ReviWool®

by MANTECO

LIFE CYCLE ASSESSMENT

Abstract

Mapping of co-products in the wool production chain and environmental assessments with Life Cycle Assessment methodology

The wool production chain is generally characterised by a high efficiency: the loss of material is very limited, since most part of sheep raw wool can be transformed into fibers for the production of different types of yarns, fabrics and garments. On the one hand, **the longest and finest fibers** (obtained from the back and shoulders of the sheep) are considered of higher quality and **are employed for the production of highly smooth and lightweight fabrics, through the so-called worsted processing**. On the other hand, **shorter and thicker fibers** (obtained from other parts of the sheep, such as belly and neck), **together with fibers discarded from the worsted processing, undergo the so-called woollen processing**, for the production of outerwear.

In this framework, **the assessment of environmental impacts of different intermediate and final products of the wool industry can result controversial. Literature on wool environmental impacts is available, but previous studies do not clearly distinguish among the different co-products of the wool transformation, resulting in assigning the same impact to fibers used in the worsted and woollen processing**.

This study firstly provides a detailed mapping of processes and products involved in the wool production chain, from the sheep grazing to the yarn production, with particular attention to the fractions considered of lower quality. Secondly, this study **employs the standardised methodology of Life Cycle Assessment (LCA) to analyse the environmental impacts of the different intermediate products. In particular, when multi-output processes occur, impacts are distributed proportionally to their relative economic value, using therefore an economic allocation, as it is usually called in the LCA jargon.**

T**his approach enabled the calculation of environmental impacts of fibers used both in the worsted and woollen processing. It results that shorter fibers, used in the woollen processing, generally have lower impacts than longest fibers addressed to the production of fine yarns.** Specifically, most part of short fibers have an impact on climate change ranging from 25 to 30 kg CO_2 eq/kg, with exception of spinning soft waste (50 kg CO_2 eq/kg) and belly wool fibers (70 kg CO_2 eq/kg). **Specifically, ReviWool® fibers by Manteco® results having an impact of 29,5 kg CO_2 eq/kg.**

As a term of comparison, the impact of 1 kg of not dyed sliver (which is the input of fine yarn spinning) is of 85,7 CO_2 eq/kg. Finally, since the grazing phase is highly variable, impacts on climate change of the analysed intermediate products have been re-calculated using the lowest and highest values of impact for the greasy wool found in literature (respectively 20 and 60 kg CO_2 eq/kg). Impacts of the analysed products vary sensibly according to the value considered for the greasy wool, but the relationship between them is highly stable.

1 Introduction
PAGE 4

2 Life Cycle Assessment Methodology
PAGE 6

3 Mapping of wool Production chain
PAGE 11

4 Literature Review
PAGE 14

5 Definition of Allocation Criteria
PAGE 16

6 Inventory of the wool Production chain
PAGE 20

7 Impact assessment of Wool products
PAGE 41

8 Conclusions
PAGE 41

1 Introduction

Life cycle assessment on ReviWool® fibers

1 Introduction

The textile industry is currently more and more active in the measurement of its environmental performances. In most cases the standardised (ISO14040-44) methodology of Life Cycle Assessment (LCA) is used to quantify the potential impacts of a product along its entire life cycle (raw material extraction, production, use, end of life, etc.).

In this study the focus is the wool production chain and an LCA approach is used to define a method to calculate the impacts of the different (co-)products.

The wool production chain is traditionally characterised by a high efficiency rate. Therefore, almost the totality of sheep raw fleeces generally find employment in the textile industry, **both the parts considered of higher quality (with finer, longer and cleaner fibers, such as the wool from the back and the shoulders of the sheep) and the lower quality parts (such as, e.g., wool from the belly and the neck)**. In addition, **the scraps generated during the transformation processes are mostly re-employed in the wool industry.** As a consequence, wool companies are characterised by integrated processes, which provide a set of fibers and related products with different characteristics. To make an example, long staple fibres are used to produce highly smooth and lightweight fabrics, such as, for example, next-to-skin baselayers, high-quality fashion, babywear, gloves. On the other side, for the production of outerwear, such as jumpers, sweater and scarves it is more adequate a bulkier fabric, made with thicker fibers.

In this framework, the distribution of environmental impacts among the different products of the wool industry can result controversial. For example, the combing process generally produces both tops (which will be transformed into a very fine yarn) and other shorter fibers (which will be transformed into a thicker yarn). Therefore, the total impacts connected to the combing process have to be split among tops and other shorter fibers through an objective criteria. According to the perspective considered, different allocation criteria could be used, such as an economic criteria or a physical criteria (based on mass, on insulation properties, on the fiber diameter, etc.).

The present study aims to identify the most adequate criteria to distribute impacts among different co-products of the wool production chain and to evaluate the environmental performances of these co-products, with particular attention to the fractions considered of lower quality.

To this goal, it is firstly provided an overview of the LCA methodology (Chapter 2). Subsequently, a clear mapping of the products, co-products and waste of the wool production chain is investigated and illustrated in chapter 3. Chapter 4 provides a literature review describing how the co-productions have been considered in previous LCA studies on wool. Chapter 5 details the allocation criteria proposed in this study and Chapters 6 and 7 respectively provide the inventory and the impact results of the wool co-products. Conclusions are provided in Chapter 8.

2 Life Cycle Assessment Methodology

Life cycle assessment on ReviWool® fibers

2 Life cycle assessment methodology

In this study, the LCA (Life Cycle Assessment) methodology was used consistently with the ISO 14040 standard (series) (The International Standards Organisation, 2006a, 2006b), the International Reference Life Cycle Data System (ILCD) guidelines (European Commission-Joint Research Center, 2010), the PEF guidelines (European Commission, 2013) and the international scientific literature.

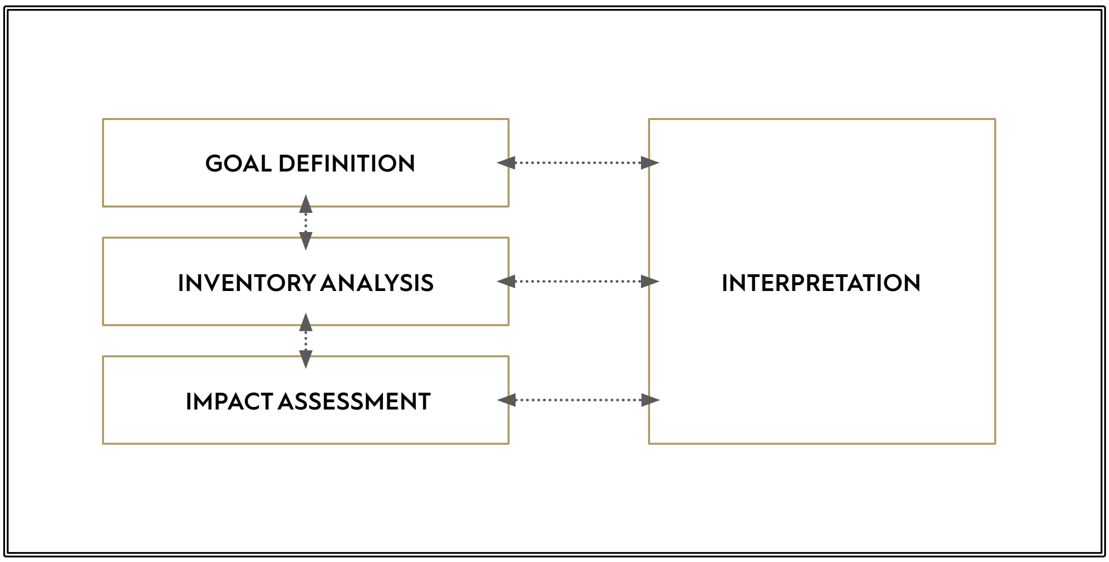
2.1 Introduction to the LCA methodology

The Life Cycle Assessment (LCA) methodology, codified by the UNI EN ISO 14040 series, can be defined as an objective environmental assessment technique for quantifying the environmental impacts of a product or process during all phases of the life cycle, through the systematic measurement of all physical exchanges to and from the environmental system.

This methodology is based on objective criteria that identify and evaluate the potential environmental impacts and energy loads of a product, through the identification of input (materials, resources and energy) and output flows (waste and polluting emissions into the environment) throughout the life cycle. **Through a so-called "cradle-to-grave" or also "cradle-to-cradle" analysis, the production system is considered from a global perspective and, consequently, hypotheses and/or attempts of improvement are evaluated with reference to the entire life cycle.** The evaluation therefore includes: the extraction and treatment of raw materials, manufacturing, transport, distribution, use, reuse, recycling and final disposal.

LCA analyses, initially more widespread in industry in the strict sense, are now commonly applied to numerous sectors. According to ISO 14040, the phases of an LCA life cycle analysis (Figure 1) are as follows:

Figure 1. Scheme of LCA according to ISO 14040 standard



Goal and scope definition

It is the initial phase, in which **the purposes and field of application, the functional unit and the boundaries of the LCA study are defined.** This phase therefore **determines the entire setting of an LCA study, describes the system being studied and deines the categories of data to be found, the assumptions and limits.**

Life Cycle Inventory analysis - LCI

It includes the collection of data and calculation procedures that allow to quantify the input/output flows of a product system. It is certainly the most important phase in an LCA study: **it realizes the construction of a model of the real system examined and allows to determine the physical inputs and outputs according to the objectives of the study.** For this reason, this phase is usually supported by dedicated software and databases.

Life Cycle Impact Assessment - LCIA

This is the phase of processing the results of the inventory acquired, with the aim of assessing the extent of the potential environmental impacts that are generated as a result of releases into the environment (emissions or waste) and of the consumption of resources caused by productive activity.

