeing mills activities were evaluated and its contribution for the environmental impacts is presented per kilogram of dyed and bleached yarn at factory gate. Burdens have been grouped along the lines of what has been done with the spinning mills. In this case the group Chemicals also comprises the production of dyestuffs and bleach.

The relative contribution of each driver to the total impact on cotton fibre production is illustrated in Figure 10.

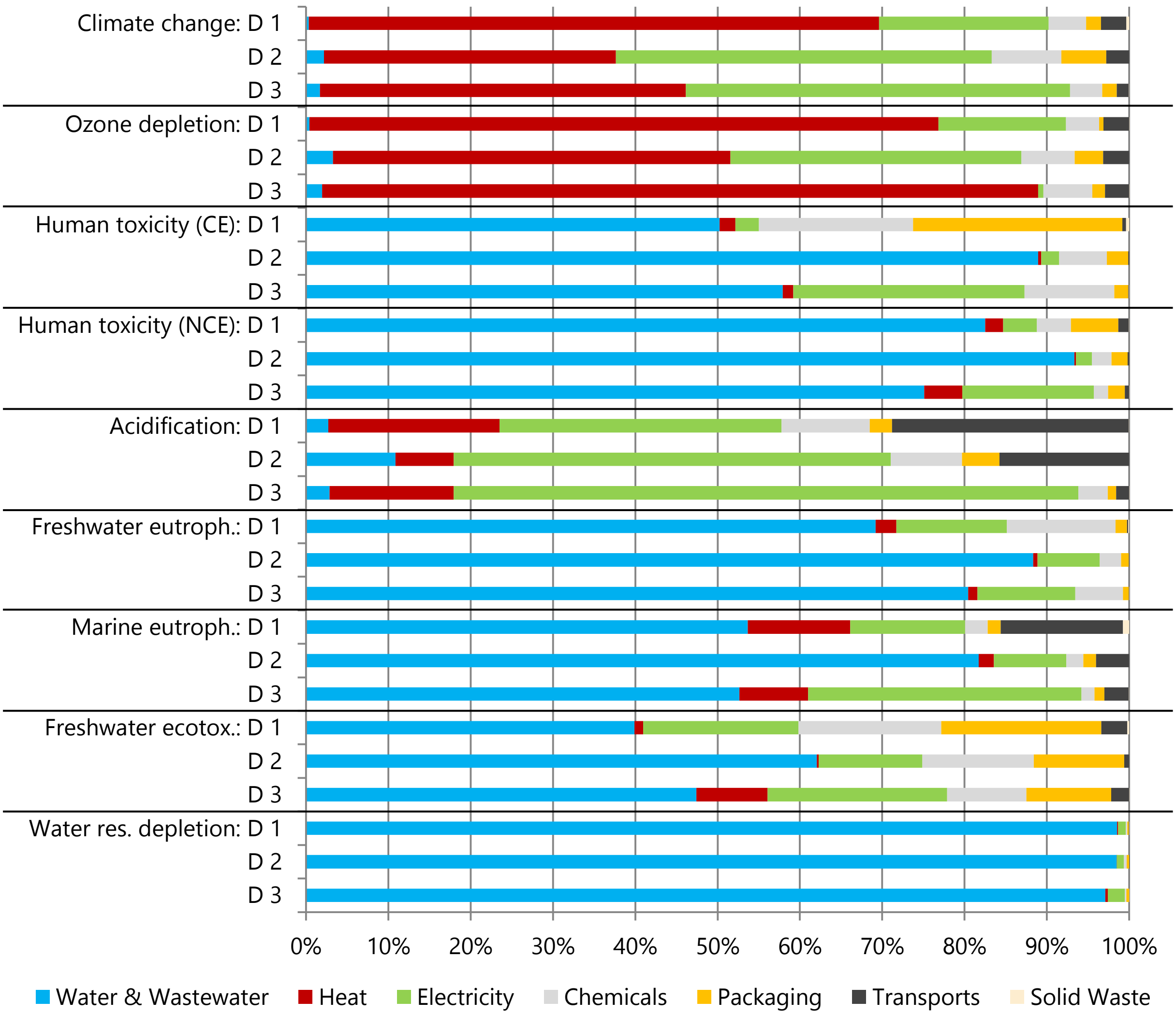

Figure 10 - Relative contribution of each activity to the overall impact for dyeing mills (D1, D2 and D3) for the production of 1 kg of dyed yarn.

The main contributors to climate change and ozone depletion are heat and electricity production, having shares up to 85% and 50% respectively. Electricity generation also has burdens larger than 35% in acidification, being the key contributor to this category. Water and wastewater emerges as the key factor for the environmental burdens in all the other categories (human toxicity, eutrophication, freshwater ecotoxicity and water resource depletion) with relative contributions ranging from 40% for freshwater ecotoxicity to 98% for water resource depletion. Chemicals and transports have meaningful shares in the overall results while solid waste doesn't account for more than 1%.

Most of the climate change burdens are shared between electricity and heat production due to the release to air of CO_2, CH_4 and N_2O from fossil fuels combustion. The same drivers have a similar share in Ozone Depletion due to the emission of halon, HCFC's and CFC's in upstream activities of natural gas and light fuel processing. Electricity in D3 has small share on the ozone depletion as its production mix is strongly based on coal which processing has smaller emissions of CFC's. Air emissions of SO_2 and NOx originated in power plants, boilers and transports from the burning of fossil fuels originate big burdens in the acidification results.

Human toxicity (cancer and non-cancer effects) and freshwater ecotoxicity are mainly affected by heavy metals emissions to air, water and soil from wastewater emissions and treatment but also from upstream processes related to the electricity production. Chromium, mercury, zinc and lead are the main pollutants which conduct these impacts. The production of packaging cardboard has some impact in freshwater ecotoxicity due to agriculture activities (pollutants releases due to losses of fertilizers and pesticides) while wire production is related to heavy metal emissions from its manufacture.

Chemicals production also has an important contribution in categories as human toxicity (cancer effects) and acidification. While in the first it is verified because of chromium and mercury emissions from electricity produced (upstream) and disposal of solid wastes generated, in the second it is due sulphur dioxide, nitrogen oxides and ammonia to air from its production processes.

Freshwater eutrophication is mainly caused by phosphate emissions from wastewater emissions and the disposal of spoil from coil and lignite mining in upstream processes of electricity production.

Marine eutrophication is most related to emissions of NOx to air from electricity production (combustion of fossil fuels) and emissions of nitrates and ammonia (ion) to water from wastewater emissions.

As dyeing consumes high quantities of water and consequently generates big amounts of wastewater, strong effects of Water & Wastewater are verified in the categories of human toxicity (cancer and non-cancer effects), eutrophication (freshwater and marine), freshwater ecotoxicity end, of course, water resource depletion. Energy consumption (mainly heat but also electricity) is most of the times associated with water use in the textile industry. This is a major issue in the potential impact categories of climate change, ozone depletion and acidification.

Comparing the inventory data for electricity, heat and water consumption per kilogram of dyed product with the energy use BAT values presented in section 2.4.2.

- The dyeing mill D1 has the highest consumptions patterns. It corresponds to 1.7 kWh against those 0.8 to 1.1 kWh in BAT and is using 3 times more energy and 5 times more water than the referenced maximum values.
- The dyeing mill D2 is consuming similar amount of electricity as D1 and 7 times more water than the referred on BAT while is consuming 11 MJ of energy that is lower than the referenced range of 13 to 16 MJ.

- D3's electricity consumption is equal to minimum in the literature (0.8 kWh) and the supplier is using 9 MJ of energy (lower than the in BAT). However its water consumption (around 80 L) is bigger than the reported 15 to 50 litres.

Water & Wastewater activities are the main problems associated with dyeing. The establishment of a roadmap fixing targets and procedures to reduce its consumption shall provide opportunities to improve the overall results. Electricity and heat are also important drivers due to the extraction, processing and use of non-renewable sources of energy for energy production. It is expected that saves on the quantity used of water might reduce the energy needs.

4.2 LCA of Cotton Yarns

4.2.1 Cotton cultivation

The contribution of each driver to the total impact on cotton fibre production from both case studies (conventional and organic cotton productions) is shown in Table 24. Similarly and to compare the relative contribution of each cotton grower, its contribution is divided by the maximum value calculated for each category.

Table 24 - Results from cotton cultivation (conventional and organic) for the production of 1 kg of ginned cotton and its relative contribution to the maximum value calculated for each category.

Impact category	Conventional	Organic	Relative contribution, %	
			Conventional	Organic
Climate change, kg CO_2 eq	2.93E+00	5.97E-01	100	20 [a)]
Ozone depletion, kg CFC-11 eq	2.09E-07	3.10E-08	100	15
Human toxicity, cancer effects, CTUh	2.04E-08	2.24E-08	91	100
Human toxicity, non-cancer effects, CTUh	4.62E-06	2.10E-05	22	100
Acidification, molc H^+ eq	2.04E-02	6.06E-03	100	30
Freshwater eutrophication, kg P eq	2.19E-03	2.01E-03	100	92
Marine eutrophication, kg N eq	4.58E-02	6.15E-04	100	1
Freshwater ecotoxicity, CTUe	2.83E+01	1.13E+01	100	40
Water resource depletion, m^3 water eq	1.29E+00	9.38E-01	100	73

a) Example of the procedure performed for the calculation of the relative contribution of each supplier in all the categories is: for organic in the climate change category = 5.97E-01 / 2.93E+00 * 100.

The organic cotton grower shows lower contributions for the overall results. This fact is justified by the low use of machinery and no consumption of pesticides. This organic cotton culture also has highest yield of production when compared with the conventional production process. That way, it is producing more with fewer inputs.

Nevertheless, the organic cotton cultivation has higher burdens in human toxicity categories, This is because the emissions of heavy metals in soil are bigger when compared with the conventional grower. According to the study from Tewolde *et al.*, (2011 [64], applying poultry litter might increase soil Zn by about 59% and soil Cu by 134% relative to applying ammonium nitrate. The concentrations of heavy-metal contents of synthetic and organic fertilizers utilized to model these emissions are summarized in Table H.3 and H.4 in the Appendix H, respectively.

The relative contribution of each activity to the total impact on cotton fibre production is illustrated in Figure 11.

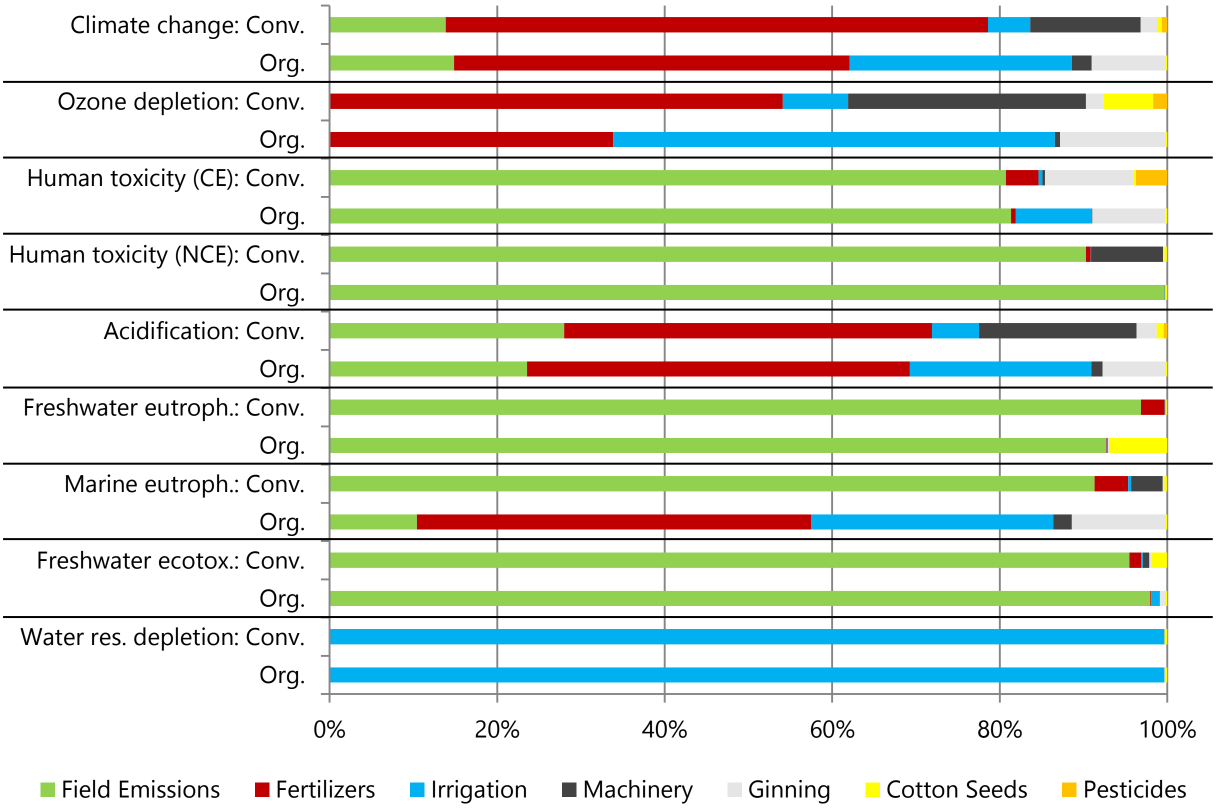

Figure 11 - Relative contribution of each activity to the overall impact for 1 kg of conventional and organic cotton production.

Cotton cultivation processes were evaluated and its contribution for the environmental impacts is presented per kilogram of cotton fibre after ginning. Burdens have been grouped by its causes as listed:

- **Field Emissions:** estimated losses of fertilizer and pesticides to air, water or soil.
- **Cotton Seeds:** production of seeds and chemicals utilized for their treatments.
- **Irrigation:** water used for irrigation as well as the energy associated.
- **Pesticides:** it includes the production of the pesticides used.
- **Fertilizers:** it includes the production of the fertilizers used.
- **Machinery:** this group comprises the machinery used in the cultivation of cotton (e.g., seeding, fertilizer and pesticide application) as well as the utilization of a tractor on transports through the farm of people and assets related to the cotton production.

- **Ginning:** transport from field to the ginning mill, processing through the cotton gin, packaging materials production (bale bags and ties) and packaging process.

Most of the climate change contribution is due to fertilizer production processes (50%) followed by field emissions (15%) and machinery operations (13%). Emissions of N_2O are the main reason behind these results.

The fertilizers production is the dominant sponsors to the category of ozone depletion in the conventional supplier (55%) and is the second main contributor in the organic supplier (40%) following Irrigation (60%). Other important contributions in conventional grower are the machinery operations which are consuming diesel. These shares are related to the release of halons, HCFC's and CFC's from electricity production in upstream processes. As mentioned in 0, nowadays, most of the ozone depleting chemicals is related to electricity production (mainly from production and refinement of fuels.).

Field emissions were identified to be a major contributor for impact categories such as human toxicity, freshwater eutrophication and freshwater ecotoxicity (relative contributions are higher than 80%). This result is also verified in marine eutrophication in the organic cotton supplier.

Fertilizers production process is in itself a source of NH_3 and NO_x emissions and which are contributing most to the impact category of acidification. This category is also strongly affected by the emissions of NH_3 and NO_x from field (25%). Machinery operations consume fuel and thus it is a source of NO_x emissions which also contributes to potential acidification in the conventional cotton production (20%). Upstream activities related to electricity generation reflect the contribution from irrigation (20% in organic grower) and ginning activities.

Cotton seeds, pesticides, machinery and ginning do not account for more than 10 to 20% of the impacts for all indicators. An exception is made to the machinery use in the organic grower which represents around 25% of the contribution to the ozone depletion potential.

Literature values for conventional production of cotton for CO_2 eq emission are 2 and 3 kilograms [27, 36] These are similar to the values here calculated. However, when the field emissions are compared with results from [36], it is possible to conclude that they are 10% lower and the production fertilizers have higher contributions.

Field application of fertilizers was the main contributor to the environmental impact in the categories of human toxicity (cancer and non-cancer effects) and freshwater ecotoxicity based on its emissions of heavy metals as chromium, cadmium, nickel lead and zinc to soil. Emissions from pesticides to the soil as prometryn and lambda cyhalothrin are also important contributors in the freshwater ecotoxicity category.

Freshwater and marine eutrophication main source is in field emissions. In the first case it is verified mainly from phosphorous and phosphate emissions to water and in the second by the releases of nitrates to water as well as nitrous oxide, nitrogen oxides and ammonia to air. The organic cotton production has an impact in Marine Eutrophication 74 times lower as its field emissions are lower due to the efficient management of the nitrogen nutrient application.

Land use and water consumption not surprisingly a burden directly related to the cotton cultivation. These categories are linked to the yield of production, each means that for the presented studies higher yields have less needs of land and water. Nevertheless, to have higher yields using similar amounts of water, a proper drainage system, efficient irrigation and use of organic fertilizer are needed.

Field emissions are a larger contributor to several environmental impact categories: human toxicity and freshwater ecotoxicity due to the use of pesticides and eutrophication was strongly influenced by nitrate and phosphorus emissions. Acidification potential was influenced by ammonia and nitrogen oxides and climate change was influenced by nitrous oxide. Precision management of nitrogen fertilizer will continue to be a high priority for the cotton producers around the world.

Fertilizer production is another important issue on climate change, ozone depletion, and acidification. Nitrogen fertilizer represents a major burden in the conventional grower cultivation while organic fertilizers in the organic cultivation. It reinforces the need for a careful management of nutrients applications to the soil (mainly of nitrogen).

4.2.2 Spinning

The contribution of each driver to the total impact in the two spinning mills that are processing cotton is presented in Table 25. The calculation allowing for the comparison of the relative contribution of each mill for each impact category is performed.

Table 25 - Results of spinning activity of each case study for the production of 1 kg of yarn and its relative contribution to the maximum value calculated for each category

Impact category	S1	S2	Relative contribution, %	
			S1	S2
Climate change, kg CO_2 eq	2.50E+00	7.07E-01	100	28[a)]
Ozone depletion, kg CFC-11 eq	7.22E-08	9.74E-08	77	100
Human toxicity, cancer effects, CTUh	1.38E-08	3.01E-09	100	22
Human toxicity, non-cancer effects, CTUh	2.37E-07	4.09E-08	100	17
Acidification, molc H^+ eq	2.64E-02	5.41E-03	100	20
Freshwater eutrophication, kg P eq	1.10E-04	5.11E-05	100	47
Marine eutrophication, kg N eq	5.30E-03	1.29E-03	100	24
Freshwater ecotoxicity, CTUe	4.51E-01	1.63E-01	100	36

Water resource depletion, m^3 water eq	1.35E-02	3.93E-03	100	29

a) Example of the procedure performed for the calculation of the relative contribution of each supplier in all the categories is: for S2 in the climate change category = 7.07E-01 / 2.50E+00 * 100.

The supplier S1 presents the larger impacts for the overall categories. This is to say that in general this company is using more resources to produce 1 kg of yarn. However the supplier S2 has a bigger contribution in the category of ozone depletion due to the use of nuclear energy on its national energy grid mix.

The relative contribution of each activity to the overall impact on cotton fibre production is illustrated in Figure 12.

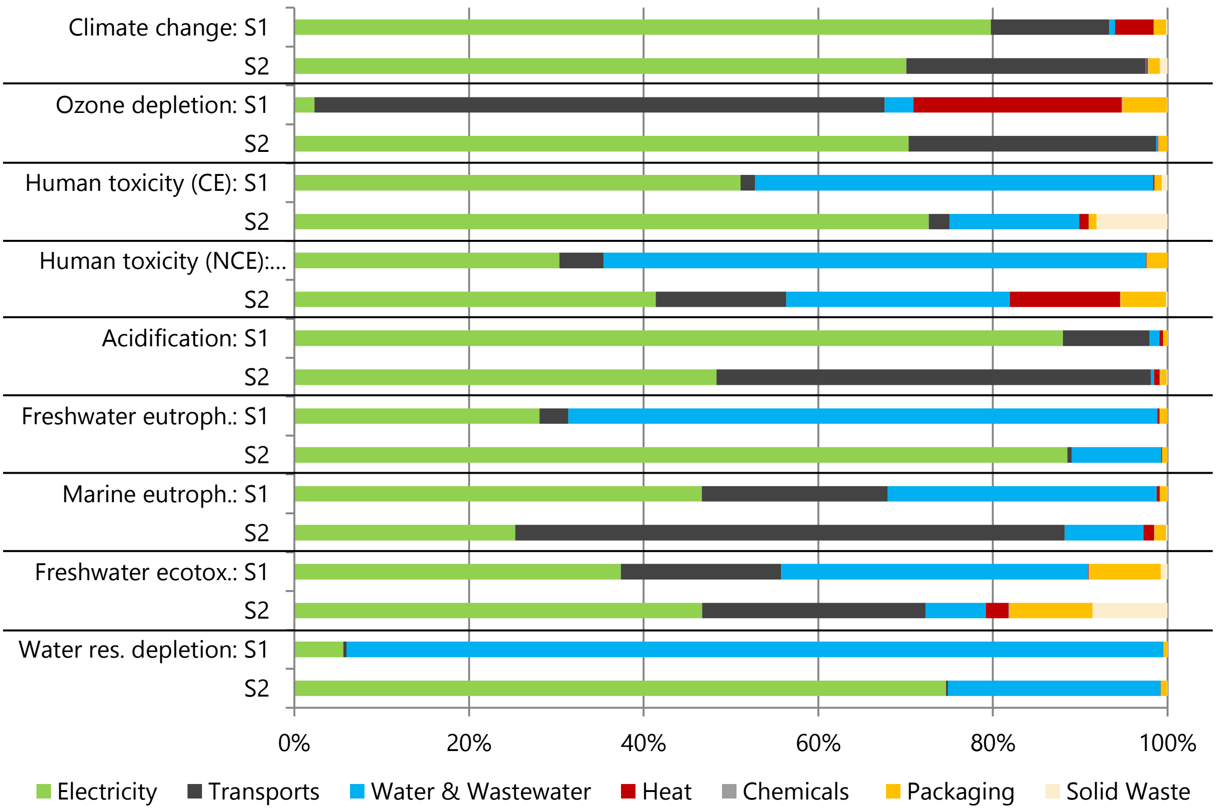

Figure 12 - Relative contribution of each activity to the total impact in spinning mills S1 and S2 for the production of 1 kg of yarn.

Spinning mill activities were evaluated and its contribution for the environmental impacts is presented per kilogram of cotton yarn at the spinning mill gate. Burdens have been grouped by its causes as listed:

- **Water & Wastewater:** consumption of water from aqueduct or well and wastewater treatment in a municipal plant.
- **Chemicals:** production of chemicals and auxiliaries.
- **Packaging:** manufacture of packaging materials.
- **Electricity:** generation of electricity in the power plant.
- **Heat:** production of calorific energy within the facilities.

- **Transports:** transport of fibres to be spun from cotton growers to the spinning mill.
- **Solid waste:** waste disposal.

Most of the climate change contribution is due to the electricity generation (70 to 80%) and transportation (15 to 25%) due to the combustion of fossil fuels and the consequent emissions of CO_2, CH_4 and N_2O in power plants and engines. The same activities are identified as the main responsible for the potential of acidification due to the emissions of SO_2 and NO_x.

Contributions to the ozone depletion are different in both case studies due to its sources of heat and electricity production mix. In one hand, S1 is using natural gas (fossil fuel) for heat production and S2 uses wood chips (wood fuel) burned in a district heating system. On the other hand the electricity mix of S2 has a strong fraction of nuclear power which contributes most to the ozone depletion (41%) as uranium enrichment plants are the main emitters of chemicals which damage the ozone layer, specifically CFC-114 (Freon) used as coolant while S1 has a small contribution from electricity production as its production mix is using mainly coal. The emissions from road transports are also different, being in S1 two times larger than S2. In summary, the processes using fossil or nuclear sources of energy have larger contributions to this impact category.

The supplier S1 consumes more water on its activities than S2 and consequently Water & Wastewater' contributions in categories as human toxicity (cancer and non-cancer effects), eutrophication (freshwater and marine), freshwater ecotoxicity and water resource depletion are also higher due to the wastewater generated. The major contribution in water resource depletion from S2's activities has origin in electricity production because of the water use (fresh and decarbonized) for cooling the nuclear reactors.