Life Cycle Interpretation

It is the final phase of Life Cycle Assessment, in which **the results obtained in the inventory analysis and impact assessment are combined consistently with the pre-established goal and the purpose to be achieved.** The Interpretation phase aims to **draw conclusions and recommendations, necessary to reduce the environmental impact of the processes or activities considered, evaluating them in an iterative manner with the same methodology.**

2.2 Environmental indicators used

To make the results obtained from the LCA analysis more usable, to fully appreciate their environmental significance and to communicate them to professionals and the public, areas of environmental interest (impact categories) must be identified and for each of them it is necessary to select appropriate indicators. These indicators (so-called category = referring to a single environmental impact) summarise the potential environmental effects that can be associated with the material/energy flows entering or leaving the studied system.

In the present study, the EF 3.0 method, a method recommended by the European Commission and in line with the PEF guidelines (EC-JRC, 2012), was used in the impact analysis phase. Impact on climate change are highlighted in detail along the production chain. A broader overview on all the indicators available in EF 3.0 is provided as well.

2.3 Multi-output processes: system allocation and expansion

When the same process generates two or more (by)products, the distribution of the impacts can be carried out with different approaches. The main distribution methods used in LCA are allocation and system expansion.

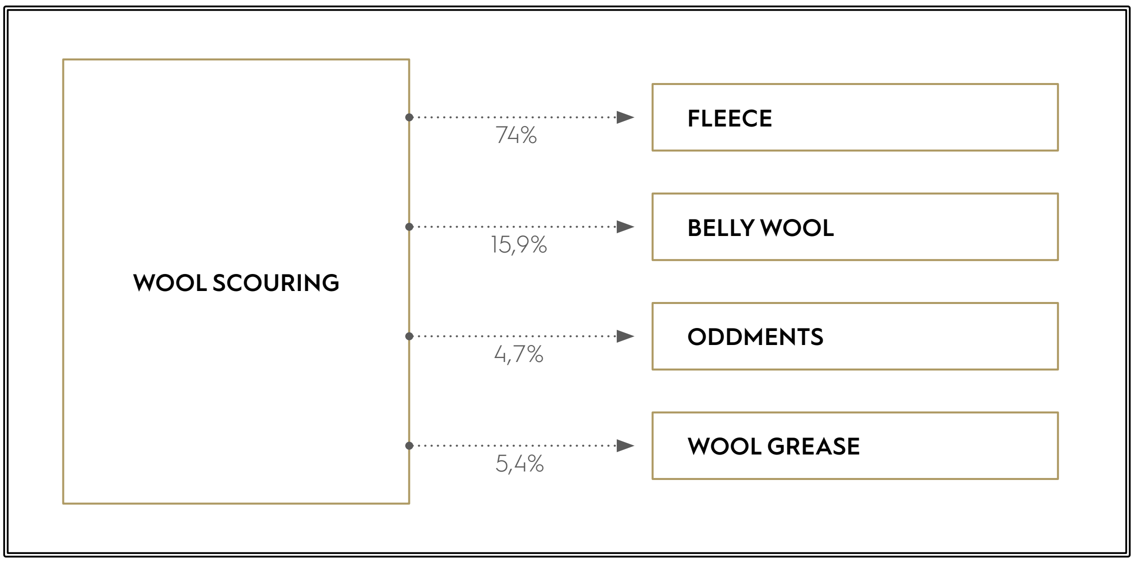
Since the choice strongly depends on the objectives of the study, the system boundaries identified and the type of process, there is currently no method more shared by the scientific community. **The allocation consists in dividing the environmental impact between the co-products. The subdivision of the impacts can be done with different criteria depending on the case study. It is possible to make an allocation on a physical basis, where the impacts are divided among the products based on physical characteristics, such as, for example, mass, volume, amount of energy, etc. However, the physical allocation may not be considered appropriate when the co-products have very different qualities and values.**

In these cases, a criteria that can be used for the allocation is the economic value of the co-products. In the case of wool scouring, it is possible to attribute economic values to the wool fleece, the belly wool, the oddments and the wool grease (i.e. lanolin). Therefore impacts can be divided in proportion to the economic value of each of these outputs.

In the case in question, 1 kg of scoured wool produce 0,5 kg of fleece (average market price: 9,50 €/kg), 0,12 kg of belly wool (8,50 €/kg), 0,10 kg of oddments (3 €/kg) and 0,07 kg of wool grease (5 €/kg), for a total value of: 0,5 * 9,50 + 0,12 * 8,50 + 0,10 * 3 + 0,07 * 5 = 6,42 €. As a consequence:

- Impacts allocated to fleece: (0,5 * 9,50)/ 6,42 = **74,0%**
- Impacts allocated to belly wool: (0,12 * 8,50)/ 6,42 = **15,9%**
- Impacts allocated to oddments: (0,10 * 3)/ 6,42 = **4,7%**
- Impacts allocated to wool grease: (0,07 * 5)/ 6,42 = **5,4%**

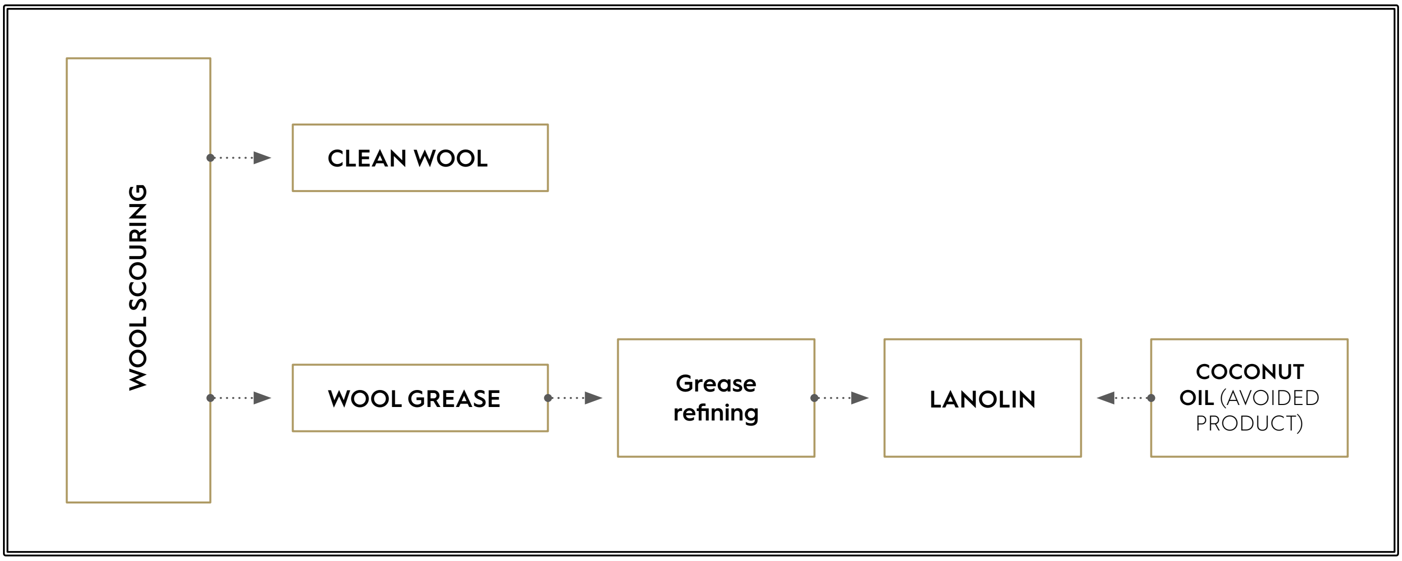
Figure 2. Multi-output processes: approach with economic allocation for the impact calculation.



In system expansion, co-products are considered to replace other products on the market. This approach takes into account the indirect impacts/benefits of inter-connected and inter-dependent systems, subtracting the impacts of the avoided product(s).

In the wool production chain, some literature studies used the system expansion approach for considering the co-production of clean wool and grease from the process of scouring. In this case the boundaries of the analysis are expanded in order to incorporate the impacts due to the grease refining and the benefits deriving from the consequent availability of lanolin to replace the production of coconut oil. **The concept is graphically showed in the diagram of Figure 3:**

Figure 3. Multi-output processes: approach with system expansion for the impact calculation.



3 Mapping of wool production chain

3 Mapping of wool production chain

The wool production chain has been investigated with the aid of Manteco, data from literature and data published by the International Wool Textile Organisation (IWTO). Figure 4 summarises the mapping of the wool production chain, hereafter described.