Human toxicity and freshwater ecotoxicity are mainly affected by heavy metals emissions to air, water and soil from upstream activities of electricity generation as disposal of lignite and hard coals ashes or the combustion of fossil fuels. Emissions of heavy metals in wastewater after treatment in municipal plant also show an important burden in this impact category. Responsible for human toxicity and freshwater ecotoxicity are the emissions to water, air and soil of chromium, mercury, lead and zinc. For the latter category emissions of antimony and vanadium are also observed.

Freshwater eutrophication is mainly caused by phosphate emissions from wastewater treatment plant and the disposal of spoil from coil and lignite mining in upstream processes of electricity production while marine eutrophication is mainly caused by emissions of NO_x to air from electricity production and transports use (combustion of fossil fuels) and emissions of nitrates and ammonia (ion) to water from the wastewater treatment plant.

It summary, electricity and transport are the main responsible for spinning impacts due to the extraction, processing and use of non-renewable sources of energy: as uranium and fossil fuels for electricity production or diesel for transportation of raw fibre to the spinning mill. Results show that electricity consumption represents the largest contribution to the overall categories. Its relative contribution is larger than 25% for the majority of the indicators assessed (reaching figures larger than 40% for most of the categories). Road transports show the larger impact. It represents more than 15% of the impact for the categories climate change, ozone depletion, acidification (10% in S1), marine eutrophication and freshwater ecotoxicity. seafreight has contributions up to 20% in categories as acidification and marine eutrophication in S2's impacts.

Another important issue is related to the contribution of water & wastewater in human toxicity, eutrophication and freshwater ecotoxicity categories. These impacts are larger in S1 (around 3 times) due to its larger consumption of water. Heat, solid waste, packaging and chemicals account for not more than 10% of the impacts in all indicators (exception for the heat contribution to ozone depletion which has a contribution of 25%).

The spinning activity has very low direct impacts, as direct emissions from this activity are almost none. The main environmental impacts of spinning mills are due to activities which happen in upstream processes as electricity production. Therefore, possible improvements are mainly depending on the supplier energy management. Direct impacts are mainly coming from heat production and, the most visible one, from water consumption and its releases.

4.2.3 Dyeing and bleaching

The contribution of each activity to the overall impact in the two dyeing & bleaching mills is shown in Table 1Table 26.

Table 26 - Results of dyeing & bleaching activity of each case study for the production of 1 kg of dyed product and its relative contribution to the maximum value calculated for each category

Impact category	D&B 2	D&B 3	Relative contribution, %	
			D&B 2	D&B 3
Climate change, kg CO_2 eq	2.27E+00	1.82E+00	100	80[a)]
Ozone depletion, kg CFC-11 eq	2.55E-07	1.37E-07	100	54
Human toxicity, cancer effects, CTUh	4.10E-08	1.07E-08	100	26
Human toxicity, non-cancer effects, CTUh	7.28E-07	1.91E-07	100	26
Acidification, molc H^+ eq	1.03E-02	1.31E-02	79	100
Freshwater eutrophication, kg P eq	3.89E-04	1.10E-04	100	28
Marine eutrophication, kg N eq	8.68E-03	3.17E-03	100	37
Freshwater ecotoxicity, CTUe	1.14E+00	3.30E-01	100	29
Water resource depletion, m^3 water eq	6.54E-02	1.61E-02	100	25

a) Example of the procedure performed for the calculation of the relative contribution of each supplier in all the categories is: for D&B 3 in the climate change category = 1.82E+00 / 2.27E+00 * 100.

The supplier D&B 2 has the largest impacts in the overall results except for the environmental category of Acidification. In general this company has highest consumption of energy (electricity, heat and transports), water and chemicals in order to dyed and bleach 1 kg of yarn than the D&B 3.

Dyeing mills activities were evaluated and its contribution for the environmental impacts is presented per kilogram of dyed and bleached yarn at factory gate. Burdens have been grouped along the lines of what has been done with the spinning mills. In this case the group Chemicals comprises the production of dyestuffs and bleach.

The relative contribution of each driver to the total impact on cotton fibre production is illustrated in Figure 13.

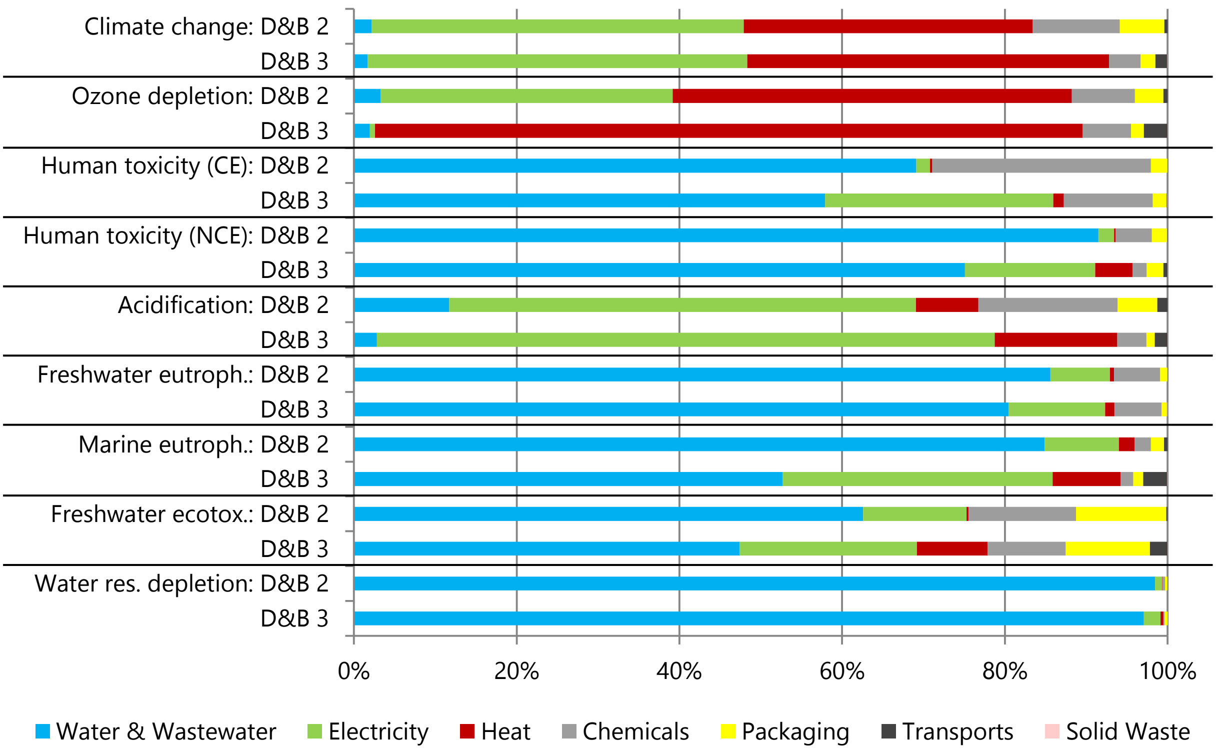

Figure 13 - Relative contribution of each activity to the total impact in both dyeing & bleaching mills for the production of 1 kg of dyed product.

Energy consumption for heat and electricity production is the biggest contributor in the potential impact categories of climate change, ozone depletion and acidification as well as marine eutrophication but only in the supplier D&B 2. Heat contribution for ozone depletion is around 90% in supplier D&B 3.

As dyeing & bleaching consumes high quantities of water and consequently generates big amounts of wastewater, strong effects of water & wastewater are verified in the categories of human toxicity, eutrophication (freshwater and marine), freshwater ecotoxicity end, of course, water resource depletion – contributions larger than 45%.

Chemicals have meaningful shares (around 10%) on the potential environmental impacts of climate change, ozone depletion, human toxicity (cancer effects), acidification and freshwater ecotoxicity as substantial amounts of dyes and other chemicals are used in this process.

Transports and solid waste account for not more than 3% of the impacts in all categories. Packaging materials production has meaningful contributions (up to 30%) in the categories of human toxicity (non-cancer effects) and freshwater ecotoxicity, especially in D&B 2.

Most of the climate change burdens are shared between electricity and heat production due to the release to air of CO_2, CH_4 and N_2O from fossil fuels combustion. The same drivers have a similar share in ozone depletion in the supplier D&B 2 due to the emission of halon, HCFC's and CFC's in upstream activities of natural gas processing for electricity and heat generation. In the case of D&B 3 his share is coming from the processing of the light fuel utilized for heat generation as its electricity production mix is mainly based on coal that has smaller emissions of CFC's.

The air emissions of SO_2 and NO_x from electricity power plants that are converting the chemical energy of fossil fuels into electricity are the main cause for Acidification results.

Human toxicity (cancer and non-cancer effects) and freshwater ecotoxicity are mainly affected by heavy metals emissions to air, water and soil from wastewater treatment plants activity and its emissions of chromium, mercury, zinc and lead to the different environmental compartments. For the latter category emissions of vanadium, zinc and copper, mercury and lead are also contributors from electricity and heat production. The production of packaging cardboard has some impact in freshwater ecotoxicity due to agriculture activities.

Freshwater eutrophication is mainly caused by phosphate emissions from wastewater treatment plant and the disposal of spoil from coil and lignite mining in upstream processes of electricity production. While marine eutrophication has origin in emissions of NO_x to air from electricity production (combustion of fossil fuels) and emissions of nitrates and ammonia (ion) to water from the wastewater treatment plant.

Chemicals production also has an important contribution in categories as human toxicity (cancer effects) and acidification. Human toxicity is mainly due to chromium and mercury emissions from electricity use and disposal of waste. Acidification is due to the releases of SO_2 and NOx due to electricity generation.

Water & wastewater activities are the main cause of dyeing & bleaching. The establishment of a roadmap fixing targets and procedures to reduce its consumption shall provide opportunities to improve the overall results. Electricity and heat are also important drivers due to the extraction, processing and use of non-renewable sources of energy for energy production. Once more, the water and energy consumption is related so as energy is needed to heat and handle the water used during processing activities.

5 ANALYSING SCENARIOS FOR YARN PRODUCTION (COTTON AND WOOL)

5.1 Identifying and assessing all scenarios

In the present section different scenarios of cotton and wool dyed yarn's production have been drawn. This is made assuming multiple combinations possible for the production of each material (cotton and wool yarn) based on the practices from each supplier that provided the data used in this work. In total 36 cases for wool and 8 for cotton are possible to draw.

Based on the average losses of material reported by suppliers, the quantity of raw materials needed in each life cycle stage to produce 1 kg of dyed yarn is calculated and illustrated in Figure 14. To create a most likely scenario of a supply chain comprising the fibre production until the production of a dyed yarn it is assumed that:

- The dyeing processes are done after spinning so as:
  - Dyeing mills are dyeing only yarns;
  - Spinning mill only spun undyed and unbleached fibres;
- All the case companies assessed can supply each other (e.g. greasy wool from F1 going to the scouring mill and then S3 and D1.

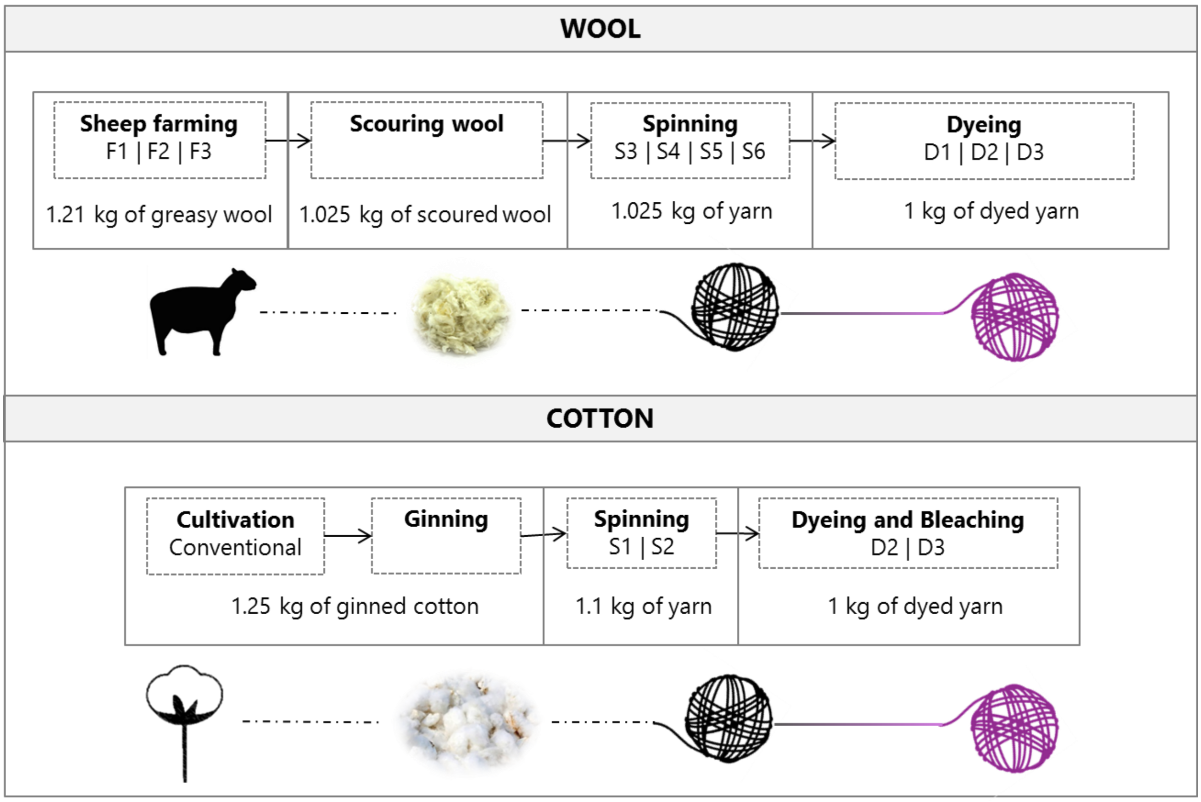

Figure 14 - Supply chain for the production of cotton and wool dyed yarns regarding to the suppliers assessed and its rate of raw fibre conversion.

5.1.1 Wool yarns

The whole set of all the possible combinations to model the yarns from wool are presented in Table 27 and the results are plotted in Figure 15.

Table 27 - Number of combinations possible for the production of dyed wool yarns.

Combinations	Suppliers			
W 1	F1 →	Scouring Wool →	S3 →	D1
W 2	F1 →	Scouring Wool →	S4 →	D1
W 3	F1 →	Scouring Wool →	S5 →	D1
W 4	F1 →	Scouring Wool →	S6 →	D1
W 5	F1 →	Scouring Wool →	S3 →	D2
W 6	F1 →	Scouring Wool →	S4 →	D2
W 7	F1 →	Scouring Wool →	S5 →	D2
W 8	F1 →	Scouring Wool →	S6 →	D2
W 9	F1 →	Scouring Wool →	S3 →	D3
W 10	F1 →	Scouring Wool →	S4 →	D3
W 11 [a)]	F1 →	Scouring Wool →	S5 →	D3
W 12	F1 →	Scouring Wool →	S6 →	D3
W 13	F2 →	Scouring Wool →	S3 →	D1
W 14	F2 →	Scouring Wool →	S4 →	D1
W 15	F2 →	Scouring Wool →	S5 →	D1
W 16	F2 →	Scouring Wool →	S6 →	D1
W 17	F2 →	Scouring Wool →	S3 →	D2
W 18	F2 →	Scouring Wool →	S4 →	D2
W 19	F2 →	Scouring Wool →	S5 →	D2
W 20 [b)]	F2 →	Scouring Wool →	S6 →	D2
W 21	F2 →	Scouring Wool →	S3 →	D3
W 22	F2 →	Scouring Wool →	S4 →	D3
W 23	F2 →	Scouring Wool →	S5 →	D3
W 24	F2 →	Scouring Wool →	S6 →	D3
W 25	F3 →	Scouring Wool →	S3 →	D1
W 26	F3 →	Scouring Wool →	S4 →	D1
W 27	F3 →	Scouring Wool →	S5 →	D1
W 28	F3 →	Scouring Wool →	S6 →	D1
W 29	F3 →	Scouring Wool →	S3 →	D2
W 30	F3 →	Scouring Wool →	S4 →	D2
W 31	F3 →	Scouring Wool →	S5 →	D2
W 32	F3 →	Scouring Wool →	S6 →	D2
W 33	F3 →	Scouring Wool →	S3 →	D3
W 34	F3 →	Scouring Wool →	S4 →	D3
W 35	F3 →	Scouring Wool →	S5 →	D3
W 36	F3 →	Scouring Wool →	S6 →	D3

a) Best case scenario

b) Worst case scenario

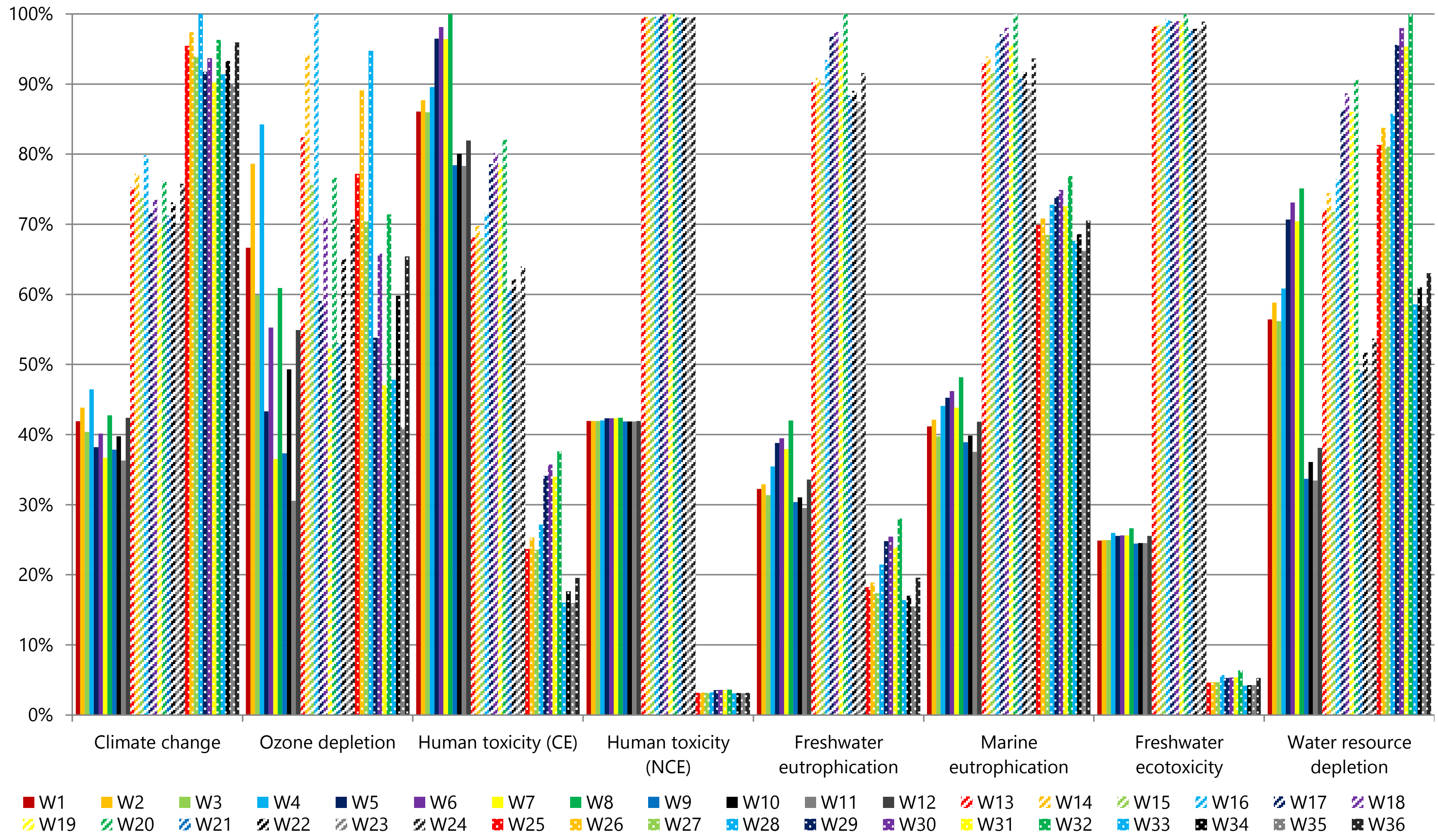

Figure 15 - Results for wool yarn combinations

In general the raw fibre production is the major contributor to the overall results except in ozone depletion and water resource depletion. Combinations which are using the supplier F2 present the worst results in most of the impact categories (ozone depletion, human toxicity (NCE), freshwater eutrophication, marine eutrophication and freshwater ecotoxicity), F3 in climate change and water resource depletion and F1 in human toxicity (CE). The lowest results are observed in four distinct categories in the suppliers by F1 and F3 namely in climate change, ozone depletion, marine eutrophication and water resource depletion for the first one and in human toxicity (cancer and non-cancer effects), freshwater eutrophication and freshwater ecotoxicity.

When the suppliers S6 and D2 are combined (yarn 8, 20 and 32) the largest contributions are observed in most of the environmental categories. While the combination of the companies S6 and D1 (yarn 4, 16 and 28) with the assessed sheep farmers (F1, F2 and F3) originates the major contributors for climate change and ozone depletion. On the other hand when S5 and D3 are combined (yarn 11, 23 and 35) with each one the sheep farmers the best results are achieved in all the impact categories analysed.

5.1.2 Cotton yarns

Table 28 lists the number of combinations possible to model the cotton yarns and its results are illustrated in Figure 16.

Table 28 - Number of combinations possible for the production of dyed cotton yarns

Combinations	Suppliers		
C 1	Conventional →	S1 →	D&B 2
C 2	Conventional →	S2 →	D&B 2
C 3	Conventional →	S1 →	D&B 3
C 4	Conventional →	S2 →	D&B 3
C 5	Organic →	S1 →	D&B 2
C 6	Organic →	S2 →	D&B 2
C 7	Organic →	S1 →	D&B 3
C 8	Organic →	S2 →	D&B 3

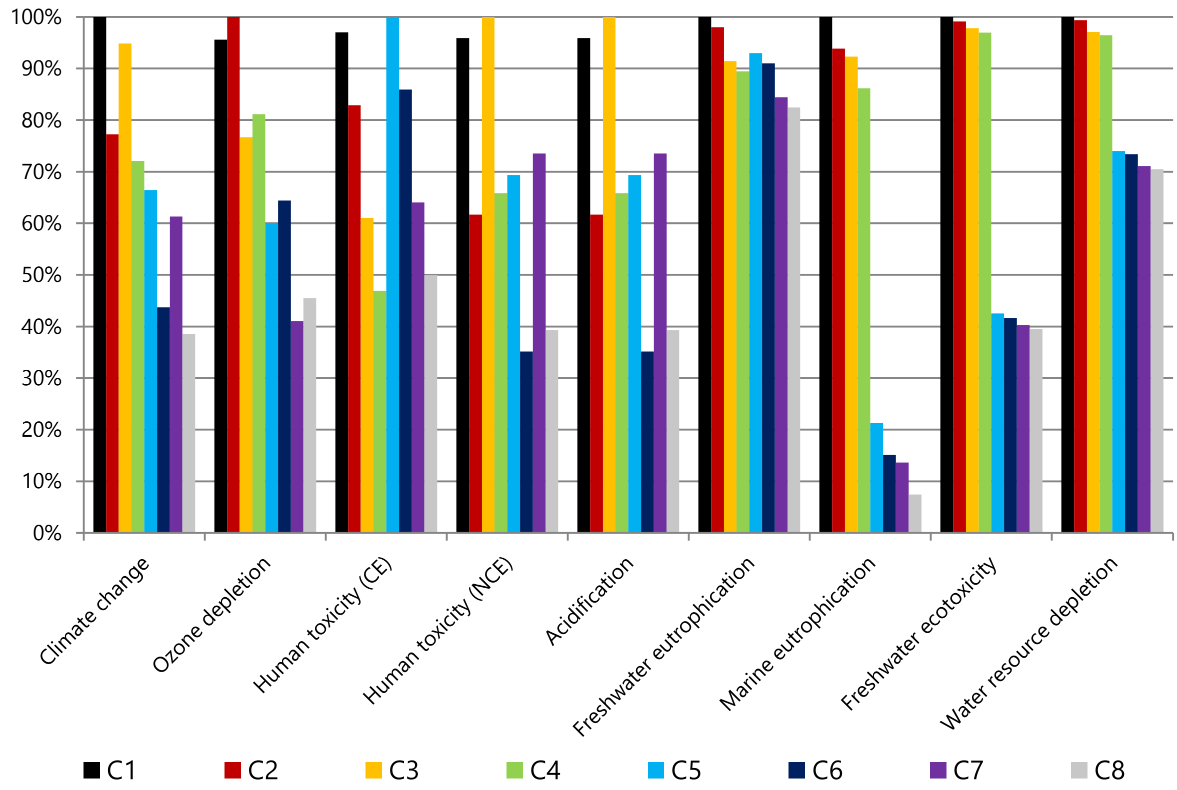

Figure 16 - Results for cotton yarn combinations.