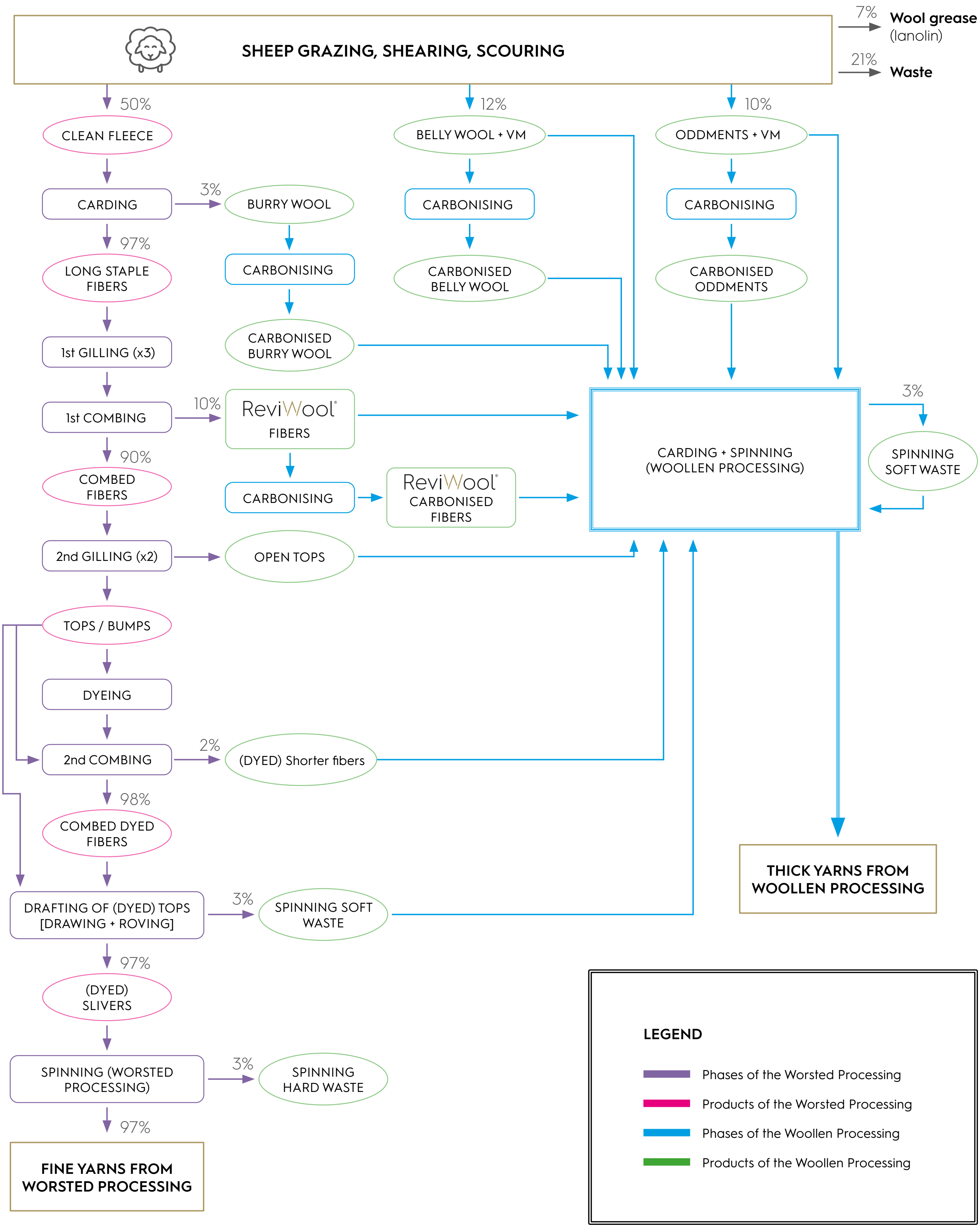


Figure 4. Flow chart of the wool production chain. Purple and pink boxes respectively identify phases and products of the worsted processing; blue and green boxes respectively identify phases and products of the woollen processing.

The first passages are the grazing, shearing and scouring to obtain wool cleaned from grease and dirt. **Specifically, from this phase is obtained the clean fleece (the part with longest and cleaner fibers, weighting for about the 50% in mass of the total of the shorn wool), the clean belly wool (12% in mass), the clean oddments (lower quality parts, about 10% in mass), wool grease (i.e. lanolin, about 7% in mass) and wastes (21% in mass).** In some cases, for belly wool and oddments, a subsequent carbonisation process is required as well to eliminate vegetable matters (VM). **The carbonisation involves a treatment with diluted sulphuric acid, which attaches to the VM, and the drying into an oven that makes the VM brittle and easier to remove.** With the passages of scouring and eventual carbonisation are obtained clean fleece, and clean (or carbonised) belly wool and oddments. **Clean fleece (having longer and finer fibers) will be transformed into very fine yarn through the so called worsed processing system. On the other hand, clean/carbonised belly wool and oddments, together with other fibers discarded from the worsted processing system, will be transformed into thicker yarns though the woollen processing system.** In both worsted and woollen processing, fibers fistly undergo a process of carding. This is a mechanical process that disentangles the fibers and reduces impurities to produce a continuous web suitable for the next passages of the production.

Looking at the worsted processing, the main product of the carding are long staple fibers (about 97% in mass), while the discarded fibers take the name of burry wool (or burs, about 3%). These latter are, in some cases carbonized, and join the woollen processing system. Long staple fibers are then gilled and combed. Generally, in worsted processing, three gilling operations are carried out prior to combing and two after combing. The gilling is useful to align the fibres in a parallel direction and produce a sliver with a more uniform weight. The combing process further straightens the fibres and removes short fibers and foreign matter. **The short fibers are about the 10% of the combed wool and are employed in the woollen processing after an eventual carbonization.** On the other side, the combed long fibers, after the two more gillings, become a continuous worsted sliver, called tops, which can be packed to form bumps. However, sometimes the top is broken or pulled apart, becoming the so called open tops, used in the woollen processing.

4 Literature review

4 Literature review

Literature on environmental assessments on virgin wool products is not highly abundant, but neither scarce. Most part of previous LCA studies mainly focused on the farming phase. For this phase, allocation procedures have been discussed in detail.

(Henry, 2012) made a review on studies developed before 2012, and she found that the main alternatives have been (1) no allocation, (2) biophysical basis or (3) economic basis. (Eady et al., 2012) showed that the allocation procedure can significantly affect the impact result. This had been confirmed by (Wiedemann et al., 2015), who applied seven methods of allocation to addressed the co-productions of wool and live weight for meat.

Therefore, during the farming phase, allocation is required to divide impacts among different co-products, including sheep wool and sheep meet, manure (used as a fertilized replacement), secondary slaughter products (i.e. hides, offal, meat/blood meal, etc). In addition, some farms have mixed production systems with different agricultural products such as beef and crops on the same property. Some studies also analysed the phases that follow the farming stage, such as the scouring phase and the transformation of raw wool into textile. During the scouring phase, the lanolin is a co-product. In the study of (Bech et al., 2019), however, no allocation has been addressed to the lanolin. In the same year, (Wiedemann et al., 2019) suggest the use of a system expansion approach, meaning that the lanolin has to be considered a product that substitute (and therefore avoid the production) of coconut oil.

As concern the transformation of raw wool into yarn, some authors (Barber and Pellow, 2006; Brent and Hietkamp, 2003) considered also the co-production of wool shorter fibers, adopting an allocation based on the weight of the outputs (mass allocation). This means that the same impact is associated to 1 kg of long fibers and 1 kg of short fibers. The same approach has been more recently used by (Wiedemann et al., 2020), who analysed the entire life cycle of a sweater produced with wool from the worsted processing.

In 2016, IWTO published Guidelines for conducting a LCA of wool textiles (International Wool Textile Organisation (IWTO), 2016), where general indications are given with regard to the allocation procedures to be followed, in accordance with ISO standards. More detailed indications are given for co-productions during farm stage (animal species; meat, wool, milk) and for co-production of wool fibres and lanolin during the processing. On the contrary, it is not specifically mentioned how to deal with co-products in the worsted/ woollen processing.

To the best of the author's knowledge, any LCA study specifically focuses on the woollen processing and no allocation procedures different from the mass basis have been employed, probably because of lack of data. **The present study, beyond providing Manteco with environmental information on its products deriving from the woollen processing, gives a contribution to the impact calculation in the field of wool textiles.**

5 Definition of allocation criteria

Life cycle assessment on MWool® fibres

5 Definition of allocation criteria

The focus of this study is the environmental assessment of wool yarn, with particular attention to the processes occurring after the farm stage. This study aims to identify in detail the co-products of the transformation process and quantify their environmental performances.

As described in Chapter 3, the main stream is the worsted processing, which starts from the longest fibers of the fleece and produces very fine yarns, employed for making extremely smooth and lightweight fabrics. On the other hand, shorter fibers and fibers discarded from the worsted processing are employed in the woollen processing, which produces thicker yarns, employed for thick, heavyweight woven or knitted garments. **The finer fibers are considered of higher quality and have a higher cost than short fibers.**

An allocation based on mass, results in associating the same impacts to 1 kg of fine yarn (from the worsted processing) and 1 kg of thick yarn (from the woollen processing). In other words, with a mass allocation it result that the valorization of the discarded and less prestigious fibres have the same impact of long smooth fibers. According to the authors of this study, an allocation based on mass is not the most appropriate for the wool production chain. Therefore, generally the core business of the wool production is the fine yarn, that, as a consequence, is expected to be charged of a share of impacts higher than the side production of thicker yarn. In addition, when a mass allocation is used, the comparability of textiles could result controversial: for example, it probably results that the final impact of a sweater produced with fine fibers (lighter, more prestigious and expensive) is inferior than a (heavier and cheaper) sweater of the same size produced with thicker fibers.

This study proposes to allocate the impacts according to an economic criteria. In other words, the impact associated to a process with multi-outputs is divided proportionally to the prices of each output. The economic value is therefore indicative of the perceived quality of the fibers. The economic allocation could be considered less objective than an allocation based on physical criteria because of instability of prices. Nevertheless, it is important to notice that the distribution of impacts reflects the ratio between the prices and not the absolute value of the price. This ratio is generally quite stable.