As raw fibre production is the major contributor in the overall results the results are mainly influenced by this life cycle stage. That way the combinations for conventional cotton yarns (1, 2, 3 and 4) have the largest contributions in the overall results with the exception in the environmental impact category of human toxicity (cancer and non-cancer effects) due to the use of organic fertilizers as mentioned in 4.2 and freshwater eutrophication due to the water emissions in D&B 2. When the suppliers S1 and D&B 2 are joint (yarn 1 and 5) the impacts are higher in most of the impact categories. For both cottons origins (conventional and organic) the lowest contributions are found when the supplier S2 and D&B 3 are combined (yarn 4 and 8).

In the following two cases are analysed: best and worst. Then, the life cycle stages of these materials are assembled in order to create a supply chain from raw fibre to dyed yarn production. This is done for wool and cotton products.

5.2 Analysing the best and worst results from scenarios

The best and worst case scenarios have been selected according to the results of the possible combinations achieved in the present chapter and assuming that the best and worst comprise a general behaviour. This, however, is not the ideal selection because there are some impact categories which scores are not the best or the worst ones (e.g. the spinning mill S2 has the lowest contributions in the overall results but it has a larger contribution in the impact category of ozone depletion).

Here, just the conventional cotton product is assessed so as organic cotton product's results are only commented based on its life cycle stage results.

As only one supplier for conventional cotton and scouring is studied, its results are equal in both cases (best and worst). Table 29 lists the case that perform best and worst for wool and cotton.

Table 29 – Selected suppliers to draw the wool and cotton supply chains for each one of the defined cases: best and worst.

Combination	Material	Performance in impact categories	Suppliers
W 11	Wool	Best	F1→Scouring→S5→D3
W 20		Worst	F2→Scouring→S6→D2
C 4	Cotton	Best	Conventional→S2→D&B 3
C 1		Worst	Conventional→S1→D&B 2

The best farm (F1) was selected based on a simple criteria analysis where each impact category was assumed to have the same weight and which calculus are explained in the Appendix I.

5.2.1 Wool yarns

Figure 17 illustrates the results for the three selected case scenarios for the production of dyed wool yarns and Figure 18 the relative contribution of each life cycle stage.

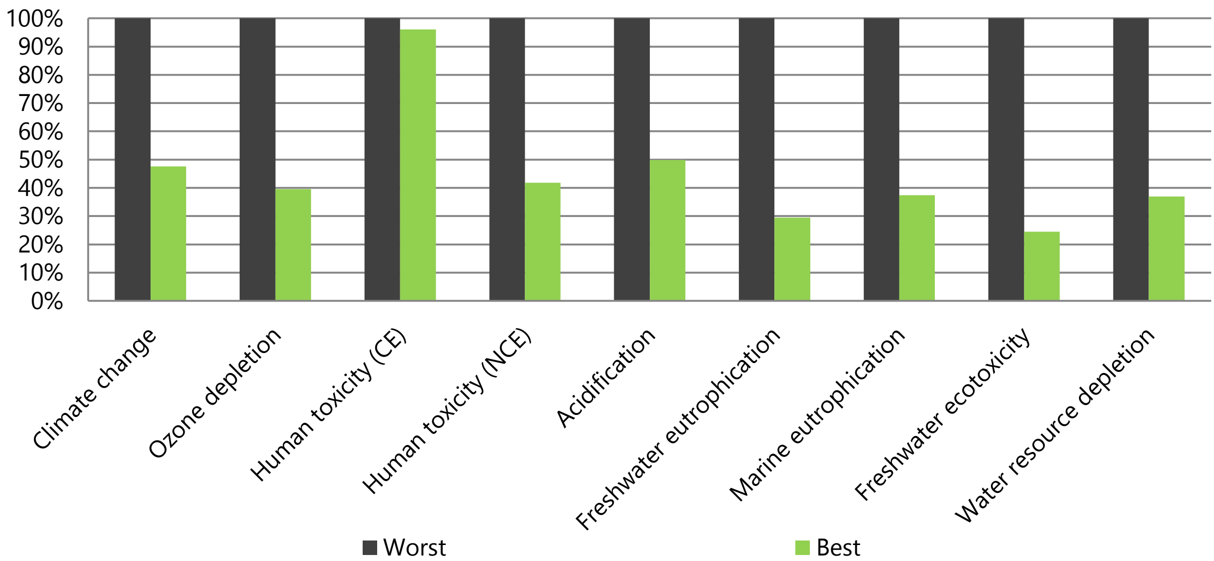

Figure 17 – LCA results for the worst and best cases studied for wool dyed yarn production. Results for the production of 1 kg of dyed yarn.

As might be observed there is a considerable potential of improvement (around 50%) in the overall results for the worst case scenario. An exception is made for the impact category of human toxicity (cancer effects) for which the two cases have similar results. A potential improvement might be expected if no fertilizers and pesticides would be used during the life cycle stage of sheep farming as in the supplier F3.

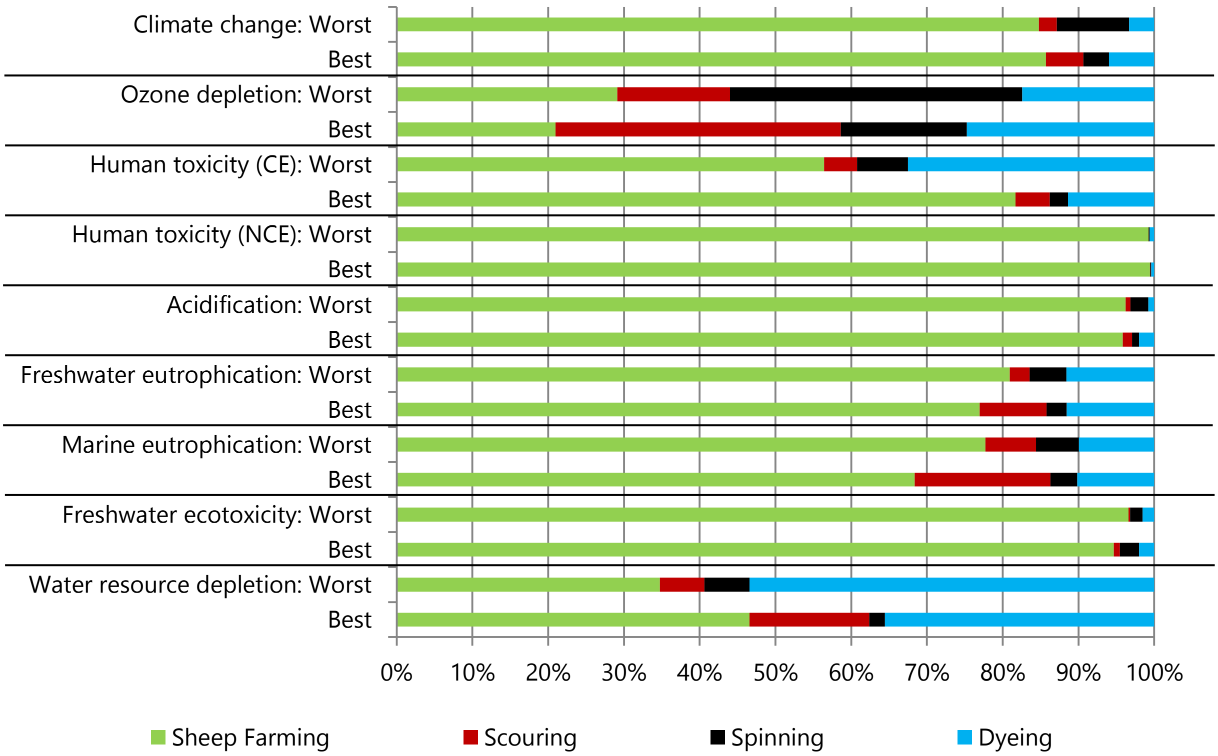

Figure 18 – Relative contribution of each life cycle stage to the total impact in the wool case scenarios: worst and best. Results for the production of 1 kg of dyed yarn.

Sheep farming emerges as the main contributor in most of the environmental impact categories except in ozone depletion (all cases) and water resource depletion (worst case). Ozone depletion has important contributions coming from the four life cycle stages. This category is highlighted by spinning in worst case and by scouring in the best case. Water resource depletion is a characteristic burden associated to dyeing and secondly to sheep farming.

Comparing the results from the scouring, spinning and dyeing activities it is verified that:

- In the worst scenario spinning is the major contributor in climate change, ozone depletion and acidification mainly due to electricity related activities while dyeing is the main contributor in the rest of the categories because of energy used to warm bowls, water consumption and emissions.
- In the best scenario spinning has very low contributions, dyeing has the larger contributions in most of the impact categories with the exception of ozone depletion and marine eutrophication where scouring contributes most.

5.2.2 Cotton yarns

In Figure 19 is illustrated the results for the three selected case scenarios for the production of dyed cotton yarns and in Figure 20 the relative contribution of each life cycle stage in these results.

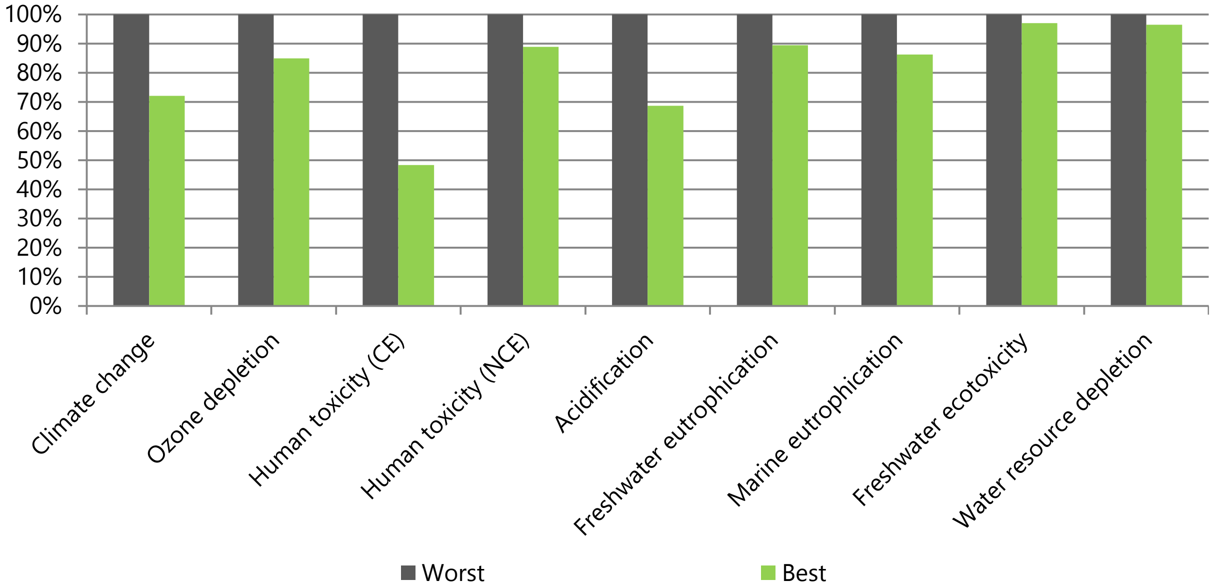

Figure 19 - LCA results for the worst, average and best cases studied for cotton dyed yarn production. Results for the production of 1 kg of dyed yarn.