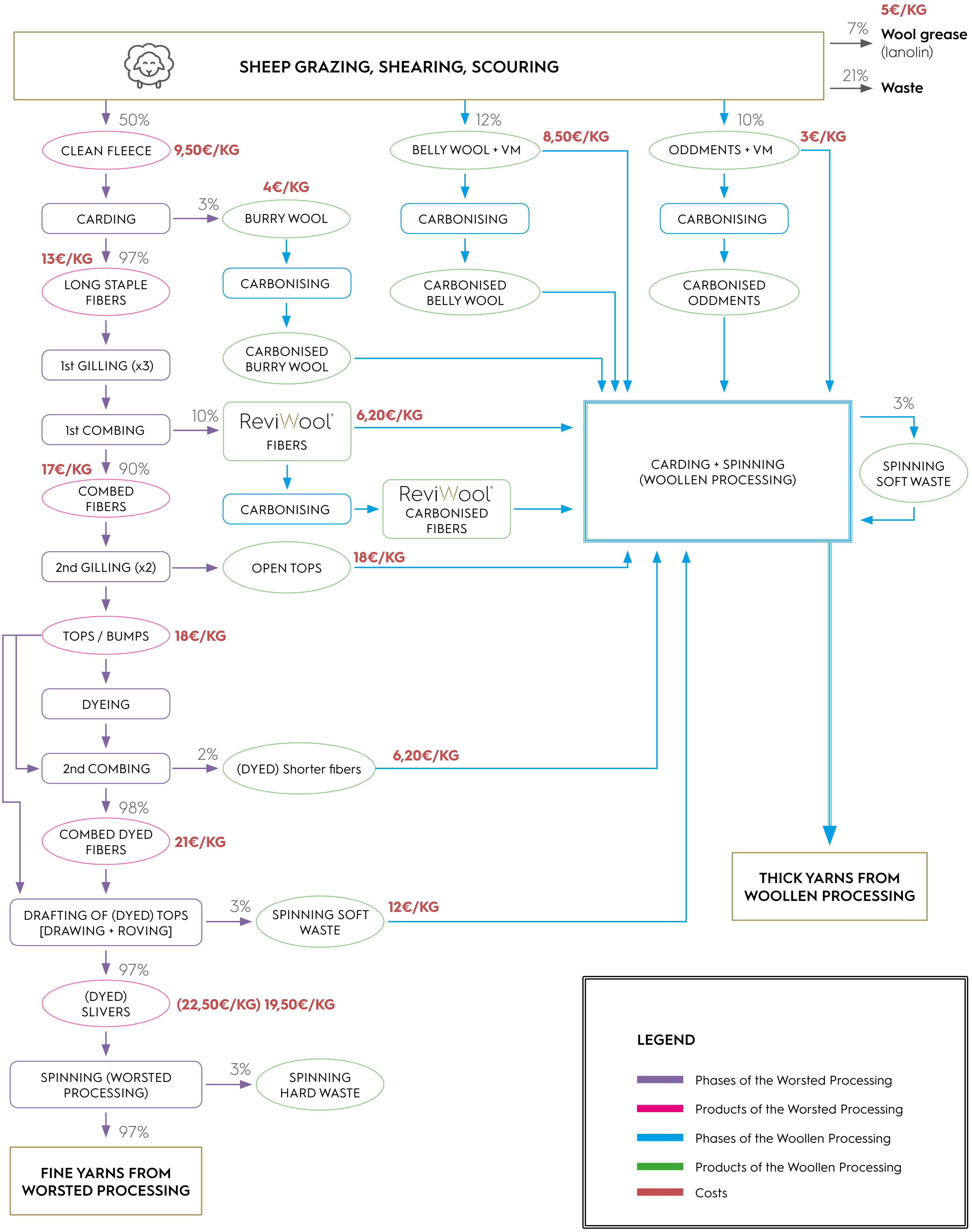
Table 1 lists the processes where an allocation has been necessary, the mass quantities of each economic outputs, their price and the allocation expressed in percentage. For sake of clarity, Figure 6 shows prices also on the wool production chain map. All the prices that have been inserted are primary data provided by Manteco. In the case of the long staple fibers (output of the carding process) and of combed fibers (output of the 1st combing) the price has been estimated, since these products are not generally sold.

Notice that no allocation has been necessary for the process of second gilling because the price of outputs (tops, bumps and open end) is the same (18 €/kg) and the quantities produced depend on the request of the market.

Table 1. Data employed for the economic allocation of multioutput processes.

PROCESS	OUTPUT HAVING ECONOMIC VALUE	MASS QUANTITY [KG]	PRICE [€/KG]	% ALLOCATION
Sheep shearing and fleece scoring (1 kg)	Clean Fleece	0,50	9,50	74,0
	Belly Wool + VM	0,11	8,50	15,9
	Oddments + VM	0,11	3	4,7
	Wool grease	0,07	5	5,4
Carding (1 kg)	Long staple fibers	0,97	13	99,1
	Burry wool	0,03	4	0,9
1st Combing (1 kg)	Combed fibers	0,9	17	96,3
	Shorter fibers	0,1	6,20	3,7
2nd Combing (1 kg)	Combed dyed tops	0,98	21	99,4
	Shorter fibers	0,02	6,20	0,6
Drafting of not-dyed tops (1 kg)	Sliver	0,97	19,50	98,1
	Spinning soft waste	0,03	12	1,9
Drafting of dyed tops (1 kg)	Dyed sliver	0,97	22,50	98,4
	Spinning soft waste	0,03	12	1,6

Figure 6. Flow chart of the wool production chain with prices used for the economic allocation.



6 Inventory of the wool production chain

Life cycle assessment on ReviWool® fibers

6 Inventory of the wool production chain

Tables in the following sub-chapters details input/output flows for each process of the wool production chain, as well as datasets used (from the database Ecoinvent 3.7).

The grazing, shearing and scouring processes takes place in many farms located in different countries. Since Manteco has no access to details on these processes, the related datasets employed for the LCA process are referred to average global production. **Therefore, this study mainly focuses on the transformation of raw wool into fibers to be spun, operated by Manteco and its net of collaborating companies. A sensitivity analysis based on literature data is developed to evaluate how results change at the varying of the impact of the farm stage.**

The processes of wool transformation takes place in Italy and data are referred to Italian companies and/or technical sheets of machineries used by Italian companies. F**or these processes, electricity is modelled according to the Italian Residual mix declared in the report of the Association of issuing bodies (AIB)[1] . Specifically, the following mix has been used:**

- **Renewable energy from biomass: 1,73%**
- **Renewable solar energy: 5,02%**
- **Renewable energy from wind: 1,75%**
- **Renewable hydro energy: 1,72%**
- **Fossil energy from hard coal: 17,40%**
- **Fossil energy from lignite: 0,54%**
- **Fossil energy from oil: 3,87%**
- **Fossil energy from natural gas: 54,43%**

6.1 Grazing and shearing

Because of unavailability of more specific data, for the processes of grazing and shearing it is considered the dataset of the Ecoinvent database named "Sheep fleece in the grease {RoW}| sheep production, for wool". This process represents average sheep production for wool with the outputs of 4.2 kg of sheep fleece in the grease and a by-product of 7.85 kg of sheep for slaughtering. A sensitivity analysis based on literature is carried for this phase.

1 https://www.aib-net.org/facts/european-residual-mix

6.2 Scouring

Table 2 summarises the inventory for the process of scouring. Data have been based on the "Made Green in Italy" guidelines (Confindustria Toscana Nord, 2021).[1]

Table 2. Data employed for the economic allocation of multioutput processes.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUT				
Clean wool, fleece	0,5	KG		*50% in mass. Economic allocation: 74%*
Clean wool, belly wool VM	0,12	KG		*12% in mass. Economic allocation: 15,9%*
Clean wool, oddments VM	0,10	KG		*10% in mass. Economic allocation: 4,7%*
Wool grease	0,07	KG		*7% in mass. Economic allocation: 5,4%*
Solid Waste	0,21	KG	*Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, S*	*21% in mass. Economic allocation: 0%*
Wastewater	2,63	L	*Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Cut-off, S*	*Economic allocation: 0%*
INPUTS				
Sheep fleece in the grease	1	KG	*Sheep fleece in the grease {RoW}| sheep production, for wool | Cut-off, S*	
Electricity	0,102	MJ	*Electricity, medium voltage {GLO}| market group for | Cut-off, S*	
Steam	6,22	KG	*Steam, in chemical industry {RoW}| production | Cut-off, S*	

1 https://www.mite.gov.it/pagina/made-green-italy

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Water	6,22	L	*Tap water {GLO}| market group for | Cut-off, S*	
Surfactant	6,57	G	*Non-ionic surfactant {GLO}| market for non-ionic surfactant | Cut-off, S*	
Soda ash, dense	4,57	G	*Soda ash, dense {GLO}| market for | Cut-off, S*	
Soda ash, light, crystalline	2,29	G	*Soda ash, light, crystalline, heptahydrate {GLO}| market for | Cut-off, S*	
Sulfuric acid	2,29	G	*Sulfuric acid {RoW}| market for sulfuric acid | Cut-off, S*	
Municipal waste collection service	0,51	KGKM	*Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Cut-off, S*	

6.3 Worsted processing: Carding

Table 3 summarises the inventory for the process of carding.

Table 3. Inventory of the carding process.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUT				
Carded fleece, long staple fibers	0,97	KG		*97% in mass. Economic allocation: 99,1%*
Burry Wool	0,03	KG		*3% in mass. Economic allocation: 0,9%*
Wastewater	0,045	L	*Wastewater, average {RoW}| treatment of, capacity 1E9l/year | Cut-off, S*	*10% in mass. Economic allocation: 4,7%*

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUT				
Clean wool, fleece	1	KG		
Electricity	0,96	kWh	*Electricity, residual mix, IT*	*From technical sheet of Carda Marzoli[1] : up to 270 kg/h. Assumption: 80% of the declared efficiency: 270*0,8 = 216 kg/h Installed power: 26 kW; assumed yield: 80%*
Compressed air	4,63	L	*Compressed air, 1000 kPa gauge {RER}| market for compressed air, 1000 kPa gauge | Cut-off, S*	*Compressed air, 1000 kPa gauge {RER}| market for compressed air, 1000 kPa gauge | Cut-off, S*
Water	0,03	L	*Tap water {Europe without Switzerland}| market for | Cut-off, S*	*3% in mass (data from Manteco SpA) + Water for oil preparation*
Oil	0,01	KG	*Glycerine {RoW}| market for glycerine | Cut-off, S + Ethoxylated alcohol (AE>20) {GLO}| market for ethoxylated alcohol (AE>20) | Cut-off, S + Benzene {GLO}| market for | Cut-off, S + Tap water {Europe without Switzerland}| market for | Cut-off, S*	*1% in mass (data from Manteco SpA), of which: Glycerine (16,5%), Ethoxylated alcohol (12%), Benzene (8%) + Water (63,5%)*

1 https://en.marzoli.camozzi.com/kdocs/1946207/carding_section_c701.pdf

6.4 Worsted processing: First Gilling

Table 4 summarises the inventory for the process of first gilling of fibers, which requires 3 passages into the chain gill machinery.

Table 4. Inventory of the gilling process.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Gilled fibers	1	KG		*97% in mass. Economic allocation: 99,1%*
INPUTS				
Carded fleece, long staple fibers	0,03	KG		*3% in mass. Economic allocation: 0,9%*
Electricity	0,0093 * 3 passages = 0,0279	kWh	*Electricity, residual mix, IT*	*From technical sheet of GC40 chain gills, NSC N. Schlumbergerup[1] : up to 100 m/min, Up to 350ktex according to material. Assumptions: 80% of declared values: 80 m/min, 280 ktex (=0,28 kg/m) 80 m/min * 0,280 kg/m = 22,4 kg/min = 22,4 * 60 kg/h = 1344 kg/h. Installed power: 15,6 kW; assumed yield: 80% 12,5 kWh*
Compressed air	0,0015 * 3 passages = 0,0045	Nm3	*Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, S*	*Assumption: 2 Nm3/h*

1 http://www.nsc-schlumberger.com/machines/gc40-chain-gills

6.5 Worsted processing: First Combing

Table 5 summarises the inventory for the process of first combing of fibers.

Table 5. Inventory for the process of first combing.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Tops	0,9	KG		*90% in mass. Economic allocation: 96,3%*
Shorter fibers	0,1	KG		*10% in mass. Economic allocation: 3,7%*
INPUTS				
Gilled fibers	1	KG		*3% in mass. Economic allocation: 0,9%*
Electricity	0,2	kWh	*Electricity, residual mix, IT*	*From technical sheet of ERA comber[1] : up to 50 kg/h. Assumption: 80% of declared values (40 kg/h). Installed power: 10 kW; assumed yield: 80% 8 kWh*
Compressed air	0,05	Nm3	*Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, S*	*Assumption: 2 Nm3/h*

http://www.nsc-schlumberger.com/machines/era-comber

6.6 Worsted processing: Second Gilling

Table 6 summarises the inventory for the process of second gilling of fibers, which requires 2 passages into the chain gill machinery.

Table 6. Inventory of the gilling process.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Tops/Bumps/ Open tops	1	KG		*Tops, bumps and open tops have the same price (18 €/kg) and the relative quantities of each output depend on the market requests.*
INPUTS				
Gilled fibers	1	KG		
Electricity	0,0093 * 2 passages = 0,0186	kWh	*Electricity, residual mix, IT*	*From technical sheet of GC40 chain gills, NSC N. Schlumbergerup[1] : up to 100 m/min, Up to 350ktex according to material. Assumptions: 80% of declared values: 80 m/ min, 280 ktex (=0,28 kg/m) 80 m/min * 0,280 kg/m = 22,4 kg/ min = 22,4 * 60 kg/h = 1344 kg/h. Installed power: 15,6 kW; assumed yield: 80% 12,5 kWh*
Compressed air	0,0015 * 2 passages = 0,003	Nm3	*Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, S*	*Assumption: 2 Nm3/h*

http://www.nsc-schlumberger.com/machines/gc40-chain-gills

6.7 Worsted processing: Dyeing

Table 7 summarises the inventory for the process of dyeing. Data from the "Made Green in Italy" (Confindustria Toscana Nord, 2021) guidelines have been used for the inventory.

Table 7. Inventory of the tops dyeing process (inventory from "Made Green in Italy").

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Tops, dyed	1	KG		
Emission: CO	97,897	MG	*Carbon monoxide*	
Emission: NOx	768,901	MG	*Nitrogen oxides, IT*	
Avoided product: sulfate pulp	2,865	G	*Sulfate pulp, unbleached {RER}| sulfate pulp production, from softwood, unbleached | Cut-off, U*	
Avoided product:	11,365	G	*Pig iron {RoW}| pig iron production | Cut-off, U*	
INPUTS				
Tops	1	KG		
Electric energy	1,271	MJ	*Residual Mix_Electricity, medium voltage {IT}| market for | Cut-off, U*	
Thermal energy	329,293	L	*Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U 50% Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating >100kW | Cut-off, U 50%*	
Water	35,414	L	*Tap water {RER}| market group for | Cut-off, U*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Acetic acid	9,157	G	*Acetic acid, without water, in 98% solution state {GLO}I market for I Cut-off, U*	
Formic acid	6,680	G	*Formic acid {RER, RoW}I market for I Cut-off, U*	
Sulfuric acid	1,920	G	*Sulfuric acid {RER, RoW}I market for sulfuric acid I Cut-off, U*	
Ammonia 18%	3,485	G	*Sodium hypochlorite, without water, in 15% solution state {RER, RoW}I market for sodium hypochlorite, without water, in 15% solution state I Cut-off, U*	
Ammonia 24.5%	1,729	MG	*Sodium hypochlorite, without water, in 15% solution state {RER, RoW}I market for sodium hypochlorite, without water, in 15% solution state I Cut-off, U*	
Ammonium sulfate	1,641	G	*Ammonium sulfate, as N {GLO}I market for I Cut-off, U*	
Detergent	46,479	MG	*Ethoxylated alcohol (AE>20, AE11, ae3, ae7) {GLO, RoW}I market for ethoxylated alcohol (AE>20) I Cut-off, U (5%) Chemical, organic {GLO}I market for I Cut-off, U (10%)*	
Reducing and whitening agent	265,586	MG	*Sodium dithionite, anhydrous {RER, RoW}I market for sodium dithionite, anhydrous I Cut-off, U 45% Sodium nitrite {RER, RoW}I market for sodium nitrite I Cut-off, U 5% Chemical, inorganic {GLO}I market for chemicals, inorganic I Cut-off, U 2%*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Detergent	804,563	MG	*Ethoxylated alcohol (AE>20, AE11, ae3, ae7) {GLO, RoW}| market for ethoxylated alcohol (AE>20) | Cut-off, U 35%* *Fatty acid {GLO}| market for | Cut-off, U 35%* *2-methyl-2-butanol {GLO}| market for | Cut-off, U 30%*	
Sodium carbonate (SOLVAY)	3,022	G	*Sodium bicarbonate {GLO}| market for sodium bicarbonate | Cut-off, U*	
Auxiliary for oil-repellent finishing	79,868	MG	*3-methyl-1-butanol {GLO}| market for | Cut-off, U 3%* *Ethoxylated alcohol (AE>20, AE11, ae3, ae7) {GLO, RoW}| market for ethoxylated alcohol (AE>20) | Cut-off, U 3%* *Chemical, organic {GLO}| market for | Cut-off, U 0,003%*	
Auxiliary for dyeing	1,279	G	*Ammonium chloride {GLO}| market for | Cut-off, U 10%* *Ethylamine {GLO}| market for | Cut-off, U 10%* *Diethylene glycol {GLO}| market for | Cut-off, U 5%*	
Leveling agent	5,958	G	*Ethoxylated alcohol (AE>20, AE11, ae3, ae7) {GLO, RoW}| market for ethoxylated alcohol (AE>20) | Cut-off, U 10%* *Alkyl sulphate (C12-14) {GLO}| market for alkyl sulphate (C12-14) | Cut-off, U 5%* *Diethylene glycol {GLO}| market for | Cut-off, U 3%*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Softener	338,095	MG	*Chemical, organic {GLO}| market for | Cut-off, U 10%* *Polydimethylsiloxane {GLO}| market for polydimethylsiloxane | Cut-off, U 5%* *Potassium hydroxide {GLO}| market for | Cut-off, U 0,2%*	
Anti-reducing agent	362,298	MG	*Alkylbenzene sulfonate, linear, petrochemical {GLO}| market for | Cut-off, U*	
Hydrogen peroxide	838,940	MG	*Hydrogen peroxide, without water, in 50% solution state {RER, RoW}| market for hydrogen peroxide, without water, in 50% solution state | Cut-off, U*	
Sodium dichromate	417,618	MG	*Sodium dichromate {GLO}| market for | Cut-off, U*	
Sodium hydrosulfite	798,438	MG	*Sodium dithionite, anhydrous {RER, RoW}| market for sodium dithionite, anhydrous | Cut-off, U*	
Sodium hydrosulfite stab.	99,527	MG	*Sodium dithionite, anhydrous {RER, RoW}| market for sodium dithionite, anhydrous | Cut-off, U*	
Auxiliary for dyeing	87,080	MG	*Tert-butyl amine {GLO}| market for | Cut-off, U 60%* *Propyl amine {GLO}| market for | Cut-off, U 15%* *Ethylamine {GLO}| market for | Cut-off, U 7,5%* *Chemical, organic {GLO}| market for | Cut-off, U 7,5%* *Ethylene glycol dimethyl ether {GLO}| market for | Cut-off, U 5%* *Ethylene glycol {GLO}| market for | Cut-off, U 5%*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Whitener	26,425	MG	*Alkylbenzene sulfonate, linear, petrochemical {GLO}I market for I Cut-off, U*	
Blue dye 1	1,791	G	*Anthraquinone {GLO}I market for I Cut-off, U 80%*	
Blue dye 1B	0,301	G	*Anthraquinone {GLO}I market for I Cut-off, U 40%*	
Blue dye 2	2,162	G	*Sodium dichromate {GLO}I market for I Cut-off, U (75% - 15)*	
Blue dye 3	0,001	G	*Sodium hydrogen sulfate {GLO}I market for sodium hydrogen sulfate I Cut-off, U 85%*	
Blue dye 4	0,011	G	*EDTA, ethylenediamine-tetraacetic acid {GLO}I market for I Cut-off, U 5%*	
Blue dye 5	0,021	G	*Chemical, organic {GLO}I market for I Cut-off, U 80%*	
Blue dye 5B	0,003	G	*Chemical, organic {GLO}I market for I Cut-off, U 50%*	
Orange dye	0,193	G	*Sodium bicarbonate {GLO}I market for sodium bicarbonate I Cut-off, U 10%* *Sodium dichromate {GLO}I market for I Cut-off, U 70%*	
Bordeaux dye	0,037	G	*Alpha-naphthol {GLO}I market for I Cut-off, U 25%*	
Brown dye 1	0,662	G	*Anthraquinone {GLO}I market for I Cut-off, U 70%*	
Brown dye 2	0,375	G	*Sodium dichromate {GLO}I market for I Cut-off, U 90%*	
Yellow dye 1	0,147	G	*Alpha-naphthol {GLO}I market for I Cut-off, U 85%*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Yellow dye 1B	0,290	G	*Alpha-naphthol {GLO}I market for I Cut-off, U 45%*	
Yellow dye 2	0,009	G	*Sodium bicarbonate {GLO}I market for sodium bicarbonate I Cut-off, U 15%*	
Yellow dye 3	0,131	G	*Sodium dichromate {GLO}I market for I Cut-off, U 75%*	
Yellow dye 4	0,163	G	*Sodium hydrogen sulfate {GLO}I market for sodium hydrogen sulfate I Cut-off, U 90%*	
Black dye 1	20,435	G	*Sodium dichromate {GLO}I market for I Cut-off, U (95% - 5)*	
Black dye 2	0,915	G	*Naphthalene sulfonic acid {GLO}I market for I Cut-off, U 90%*	
Red dye	1,349	G	*Naphthalene sulfonic acid {GLO}I market for I Cut-off, U 75%*	
Green dye 1	0,790	G	*Methane sulfonic acid {GLO}I market for I Cut-off, U 95%*	
Green dye 2	0,009	G	*Chemical, organic {GLO}I market for I Cut-off, U 90%*	
Violet dye 1	0,010	G	*Naphthalene sulfonic acid {GLO}I market for I Cut-off, U 75%*	
Violet dye 2	0,024	G	*Alpha-naphthol {GLO}I market for I Cut-off, U 56%* *Sodium sulfate, anhydrite {RER, Row}I market for I Cut-off, U 38,5%*	
Film PE	1,818	G	*Packaging film, low density polyethylene {GLO}I market for I Cut-off, U*	
Iron	3,636	G	*Steel, low-alloyed {GLO}I market for I Cut-off, U* *Wire drawing, steel {RER, RoW}I processing I Cut-off, U*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Lorry	25,136	KGKM	*Transport, freight, lorry 3.5-7.5 metric ton, EURO3, 4, 5, 6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cut-off, U*	
Lorry for waste collection	1,291	KGKM	*Municipal waste collection service by 21 metric ton lorry {CH}| processing | Cut-off, U*	
Wastewater treatment	33,728	L	*Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, U*	
Disposal of residues	25,828	G	*Municipal solid waste {CH}| treatment of, sanitary landfill | Cut-off, U*	
Waste paper sorting	2,865	G	*Waste paper, sorted {Europe without Switzerland}| treatment of waste paper, unsorted, sorting | Cut-off, U*	
Waste iron sorting	11,365	G	*Iron scrap, sorted, pressed {RER}| sorting and pressing of iron scrap | Cut-off, U*	