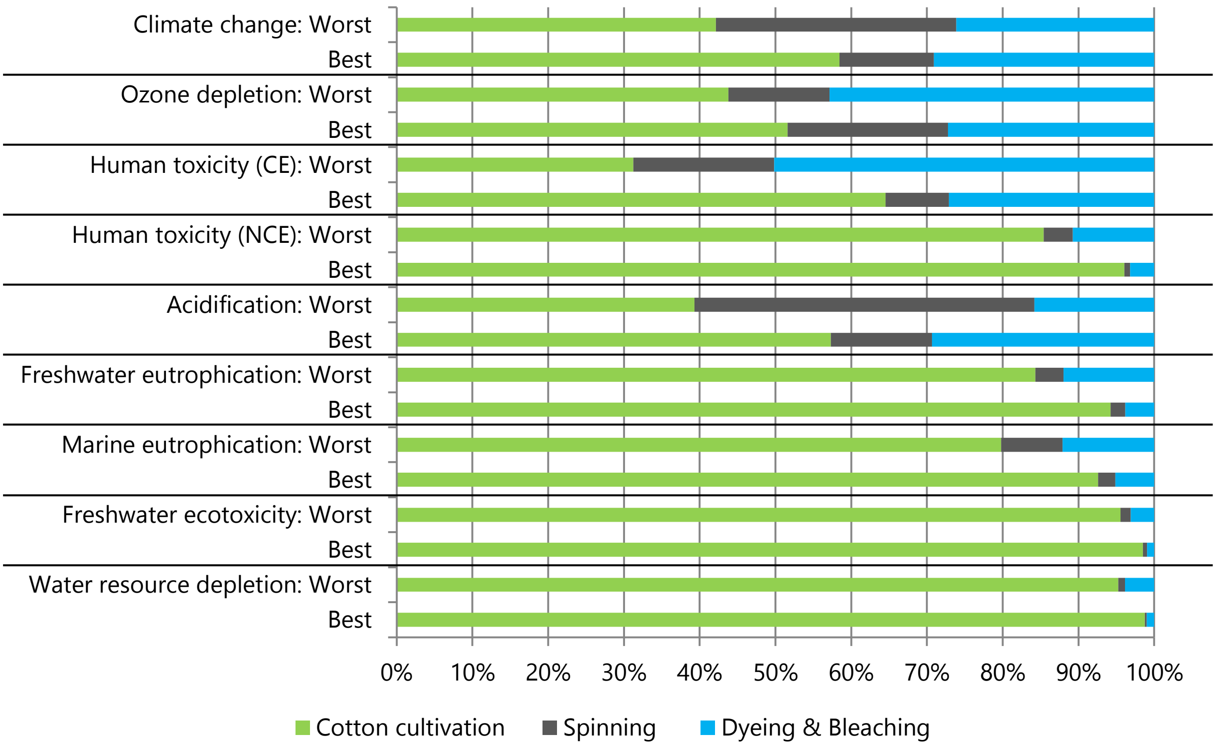

Figure 20 - Relative contribution of each life cycle stage to the total impact in the cotton case scenarios: worst, average and best. Results for the production of 1 kg of dyed yarn.

According to these results it is verified that significant potential improvements on the supply chain might be observed for the environmental impact categories of climate change, human toxicity (cancer effects) and acidification where reductions on its impacts might achieve values around 30%. These impact categories are strongly influenced by the spinning and dyeing & bleaching mills activities. For the overall results, cotton cultivation emerges as the main contributor (with the exception but with similar figures in human toxicity and acidification in the worst case scenario).

Comparing spinning and dyeing activities it is verified that:

- In the worst scenario spinning is the major contributor in climate change (but with similar figures as dyeing) and acidification while dyeing has the largest contributions in all the other categories. Spinning as significant contribution in the categories of ozone depletion and human toxicity (cancer effects)
- In the best scenario dyeing is the major contributor in all the impact categories, spinning has significant contribution in climate change, ozone depletion, human toxicity (cancer effects) and acidification.

5.3 Comparative analysis of cotton and wool

In order to compare dyed yarns made with wool and the ones made of cotton the case scenarios of each material are analysed for the minimum and maximum results (worst and best cases scenarios) obtained for each impact category. The relative contribution for the production of one kilogram each product is illustrated in Figure 21.

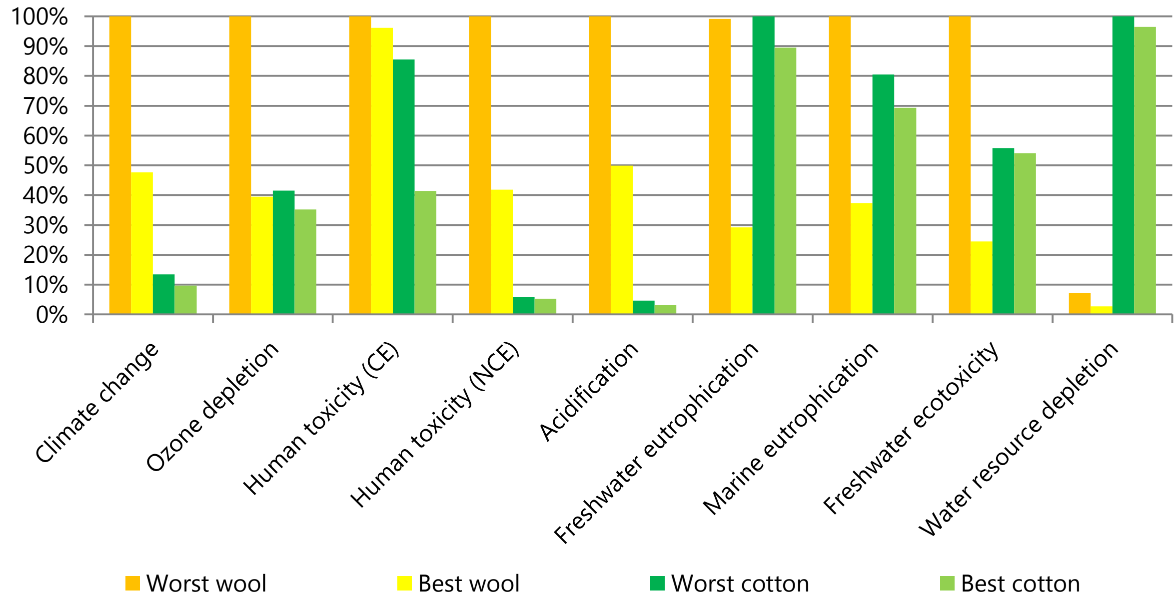

Figure 21 - Relative impact of each product (wool and cotton) for worst and best case scenarios. Results for the production of 1 kg of dyed yarn.

Observing the worst case scenario results, wool has the largest impacts in the overall results except in freshwater eutrophication (which figures are similar) and water resource depletion. On the other hand, looking into the best case results of each product, wool has the largest impacts in: climate change, ozone depletion, human toxicity and acidification; while cotton in water-related categories as: freshwater eutrophication, marine eutrophication, freshwater ecotoxicity and water resource depletion. Wool and cotton have approximate values in human toxicity (cancer effects) and marine eutrophication categories.

Field emissions show up as the main contributors in most of the impact categories but, it has to be mentioned that wool processing has one more life cycle stage which also affects the final results as wool is a much more dirty fibre when compared with cotton. That way, washing, cleaning and other handling processes are more intensive and it reflects the results. On the other hand, cotton is a crop which is highly associated to the use of water, fertilizers and pesticides and that way, water and toxic related categories are the cause of its minor environmental performances.

At this level of comparison, but remembering that different methods were applied, similar results to the one presented in *Environmental Improvement Potential of Textiles* (2006) for breakline contributions from life cycle stages of different textiles were analysed, are obtained for the best case scenario. In that study wool is pointed as the major contributor in climate change and human toxicity (mainly due to the production of raw fiber), while cotton has the largest impacts in the categories of freshwater ecotoxicity (mainly due to the production of raw fiber).

It would be expected that the use of organic cotton would mainly reduce the impacts in climate change, ozone depletion, eutrophication (freshwater and marine) and water resource depletion while increases in human toxicity would be verified in both case scenarios for cotton.

6 CONCLUSIONS

The number of companies assessed cannot be seen as a representative sample of the worldwide textile industry and it was possible to identify variations in the consumption of electricity, heat and water among companies. Moreover, a small number of samples were used in the inventory.

The results obtained have to analysed in accordance to that and the present study doesn't aim to represent the world production of each material but to give an overall overview of the suppliers' behaviour and, at the same time, to offer them the opportunity to benchmark themselves and to understand how their environmental performance along all the life cycle stages.

For the full supply chain for cotton and wool it was possible to conclude the following:

- Raw fibre production is the main contributor to both raw fibre productions (wool and cotton). This is in line with the results from Beton *et al.* (2006)[27].
- Wool has the largest impacts for all the environmental impact categories (except in freshwater eutrophication and water resource depletion). However, when a best case scenario is regarded, cotton has the largest burdens in categories as freshwater eutrophication, marine eutrophication, freshwater ecotoxicity and water resource depletion mainly.
- When comparing similar categories of impact studied in Beton *et al.* (2006)[27] for a breakdown scenario with the results presented here for the best case scenario, the main contributors are the same i.e.: wool is the major contributor to climate change and human toxicity (mainly due to the production of raw fibre), while cotton has the largest impacts in the category of freshwater ecotoxicity (mainly due to the production of raw fibre).

Despite this fact the main conclusions drawn for each life cycle stage are similar to other life cycle assessment studies. The following conclusion may be drawn:

Wool

- Sheep farming belongs to one of the largest polluter sector worldwide: agriculture. Even if small amounts of fertilizers or pesticides are applied, enteric fermentation and manure management naturally ensure a large share on the environmental impacts of this activity.
- Wool is a much more dirty fibre when compared with cotton. That way, washing, cleaning and other handling processes are more intensive and needed in order to obtain a clean fibre ready to be processed. Consequently wool processing has one more life cycle stage (scouring wool). As a wet process it adds extra burdens to the textile products made of wool.

Cotton

- Raw cotton is a much cleaner raw fiber than wool and its initial operation of cleaning the fibre (ginning) has low contributions.
- Cotton is a crop that needs water, fertilizers and pesticides causing water and toxic related categories.

Life cycle stages

- Field emissions to the air, water or soil comprising the releases of fertilizer and pesticides but mainly livestock emissions are identified to be major contributors to the results. The production of fertilizers and the losses to environment due to its application has also a significant burden.
- Cotton cultivation: field emissions from fertilizers and pesticides application were a major contributor to several environmental impact categories. The fertilizer production also has significant impacts on the overall results. Such that an efficient management of fertilizer use will allow a better best performance of the conventional farmer. Organic cotton production has relatively smallest impacts; however, the use of poultry manure is associated to the high release of heavy metals.
- Spinning: due to its high energy demand, electricity production leads the major contribution in the cotton and wool yarns production. Packaging materials (mainly in spun wool) and water use might have significant burdens in some systems.
- Dyeing (and bleaching): considerable amounts of water are used throughout these processes. Associated to this consumption is the energy needed to process it. Water and wastewater arises as the major hotspot of these processes for both wool and cotton materials followed by the energy consumption (heat and electricity).
- Scouring wool: this supplier follows the average consumption patterns for energy and has a wet process consumes high amounts of water. That way, water consumption and energy (mainly for heat the bowls) are the main contributors to this life cycle stage. Activities which are not directly associated to the company activity as the production of wire used for packaging and transoceanic transports emerge as important contributors in toxicity categories.

Improvements

- An efficient management of the fertilizers used in sheep farming and cotton cultivation might improve environmental performance at two levels: reducing field emissions and impacts from production.
- The establishment of a roadmap by defining targets and procedures to reduce the energy demand. Despite the fact that is a transversal issue to all the life cycle stages, the focus remain mainly in mechanical and chemical processes for dyed yarn production. Another issue for improvement is associated with the water consumption and its

subsequent emissions. Furthermore, chemicals and packaging use shall also provide opportunities to improve the overall results.

- Benchmark results from this study as well as best available technologies shows that improvements might be achieved from both material and in different life cycle stage.

7 RECOMMENDATIONS FOR FUTURE WORKS

The limitation of the work performed as well as further improvements are identified below. These include limitations related with data collection from the suppliers, datasets selection and its geographical and temporal limitations, methods boundaries (made mainly for European countries) and the worldwide representativeness of agricultural models.