6.8 Worsted processing: Second Combing

Table 8 summarises the inventory for the process of second combing of fibers.

Table 8. Inventory for the process of first combing.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Tops	0,98	KG		*98% in mass. Economic allocation: 99,4%*
Shorter fibers	0,02	KG		*2% in mass. Economic allocation: 0,6%*
INPUTS				
Gilled fibers	1	KG		*3% in mass. Economic allocation: 0,9%*
Electricity	0,2	kWh	*Electricity, residual mix, IT*	*From technical sheet of ERA comber[1] : up to 50 kg/h. Assumption: 80% of declared values (40 kg/h). Installed power: 10 kW; assumed yield: 80% 8 kWh*
Compressed air	0,05	Nm3	*Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, S*	

http://www.nsc-schlumberger.com/machines/era-comber

6.9 Worsted processing: Drafting

Table 8 summarises the inventory for the process of drafting. **Five machineries are used for this process, namely, the horizontal rubbing frame, the rubbing frame with can delivery, the vertical rubbing frame, the chain gkill and the vertical gill.** Data from technical sheets of the worsted spinning preparation lines published by NSC (n.schulemberger)[1] are used.

Table 9. . Inventory for the process of first drafting.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
(Dyed) sliver	0,97	KG		*97% in mass. (Economic allocation: 98,4%) Economic allocation: 98,1%*
(Dyed) spinning soft waste	0,3	KG		*3% in mass. (Economic allocation: 1,62%) Economic allocation: 1,87%*
INPUTS				
(Dyed) Tops/ Bumps	1	KG		
Electricity	5,9	kWh	*Electricity, residual mix, IT*	*From technical sheets. Assumption for machineries efficiency: 80% of declared values.*
Compressed air	0,513	Nm3	*Compressed air, 600 kPa gauge {RER}I market for compressed air, 600 kPa gauge I Cut-off, S*	

http://www.nsc-schlumberger.com/production-line/worsted-spinning-preparation-lines

6.10 Worsted/Woollen processing: Spinning

Table 10 summarises the inventory of the spinning process. **In the worsted processing the sliver is transformed in a very fine yarn and hard spinning waste is produced. In the woollen processing shorter fibers are transformed in a thick yarn and soft spinning waste is produced. However, this latter re-enter in the spinning process and, as a consequence from the woollen processing there is negligible loss of material.**

The thread is wound on a plastic coil (weight: 15 g), which carries 150-180 g of thread (150 g is considered in the study, as conservative assumption). The plastic coil can be reused (assumption of 100 reuses). Spinning oil is used, based on ethoxylated alcohols, fatty acids and polyethylene glycols.

Table 10. Inventory for the process of spinning.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Very fine yarn (worsted processing) or Thick yarn (woollen processing)	0,97	KG		*Economic allocation: 100%*
Spinning hard waste (worsted processing)	0,3	KG		*3% in mass. Economic Allocation: 0%*
INPUTS				
Sliver or Fibers from worsted processing	1,11	KG		*90% yield of yarning*
Electricity	1,44	kWh	*Electricity, residual mix, IT*	
Transport with lorry	1,11*20 = 22,2	KGKM	*Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, S*	*Transport of fibres to the spinning company*
Water	0,59	KG	*Tap water {Europe without Switzerland}| market for | Cut-off, S*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Plastic coil	0,015/100 * 1/0,150 = 0,001	KG	*Polypropylene, granulate {GLO}| market for | Cut-off, S + Injection moulding {GLO}| market for | Cut-off, S*	*Assumption: weight of 0,015 kg; reused 100 times; each coil carries 0,150 kg of thread*
Spinning oil 1	0,0183	KG	*Fatty acid {RER}| fatty acid production, from coconut oil | Cut-off, S*	
Spinning oil 2	0,0183	KG	*Ethoxylated alcohol (AE11) {RER}| ethoxylated alcohol (AE11) production, palm oil | Cut-off, S*	
Spinning oil 3	0,0183	KG	*Triethylene glycol {RER}| ethylene glycol production | Cut-off, S*	
Wastewater treatment	0,59	KG	*Wastewater, average {Europe without Switzerland}| market for wastewater, average | Cut-off, S*	
Waste treatment for plastic coils	0,001	KG	*Waste polypropylene {IT}| market for waste polypropylene | Cut-off, S*	
Waste treatment for spinning waste	0,11	KG	*Waste yarn and waste textile {GLO}| market for waste yarn and waste textile | Cut-off, S*	

6.11 Woollen processing: Carbonising

Table 3 summarises the inventory for the carbonization of burry wool/belly wool with vegetable matters/ oddments with vegetable matters/Shorter fibers. **Input/output flows are assumed to be the same of the fabric carbonization, whose data were provided for a previous project by Manteco.**

Table 11. Inventory for the cabonising process, for 1 kg of wool.

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
OUTPUTS				
Carbonized burs or Carbonized belly wool or Carbonized oddments or Carbonized Shorter fibers	1	KG		
INPUTS				
Burry wool or Belly wool + VM or Oddments + VM or Shorter fibers	1	KG		*Respective inputs for the listed outputs*
Water	4,4	KG	*Tap water {Europe without Switzerland}| market for | Cut-off, S*	
Sulfuric acid	0,0371	KG	*Sulfuric acid {RER}| market for sulfuric acid | Cut-off, S*	
Heat	0,872	kWh	*Heat, district or industrial, natural gas {RER}| market group for | Cut-off, S*	
Electricity in Italy (residual mix)	0,255	kWh	*Electricity, Residual Mix, IT*	

FLOW	QUANTITY	UNIT OF MEASURE	ECOINVENT DATASET	NOTES
Waste: textile	0,0073	KG	*Municipal solid waste {CH}I treatment of, sanitary landfill I Cut-off, S*	
Waste: packaging paper	7,66E-5	KG	*Municipal solid waste {CH}I treatment of, sanitary landfill I Cut-off, S*	
Waste: plastic	1,19E-4	KG	*Waste plastic, mixture {IT}I market for waste plastic, mixture I Cut-off, S*	
Wastewater	4,4	DM^3	*Wastewater, average {Europe without Switzerland}I market for wastewater, average I Cut-off, S*	

7 Impact assessment results of wool products

Life cycle assessment on ReviWool® fibers

7 Impact assessment results of wool products

The potential impacts of the intermediate products of the wool production chain are here calculated, using the allocation criteria previously detailed. **The EF 3.0 method is employed, in line with the PEF guidelines (EC-JRC, 2012). Impact on climate change are highlighted in detail along the production chain. A broader overview on all the indicators available in EF 3 is provided as well.**

7.1 Intermediate products of the worsted processing

Table 12 lists the potential impacts of the following intermediate products of the worsted processing:

- 1 kg of clean fleece
- 1 kg of top/bumps
- 1 kg of combed dyed tops
- 1 kg of not dyed sliver
- 1 kg of dyed sliver
- 1 kg of very fine yarn, not dyed
- 1 kg of very fine yarn, dyed

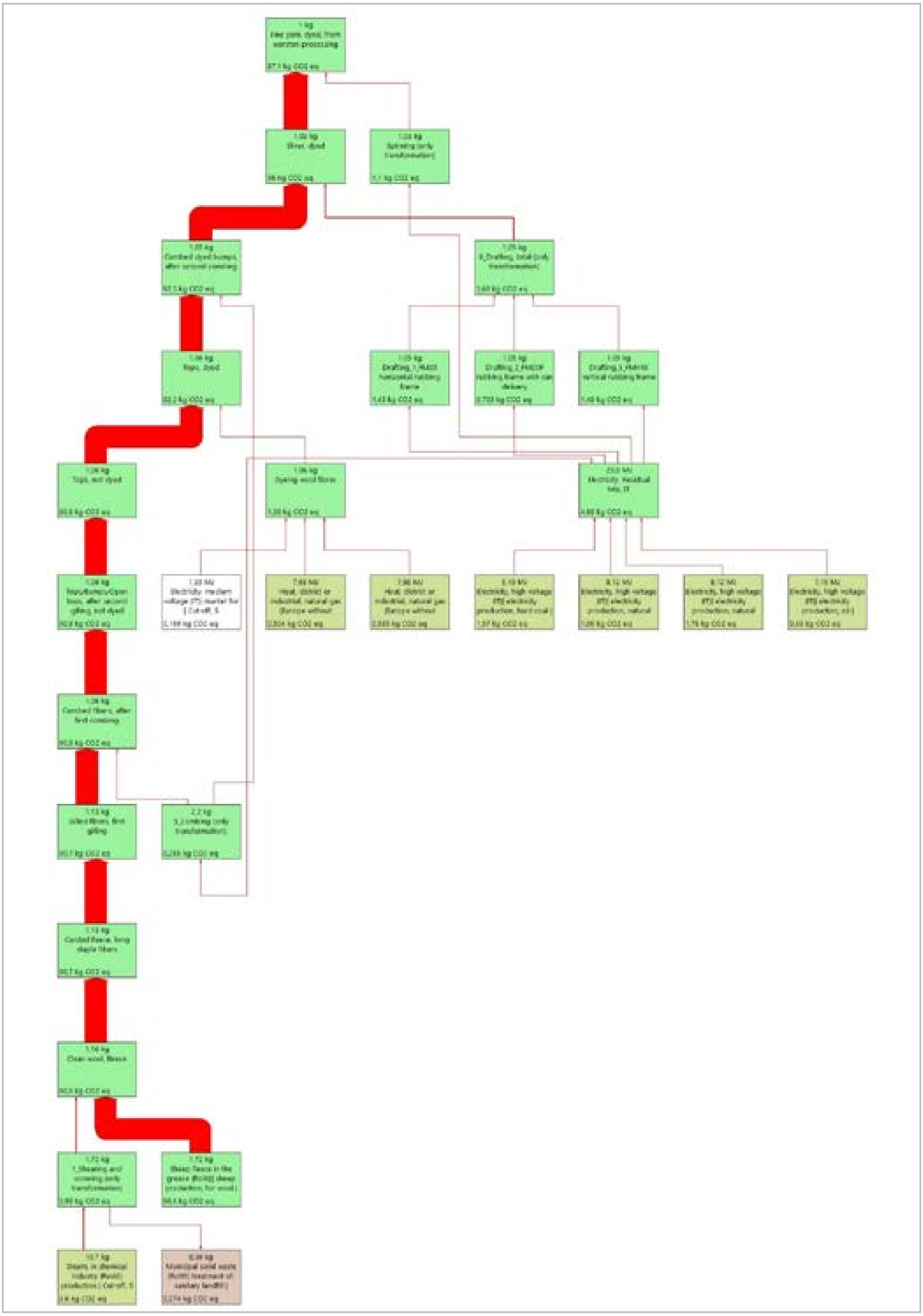
Table 12. Potential impacts of 1 kg of the intermediate products of the worsted processing.

IMPACT CATEGORY	UNIT	CLEAN FLEECE	TOPS /BUMPS	COMBED DYED BUMPS	SLIVER, NOT DYED	SLIVER, DYED	FINE YARN, NOT DYED	FINE YARN, DYED
Climate change	kg CO^2 eq	7,82E+01	8,57E+01	8,83E+01	9,02E+01	9,31E+01	9,41E+01	9,71E+01
Ozone depletion	kg CFC11 eq	9,21E-07	1,04E-06	1,27E-06	1,54E-06	1,77E-06	171E-06	1,96E-06
Ionising radiation	kBq U-235 eq	3,90E-01	4,60E-01	5,32E-01	9,90E-01	1,06E+00	1,16E+00	1,24E+00
Photochemical ozone formation	kg NMVOC eq	6,76E-02	7,44E-02	7,81E-02	8,26E-02	8,66E-02	8,76E-02	9,17E-02
Particulate Matter	Desease inc.	1,26E-05	1,37E-05	1,40E-05	1,39E-05	1,42E-05	1,44E-05	1,47E-05
Human toxicity, non-cancer	CTUh	5,79E-07	6,34E-07	6,50E-07	6,55E-07	6,73E-07	6,82E-07	7,01E-07
Human toxicity, cancer	CTUh	1,91E-08	2,10E-08	2,76E-08	2,17E-08	2,85E-08	2,29E-08	2,99E-08
Acidification	mol H+ eq	1,77E+00	1,94E+00	1,97E+00	1,98E+00	2,01E+00	2,04E+00	2,08E+00
Eutrophication, freshwater	kg P eq	1,91E-02	2,09E-02	2,14E-02	2,19E-02	2,24E-02	2,28E-02	2,33E-02

IMPACT CATEGORY	UNIT	CLEAN FLEECE	TOPS /BUMPS	COMBED DYED BUMPS	SLIVER, NOT DYED	SLIVER, DYED	FINE YARN, NOT DYED	FINE YARN, DYED
Eutrophication, marine	kg N eq	3,04E-01	3,32E-01	3,38E-01	3,38E-01	3,46E-01	3,50E-01	3,58E-01
Eutrophication, terrestrial	mol N eq	7,83E+00	8,56E+00	8,69E+00	8,69E+00	8,84E+00	8,96E+00	9,12E+00
Ecotoxicity, freshwater	CTUe	1,24E+03	1,36E+03	1,40E+03	1,40E+03	1,45E+03	1,46E+03	1,51E+03
Land use	Pt	8,19E+03	8,95E+03	9,08E+03	9,06E+03	9,22E+03	9,36E+03	9,52E+03
Water use	m3 depriv.	1,42E+01	1,55E+01	1,62E+01	1,61E+01	1,67E+01	1,70E+01	1,77E+01
Resource use, fossils	MJ	1,03E+02	1,16E+02	1,40E+02	1,74E+02	1,98E+02	1,96E+02	2,21E+02
Resource use, minerals and metals	kg Sb eq	1,41E-04	1,54E-04	1,61E-04	1,61E-04	1,68E-04	1,70E-04	1,77E-04
Climate change - Fossil	kg CO² eq	2,33E+01	2,57E+01	2,75E+01	2,96E+01	3,15E+01	3,15E+01	3,34E+01
Climate change - Biogenic	kg CO² eq	4,72E+01	5,16E+01	5,23E+01	5,22E+01	5,31E+01	5,383E+01	5,48E+01
Climate change - Land use and LU change	kg CO² eq	7,65E+00	8,36E+00	8,48E+00	8,46E+00	8,60E+00	8,75E+00	8,90E+00
Human toxicity, non-cancer-organics	CTUh	1,27E-07	1,39E-07	1,42E-07	1,41E-07	1,44E-07	1,46E-07	1,49E-07
Human toxicity, non-cancer-inorganics	CTUh	1,63E-07	1,79E-07	1,82E-07	1,82E-07	1,86E-07	1,89E-07	1,93E-07
Human toxicity, non-cancer-metals	CTUh	2,89E-07	3,17E-07	3,28E-07	3,33E-07	3,45E-07	3,48E-07	3,61E-07
Human toxicity, cancer-organics	CTUh	1,20E-08	1,32E-08	1,35E-08	1,35E-08	1,38E-08	1,42E-08	1,46E-08
Human toxicity, cancer-metals	CTUh	7,09E-09	7,78E-09	1,41E-08	8,23E-09	1,47E-08	8,66E-09	1,53E-08
Ecotoxicity, freshwater-organics	CTUe	3,50E+02	3,82E+02	3,88E+02	3,87E+02	3,94E+02	4,03E+02	4,10E+02
Ecotoxicity, freshwater-inorganics	CTUe	1,95E+2	2,14E+02	2,20E+02	2,19E+02	2,26E+02	2,27E+02	2,34E+02
Ecotoxicity, freshwater-metals	CTUe	6,93E+02	7,60E+02	7,89E+02	7,94E+02	8,26E+02	8,29E+02	8,61E+02

Figure 7 shows the impacts on climate change of the production chain of dyed fine yarn. **The total impact results of 97,1 kg CO2 eq/kg. As it can be noticed, the main contribution is the grazing phase, accounting for 89% of the total impact. All the other transformations together (shearing and scouring, carding, gilling, combing, dying, drafting and spinning) accounts for the 11% of the total impact.**

Figure 7. Carbon footprint of 1 kg of dyed fine yarn (visualization cut-off of 1%).



7.2 Intermediate products of the woollen processing

Table 13 lists the potential impacts of the following intermediate products of the woollen processing:

- 1 kg of belly wool + vegetable matter
- 1 kg of carbonised belly wool
- 1 kg of oddments + vegetable matter
- 1 kg of carbonised oddments
- 1 kg of burry wool
- 1 kg of carbonised burry wool
- 1 kg of open tops
- 1 kg of Shorter fibers (ReviWool® fibers)
- 1 kg of dyed Shorter fibers
- 1 kg of carbonised Shorter fibers (ReviWool® fibers)
- 1 kg of carbonised dyed Shorter fibers
- 1 kg of spinning soft waste

Table 12. Potential impacts of 1 kg of the intermediate products of the worsted processing.