- The primary data supplied has a degree of uncertainty. In an ideal situation, team member would have been able to visit each supplier and collect data directly from machines and energy meters.
- Secondary data from ecoinvent are sometimes not specific to the regions assessed as for example the machinery utilized in agriculture or wastewater treatment is modelled using Swiss data and electricity generation (not from standard grid) or chemicals and materials are mainly modelled using European data. This may be overcome by using more detailed data concerning the local realities, however it can be time consume.
- Although the selection of datasets been carried out with the maximum care and selected by experts, the datasets used are sometimes not specific or old. This is the example of the chemicals and auxiliaries utilized because most of the times have no specific dataset so that proxies are utilized (as presented in Table B.5 in Appendix B). Another example is the datasets for energy production (standard grid) which are not updated to the production mix of nowadays but, in some cases for 1995.
- Most of the impact categories were created regarding the European reality while some of the suppliers are located in other non-European countries.
- Another action that may be performed is a sensitivity analysis to some parameters in order to assess the robustness of the results and assess the sensivity of results to changes in parameters or models. Some examples of this analysis would be on the emissions factors utilized from IPCC for livestock emissions which have associated and precision of ±20% or on the chemicals' proxies used. Nevertheless comparing the different emissions of each supplier it might be ascertained about the influence of these parameters.

At the end it is important to refer that agricultural systems models are difficult to generalize This is to say that differences in weather conditions, spatial variations in soil type, topography, pasture types, species of animal and individual supplier management practices have a large degree of variability and sometimes not easy to be monitored. The use of site specific models capable to better understand what actually fate has the losses of fertilizers and pesticides.

The models followed during the present study are part of the EcoLogTex project which stills going on. Efforts are being done in order to continuously improve the models created so that limitations may be overcome.

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Appendixes

Appendix A: ecoinvent datasets used for energy

ELECTRICITY

Table A. 1 – Electricity production and modelling correspondence in ecoinvent dataset.

Source	ecoinvent dataset
Standard Grid	
Country mix in ecoinvent	Electricity, low voltage, at grid
Oil	Electricity, oil, at power plant
Gas	Electricity, natural gas, at turbine, 10MW
Coal	Electricity, hard coal, at power plant
Hydro	Electricity, hydropower, at run-of-river power plant
Solar	Electricity, production mix photovoltaic, at plant
Nuclear	Electricity, nuclear, at power plant
Renewables	Electricity, pellets, allocation energy, at stirling cogen unit 3kwe, future
Own Production	
Diesel	Diesel, burned in diesel-electric generating set
Hydro	Electricity, hydropower, at run-of-river power plant

HEAT

Heat is produced inside the facilities or is provided by district heating sources. Regarding to the type of fuel used, boiler capacity and burner type utilized datasets was selected. As the heat fuels are entered in several units, the conversion factor is used to transform the unit given in the questionnaire into the unit (MJ) of the ecoinvent dataset.

Inventory flow heat = Quantity of fuel * conversion factor

Conversions factors as well as datasets selected per source of energy are presented in Table A. 2

Table A. 2 - Heat datasets from ecoinvent utilised for each supplier.

Heat source	Unit reported	Conversion factor: unit to MJ	ecoinvent dataset	Suppliers
District heat	MJ	-	Wood chips, from forest, mixed, burned in furnace 1000kw/RER U	S2
Diesel	L	36.7 MJ/L	Light fuel oil, burned in boiler 100kw, non-modulating/CH U	D3
Natural gas	m^3	36.5 MJ/m^3	Heat, natural gas, at boiler condensing modulating <100kw/RER U	S1 and D2
			Heat, natural gas, at industrial furnace >100kw/RER U	S4, S5, S6 and D1

Appendix B: ecoinvent datasets used for agriculture (sheep farming and cotton cultivation)

MACHINERY

Table B. 1 - Conversion factors for correspondence between fuel use in farming machinery and ecoinvent datasets.

Machinery used for:	ecoinvent dataset	Conversion Factor L/FU[a)]	FU in ecoinvent
Pesticide application	Application of plant protection products	2.0952381	ha
Harvesting	Combine harvesting	39.6547619	ha
Fertilize application	Fertilising, by broadcaster	6.29761905	ha
Sowing	Sowing	4.54761905	ha
Cleaning	Mowing, by rotary mower	4.086538462	ha
Harrowing	Tillage, harrowing, by spring tine harrow	5.28571429	ha
Soil preparation	Tillage, ploughing	31.0833333	ha
Transports (tractor)	Transport, tractor and trailer	0.04761905	tkm

a) FU = functional unit

Conversion to FU = Litres consumed (L) / Rate of diesel consumption of the dataset (L/FU)

FEEDSTUFF

Table B. 2 - ecoinvent dataset used to model the feedstuff production.

Feedstuff	ecoinvent dataset
Silage	Grass silage IP, at farm
Maize grain	Grain maize IP, at feed mill
Hay	Hay intensive IP, at farm

FERTILIZERS

Table B. 3 - ecoinvent dataset used to model the fertilizers production.

Fertilizers	ecoinvent dataset
Ammonium nitrate, as N	Ammonium nitrate, as N, at regional storehouse
Ammonium nitrate phosphate, as P_2O_5	Ammonium nitrate phosphate, as N, at regional storehouse
Compost	Compost, at plant
Monoammonium phosphate	Monoammonium phosphate, as N, at regional storehouse
Potassium chloride, as K_2O	Potassium chloride, as K2O, at regional storehouse
Poultry manure	Poultry manure, dried, at regional storehouse
Single superphosphate	Single superphosphate, as P2O5, at regional storehouse

Urea ammonium nitrate	Urea ammonium nitrate, as N, at regional storehouse

PESTICIDES

Table B. 4 - ecoinvent dataset used to model the pesticides production.

Pesticides reported	ecoinvent datasets
Paraquat	Pyridine-compounds
Glyphosate	Glyphosate
Lambda-cyhalothrin	Pyretroid-compounds
Prometryn	Triazines
Diquat	Herbicide, unspecified

CHEMICAL TREATMENTS OF SHEEP AND COTTON SEEDS

Table B. 5 - ecoinvent dataset used to model the production of the chemicals used for sheep and seed treatments.

Chemical treatments	ecoinvent datasets
Sheep treatments	
Chlorpyrifos	Organophosphorus-compounds
Cryomazine	Triazine-compounds
Dicyclanil	Growth regulators
Abamectin	Organophosphorus-compounds
Albendazole oxide	Benzimidazole-compounds
Levamasole hydrochloride	Benzimidazole-compounds
Spinosad	Insecticides, unspecified
Vaccines	Chemicals organic
Seeds treatment	
Bronopol	Pesticide unspecified
Carboxin	Fungicides
Thiram	Dihitrocarbamate

EMISSIONS

Table B. 6 – ecoinvent datasets and its categories and subcategories used to model emissions from grazing sheep and cotton cultivation.

Emission	Name Ecoinvent	Category	Sub-Category
To air			
Ammonia	Ammonia	air	unspecified
Methane (CH_4)	Methane, biogenic	air	unspecified
Nitrou oxide (N_2O)	Dinitrogen monoxide	air	unspecified
Nitrogen oxides NO_x	Nitrogen oxides	air	unspecified
To water			
Nitrate	Nitrate	water	ground-
Phosphate	Phosphorus	water	river
Phosphate	Phosphate	water	ground-
To soil			
Heavy metals:			
Cadmium (Cd)	Cadmium	soil	agricultural
Chromium (Cr)	Chromium	soil	agricultural
Copper (Cu)	Copper	soil	agricultural
Lead (Pb)	Lead	soil	agricultural
Nickel (Ni)	Nickel	soil	agricultural
Zinc (Zn)	Zinc	soil	agricultural
Pesticides:			
Carboxin	Carboxin	soil	agricultural
Bronopol	Pesticide, unspecified	soil	agricultural
Diquat	Diquat	soil	agricultural
Glyphosate	Glyphosate	soil	agricultural
Lambda-cyhalothrin	Lambda-cyhalothrin	soil	agricultural
Paraquat	Paraquat	soil	agricultural
Prometryn	Prometryn	soil	agricultural
Thiram	Thiram	soil	agricultural

Appendix C: ecoinvent datasets used for packaging materials

Table C. 1 - ecoinvent dataset used to model the packaging material production.

Packaging material, kg	ecoinvent dataset
Cardboard	Packaging, corrugated board, mixed fibre, single wall, at plant
Cotton	Textile, woven cotton
Paper	Kraft paper, bleached
PET	Polyethylene terephthalate, granulate, amorphous, at plant
Polyester	Polyester resin, unsaturated, at plant
Polyethylene HDPE	Polyethylene, HDPE, granulate, at plant
Polylaminaten (plastics)	Polyethylene terephthalate, granulate, amorphous, at plant
Polypropylne	Polypropylene, granulate, at plant
Wire	Steel, low-alloyed, at plant
Metal rings	Steel, low-alloyed, at plant

Appendix D: ecoinvent datasets used for water, wastewater treatment and water emissions

WATER CONSUMPTION

Table D. 1 – ecoinvent dataset for type of water consumed

Water	ecoinvent dataset
Decarbonized	water, decarbonised, at plant
Rain	water, unspecified natural origin
River	water, river
For sheep (drinking)	water, unspecified natural origin
Tap Water	tap water, at user
Well Water	water, well, in ground

WASTEWATER TREATMENT PLANT

Table D. 2 – ecoinvent dataset for wastewater treatment modelling process.

Wastewater treatment	ecoinvent dataset
External treatment	treatment, sewage, to wastewater treatment, class 3

WATER EMISSIONS

Table D. 3 - Conversion factors and ecoinvent dataset for water emissions in Emmenneger (2013)

Type of water emission / parameters	Unit of measurement	Conversion Factor WE	ecoinvent (all in compartment "water, unspecified")
Active chlorine, Cl	(mg Cl/l)	1	Chlorine
Adsorbable Organic Halogens, AOX, as Cl	(mg Cl/l)	1	AOX, Adsorbable Organic Halogen as Cl
Aldehydes, like CH_2O	(mg/l)	1	aldehydes, unspecified
Ammonium, NH_4-N	(mg N/l)	1.285	Ammonium, ion
Arsenic and ist compounds, As	(mg/l)	1	Arsenic, ion
Benzene-Toluene-Ethylbenzene-Xylene, BTEX	(mg/l)	1	Proxy: Benzene
Biochemical Oxygen Demand in 5 days, BOD_5	(mg O2/l)	1	BOD5, Biological Oxygen Demand
Cadmium and its compounds, Cd	(mg/l)	1	Cadmium, ion
Chemical Oxigen Demand, COD	(mg O2/l)	1	COD, Chemical Oxygen Demand
Chlorides, Cl^-	(mg Cl/l)	1	Chloride
Chlorinated solvents	(mg/l)	1	Chlorinated solvents, unspecified
Chromium and its compounds, Cr	(mg/l)	1	Chromium, ion
Copper and its compounds, Cu	(mg/l)	1	Copper, ion
Dissolved solids	(mg/l)	1	Dissolved solids
Hydrogen sulfide, H_2S	(mg/l)	1	Hydrogen sulfide
Iron and its compounds, Fe	(mg/l)	1	Iron, ion
Lead and its compounds, Pb	(mg/l)	1	Lead
Mercury and its compounds, Hg	(mg/l)	1	Mercury
Nickel and its compounds, Ni	(mg/l)	1	Nickel, ion
Nitrate, NO_3-N	(mg N/l)	4.43	Nitrate
Nitrite, NO_2-N	(mg N/l)	3.29	Nitrite
Organic nitrogen, N-org	(mg N/l)	1	Nitrogen, organic bound
Phosphate	(mg/l)	1	Phosphate
Polycylic Aromatic Hydrocarbon, PAH	(mg/l)	1	PAH, polycyclic aromatic hydrocarbons
Sulfates, SO_4	(mg/l)	1	Sulfate
Sulfide, S_2^-	(mg/l)	1	Sulfide
Sulfites, SO_3	(mg/l)	1	Sulfite
Suspended solids	(mg/l)	1	Suspended solids, unspecified
Total hydrocarbons	(mg/l)	1	hydrocarbons, unspecified
Total Organic Carbon, TOC	(mg/l)	1	TOC, Total Organic Carbon
Total phenols, Ph-OH	(mg/l)	1	Phenol
Total phosphorus, P	(mg P/l)	1	Phosphorus
Zinc and its compounds, Zn	(mg/l)	1	Zinc, ion

Note: All the emissions are modelled as emitted to the ecoinvent category water and sub-category unspecified

Appendix E: ecoinvent datasets used for chemicals, dyestuffs and auxiliaries

Table E. 1 - ecoinvent dataset used to model the production of chemicals, dyestuffs and auxiliaries.

Chemicals	ecoinvent dataset
Paraffin waxes	Paraffin, at plant RER kg
Lubricants	Lubricating oil, at plant, rer
Ester oils	Chemicals organic, at plant/glo u
Fatty acid triglycerides	Chemicals organic, at plant/glo u
Hydrogen peroxide (bleaching)	Hydrogen peroxide, 50% in H2O, at plant/kg/RER
Sodium hypochlorite (bleaching)	Sodium hypochlorite, 15% in H2O, at plant/kg/RER
Sodium chlorite (bleaching)	Chlorine dioxide, at plant/kg/RER
Optical brightener (brightening agent)	Optical brighteners, in paper production, at plant/RER U
Dyestuffs	50% Chemicals organic, at plant/GLO U + 50% Chemicals inorganic, at plant/GLO
Sodium sulfate (dye auxiliarie)	Sodium sulphate, powder, production mix, at plant
Magnesium sulfate (stabilizer)	Magnesium sulphate, at plant/kg/R
Caustic Soda (washing)	Sodium hydroxide, 50% in H2O, production mix, at plant/kg/RER
Alcohol ethoxylates (surfactant, detergent or emulsifier)	Ethoxylated alcohols, unspecified, at plant/RER U
Sodium carbonate (builder)	Sodium carbonate from ammonium chloride production, at plant/GLO
Antistatic agent	Chemicals organic, at plant/glo u
Mono and diesters of phosphorus pentoxides (antistatic agents)	Chemicals organic, at plant/GLO U
Non-ionic surfactants	Chemicals organic, at plant/GLO U
Acetic acid	Acetic acid, 98% in H2O, at plant/RER U
Formic acid	Formic acid, at plant
Ammonium sulfate	Ammonium sulphate, as N, at regional storehouse
Salt	Sodium chloride, powder, at plant
Water-repellent	50% Chemicals organic, at plant/GLO U + 50% Chemicals inorganic, at plant/GLO
Softener	50% Chemicals organic, at plant/GLO U + 50% Chemicals inorganic, at plant/GLO

Appendix F: ecoinvent datasets used for transports

Table F. 1 - ecoinvent dataset utilized to model the transports

Mode of transports	ecoinvent dataset
Sea	Transport, freight, sea, transoceanic ship
Road	Transport, lorry 3.5-16t, fleet average
Rail	Transport, freight, rail

Appendix G: ecoinvent datasets used for solid waste

Table G. 1 - ecoinvent dataset utilized to model the solid waste disposal

Final disposal	ecoinvent dataset
Municipal landfill	Disposal, municipal solid waste, 22.9% water, to sanitary landfill
Municipal incinerator (with energy recovery)	Disposal, municipal solid waste, 22.9% water, to municipal incineration
Special treatment for hazardous waste	Disposal, hazardous waste, 25% water, to hazardous waste incineration

Appendix H: Heavy metal content in fertilizers, wool and cotton

HEAVY METALS IN WOOL

For sheep pasture we only consider external import of heavy metal due to application of mineral fertilizers or organic fertilizer from other sources than sheep.

Table H. 1 - Allocation factor for the single heavy metals

Heavy Metals	Allocation factor		Sources from literature	
	Wool %	Meat %	Wool	Meat
Cd	95	5	Kazemeini et al (2010)	Average from literature [5] Patkowska *et al*. (2009) Smith *et al*. (2010)
Cu	82	18.	Nemecek et al. (2004)	
Zn	64	36.		
Pb	95	5		
Ni	-	100		
Cr	-	100.		
Hg	99	0.64%		

Table H. 2 - Heavy metal uptake of wool

Heavy metals	Concentration		Sources from literature	
	Wool kg/kg	Meat kg/kg	Wool	Meat
Cd	2.57E-07	6.99E-09	Average from literature[5]	Average from literature[5]
Cu	7.46E-06	9.00E-07	Nemecek et al. (2004)	Average from literature[5]
Zn	7.51E-05	2.30E-05	Nemecek et al. (2004)	Average from literature[5]
Pb	2.17E-06	6.50E-08	Nemecek et al. (2004)	Average from literature[5]
Ni	-	2.00E-08	Nemecek et al. (2004)	Average from literature[5]
Cr	-	4.00E-08	Nemecek et al. (2004)	Average from literature[5]
Hg	1.45E-07	5.00E-10	Nemecek et al. (2004)	Average from literature[5]

[5] Average from values in Patkowska-Sokoła B, Dobrzański Z, Osman K, et al. (2009) The content of chosen chemical elements in wool of sheep of different origins and breeds. Arch Tierz 4:410–418 and in Smith K, Dagleish M, Abrahams P (2010) The intake of lead and associated metals by sheep grazing mining-contaminated floodplain pastures in mid-Wales, UK: II. Metal concentrations in blood and wool. Sci Total Environ 408:1035–42. doi: doi: 10.1016/j.scitotenv.2009.10.023

HEAVY METALS IN FERTILIZERS

Table H. 3 - Heavy metal content of synthetic fertilizers [33]

Mineral fertilisers (%N/%P_2O_5/%K_2O/%Mg)	Cd mg/kg nutrient	Cu mg/kg nutrient	Zn mg/kg nutrient	Pb mg/kg nutrient	Ni mg/kg nutrient	Cr mg/kg nutrient
Urea (46/0/0) kg N	0.11	13.04	95.65	2.39	4.35	4.35
Calcium ammonium nitrate (20/0/0) kg N	0.25	60.00	155.00	5.50	90.00	10
Ammonium nitrate (27.5/0/0) kg N	0.18	25.45	181.82	6.91	47.27	14.55
Ammonium sulphate (21/0/0) kg N	0.24	19.05	142.86	5.24	8.57	9.52
Calcium ammonium nitrate (27/0/0) kg N	0.19	8.52	100.00	5.93	12.59	2.96
Magnesium ammonium nitrate (23/0/0/5) kg N	0.43	56.52	4.35	4.35	21.74	6.09
Generic mean N	0.21	22.25	121.43	5.37	17.17	7.81
Triple superphosphate (0/46/0) kg P_2O_5	113.04	97.83	650.00	7.61	95.65	567.39
Superphosphate (0/19/0) kg P_2O_5	52.63	121.05	852.63	578.95	105.26	342.11
Thomas meal (0/16/0) kg P_2O_5	1.56	250.00	425.00	75.00	125.00	1212.50
Hyperphosphate/raw phosphate (0/26/0) kg P_2O_5	50.00	115.38	915.38	23.85	76.92	611.54
Generic mean P	51.32	118.22	751.32	49.42	100.46	589.46
Potassium chloride (0/0/60) kg K_2O	0.10	8.33	76.67	9.17	3.50	3.33
Potassium sulphate(0/26/50) kg K_2O	0.10	4.00	64.00	6.60	1.60	4.00
Raw potassium (0/26/5) kg K_2O	0.19	173.08	153.85	11.54	11.54	173.08
Lime kg CaO	0.12	4.00	8.00	3.60	12.20	314.00
Generic mean K	0.11	6.17	70.33	7.88	7.52	88.54

Table H. 4 - Heavy metal content of farmyard manure and organic fertilizers [33]

Farmyard manure	Cd mg/kg DM	Cu mg/kg DM	Zn mg/kg DM	Pb mg/kg DM	Ni mg/kg DM	Cr mg/kg DM	Hg mg/kg DM	DM content %
Cattle liquid slurry	0.178	37.1	162.2	3.77	4.3	3.9	0.4	9.0
Cattle slurry	0.16	19.1	123.3	2.92	3.1	2.1	0.6	7.5
Cattle staple manure	0.172	23.9	117.7	3.77	4.3	3.9	0.4	19.0
Cattle manure from loose housing	0.151	22.0	91.1	2.81	4.3	3.9	0.4	21.0
Pig liquid manure	0.21	115.3	746.5	1.76	8.6	6.7	0.8	5.0
Pig solid manure	0.21	115.3	746.5	1.76	8.6	6.7	0.8	27.0
Litter from broilers	0.292	43.8	349.2	2.92	40	10	0.2	65.0
Litter from belts from laying hens	0.2525	39.6	468.4	2.235	7.9	5.5	0.2	30.0
Litter from deep pits from laying hens	0.2525	39.6	468.4	2.235	7.9	5.5	0.2	45.0

HEAVY METALS UPTAKE IN COTTON

Table H. 5 - Heavy metal content of biomass [33]

Heavy Metal	Cd	Cu	Zn	Pb	Ni	Cr	Hg
Crop	kg/kg	kg/kg	kg/kg	kg/kg	kg/kg	kg/kg	kg/kg
generic mean/cotton	8.90E-08	5.87E-06	2.85E-05	4.81E-07	9.26E-07	4.90E-07	3.56E-08
grass / hay	1.17E-07	7.74E-06	3.60E-05	1.08E-06	1.51E-06	9.81E-07	1.35E-07
grain maize	2.58E-08	2.15E-06	1.85E-05	2.58E-07	9.98E-07	2.75E-07	0.00E+00
silage maize	8.60E-08	4.30E-06	2.97E-05	1.38E-06	4.13E-07	6.02E-07	8.60E-09
wheat grains	8.50E-08	2.81E-06	1.79E-05	1.70E-07	1.70E-07	1.70E-07	8.50E-09
wheat straw	1.70E-07	2.13E-06	8.16E-06	5.10E-07	5.10E-07	5.95E-07	0.00E+00
barley grains	2.55E-08	3.66E-06	2.26E-05	1.70E-07	8.50E-08	8.50E-08	0.00E+00
barley straw	8.50E-08	4.08E-06	9.44E-06	5.10E-07	6.80E-07	1.02E-06	0.00E+00
rye straw	8.50E-08	2.72E-06	1.11E-05	3.40E-07	5.95E-07	4.25E-07	0.00E+00
potatoes	8.80E-09	1.42E-06	3.30E-06	1.21E-07	7.26E-08	1.25E-07	1.98E-08
rape seed	1.50E-06	3.10E-06	4.51E-05	4.94E-06	2.44E-06	4.70E-07	9.40E-08
fava beans	3.48E-08	5.22E-06	2.62E-05	7.57E-07	1.13E-06	6.00E-07	0.00E+00
soy bean	5.34E-08	1.34E-05	4.25E-05	7.12E-08	4.73E-06	4.63E-07	0.00E+00
protein peas	7.83E-08	8.70E-06	6.35E-05	1.39E-07	7.22E-07	2.78E-07	8.70E-09
sugar beet	9.20E-08	2.76E-06	8.37E-06	2.67E-07	2.48E-07	4.08E-07	2.19E-08
oil palm	5.30E-08	3.50E-06	1.70E-05	2.86E-07	5.51E-07	2.92E-07	2.12E-08
sugar cane	5.13E-10	1.28E-08	6.41E-08	2.57E-09	5.13E-09	2.57E-09	0.00E+00

Appendix I: Selection of the best supplier for sheep farming

In order to select the best supplier for the best case scenario the procedure followed is presented as following:

1) The 9 categories are assumed to have the same weight (=1/9)
2) The relative contribution of each supplier in each impact category are multiplied by the weigh (e.g. for the F1 in climate change = 1/9*36.7)
3) The final score is calculated summing up the values of estimated in 2) for all the impact category

Table I. 1 – Relative contribution for each supplier and final score calculated.

Suppliers	F1	F2	F3
Impact category	Relative contribution		
Climate change	36.7	76.2	100
Ozone depletion	28.4	100	76.2
Human toxicity (CE)	100	71.8	2.0
Human toxicity (NCE)	41.9	100	2.9
Acidification	49.7	100	75.7
Freshwater eutrophication	28.0	100	10.6
Marine eutrophication	32.9	100	70.1
Freshwater ecotoxicity	24.0	100	3.0
Water resource depletion	38.1	76.9	100
Final Score	**42.2**	**91.7**	**48.9**