IMPACT CATEGORY	UNIT	BELLY WOOL + VM	CARBONISED BELLY WOOL	ODDMENTS + VM	CARBONISED ODDMENTS	BURRY WOOL	CARBONISED
Climate change	kg CO² eq	6,99E+01	7,03E+01	2,47E+01	2,50E+01	2,46E+01	2,49E+01
Ozone depletion	kg CFC11 eq	8,24E-07	8,69E-07	2,91E-07	3,36E-07	2,92E-07	3,37E-07
Ionising radiation	kBq U-235 eq	3,49E-01	3,74E-01	1,23E-01	1,48E-01	1,25E-01	1,50E-01
Photochemical ozone formation	kg NMVOC eq	6,05E-02	6,10E-02	2,13E-02	2,19E-02	2,13E-02	2,18E-02
Particulate Matter	Desease inc.	1,12E-05	1,12E-05	3,97E-06	3,97E-06	3,95E-06	3,95E-06
Human toxicity, non-cancer	CTUh	5,18E-07	5,19E-07	1,83E-07	1,84E-07	1,82E-07	1,83E-07
Human toxicity, cancer	CTUh	1,71E-08	1,72E-08	6,04E-09	6,10E-09	6,02E-09	6,08E-09
Acidification	mol H+ eq	1,59E+00	1,59E+00	5,60E-01	5,61E-01	5,57E-01	5,58E-01
Eutrophication, freshwater	kg P eq	1,71E-02	1,71E-02	6,03E-03	6,07E-03	6,01E-03	6,05E-03
Eutrophication, marine	kg N eq	2,72E-01	2,72E-01	9,59E-02	9,61E-02	9,54E-02	9,57E-02
Eutrophication, terrestrial	mol N eq	7,01E+00	7,01E+00	2,47E+00	2,47E+00	2,46E+00	2,46E+00

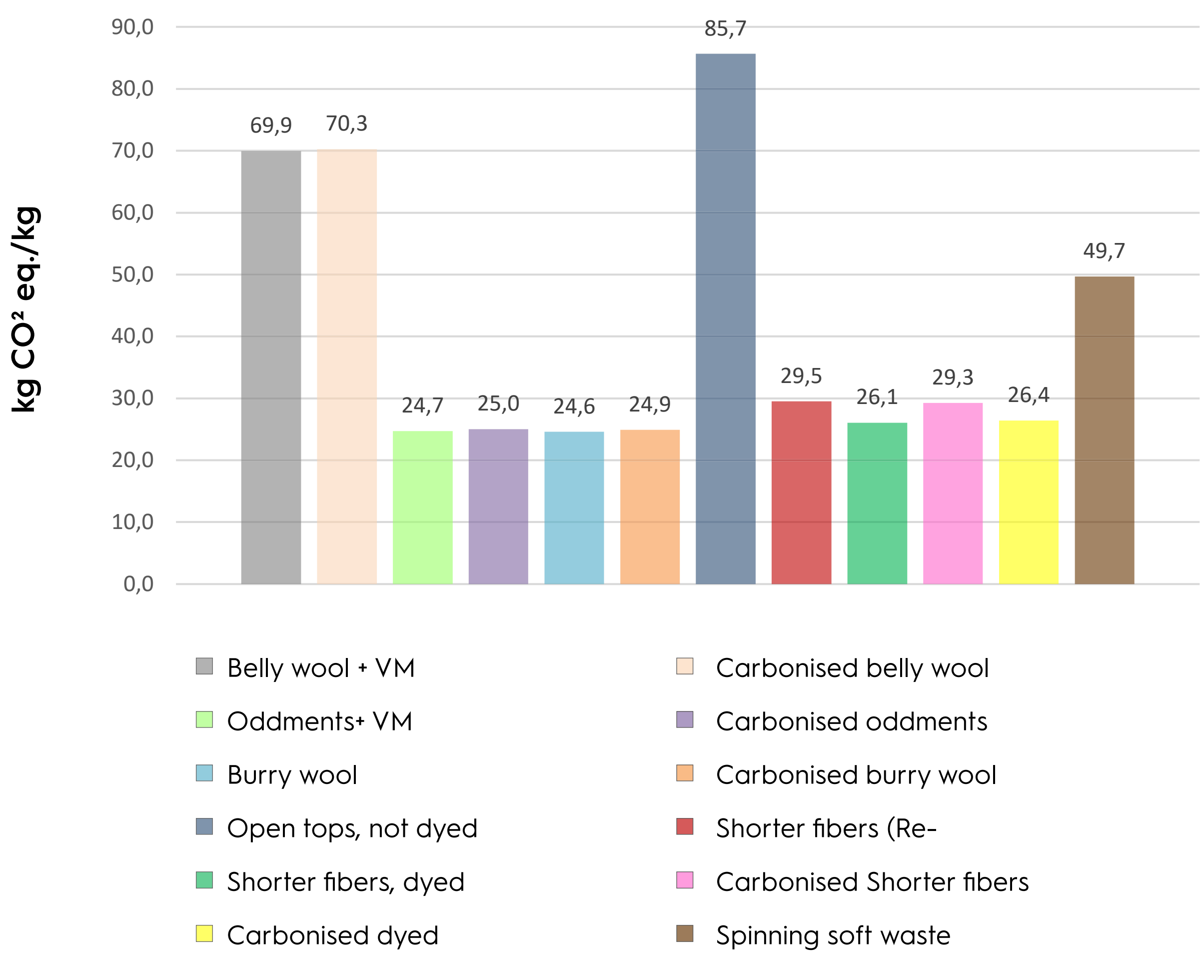
IMPACT CATEGORY	UNIT	BELLY WOOL + VM	CARBONISED BELLY WOOL	ODDMENTS + VM	CARBONISED ODDMENTS	BURRY WOOL	CARBONISED
Ecotoxicity, freshwater	CTUe	1,11E+03	1,11E+03	3,91E+02	3,95E+02	3,90E+02	3,93E+02
Land use	Pt	7,33E+03	7,33E+03	2,59E+03	2,59E+03	2,57E+03	2,57E+03
Water use	m3 depriv.	1,27E+01	1,28E+01	4,48E+00	4,55E+00	4,46E+00	4,53E+00
Resource use, fossils	MJ	9,18E+01	9,71E+01	3,24E+01	3,76E+01	3,26E+01	3,78E+01
Resource use, minerals and metals	kg Sb eq	1,26E-04	1,26E-04	4,44E-05	4,50E-05	4,43E-05	4,49E-05
Climate change - Fossil	kg CO² eq	2,09E+01	2,12E+01	7,37E+00	7,69E+00	7,35E+00	7,67E+00
Climate change - Biogenic	kg CO² eq	4,22E+01	4,22E+01	1,49E+01	1,49E+01	1,48E+01	1,48E+01
Climate change - Land use and LU change	kg CO² eq	6,84E+00	6,84E+00	2,41E+00	2,41E+00	2,40E+00	2,40E+00
Human toxicity, non-cancer-organics	CTUh	1,14E-07	1,14E-07	4,02E-08	4,03E-08	4,00E-08	4,01E-08
Human toxicity, non-cancer-inorganics	CTUh	1,46E-07	1,46E-07	5,16E-08	5,17E-08	5,13E-08	5,15E-08
Human toxicity, non-cancer-metals	CTUh	2,59E-07	2,60E-07	9,13E-08	9,25E-08	9,09E-08	9,21E-08
Human toxicity, cancer-organics	CTUh	1,08E-08	1,08E-08	3,80E-09	3,82E-09	3,79E-09	3,81E-09
Human toxicity, cancer-metals	CTUh	6,34E-09	6,38E-09	2,24E-09	2,28E-09	2,23E-09	2,27E-09
Ecotoxicity, freshwater-organics	CTUe	3,13E+02	3,13E+02	1,10E+02	1,10E+02	1,10E+02	1,10E+02
Ecotoxicity, freshwater-inorganics	CTUe	1,75E+02	1,75E+02	6,17E+01	6,21E+01	6,15E+01	6,19E+01
Ecotoxicity, freshwater-metals	CTUe	6,20E+02	6,23E+02	2,19E+02	2,22E+02	2,18E+02	2,21E+02

IMPACT CATEGORY	UNIT	OPEN TOPS, NOT DYED	Shorter fibers (REVIWOOL®)	Shorter fibers, DYED	CARBONISED REVIWOOL® Shorter fibers	CARBONISED DYED Shorter fibers	SPINNING SOFT WASTE
Climate change	kg CO² eq	8,57E+01	2,95E+01	2,61E+01	2,93E+01	2,64E+01	4,97E+01
Ozone depletion	kg CFC11 eq	1,04E-06	3,57E-07	3,74E-07	4,05E-07	4,19E-07	9,46E-07
Ionising radiation	kBq U-235 eq	4,60E-01	1,58E-01	1,57E-01	1,82E-01	1,82E-01	5,68E-01
Photochemical ozone formation	kg NMVOC eq	7,44E-02	2,56E-02	2,30E-02	2,57E-02	2,36E-02	4,62E-02
Particulate Matter	Desease inc.	1,37E-05	4,73E-06	4,12E-06	4,63E-06	4,12E-06	7,57E-06
Human toxicity, non-cancer	CTUh	6,34E-07	2,18E-07	1,92E-07	2,15E-07	1,93E-07	3,59E-07
Human toxicity, cancer	CTUh	2,10E-08	7,22E-09	8,14E-09	7,44E-09	8,21E-09	1,52E-08
Acidification	mol H+ eq	1,94E+00	6,68E-01	5,81E-01	6,54E-01	5,83E-01	1,07E+00
Eutrophication, freshwater	kg P eq	2,09E-02	7,21E-03	6,31E-03	7,10E-03	6,35E-03	1,20E-02
Eutrophication, marine	kg N eq	3,32E-01	1,14E-01	9,99E-02	1,12E-01	1,00E-01	1,84E-01
Eutrophication, terrestrial	mol N eq	8,56E+00	2,95E+00	2,57E+00	2,89E+00	2,57E+00	4,71E+00
Ecotoxicity, freshwater	CTUe	1,36E+03	4,67E+02	4,12E+02	4,61E+02	4,16E+02	7,71E+02
Land use	Pt	8,95E+03	3,08E+03	2,68E+03	3,02E+03	2,68E+03	4,92E+03
Water use	m3 depriv.	1,55E+01	5,35E+00	4,77E+00	5,32E+00	4,84E+00	8,93E+00
Resource use, fossils	MJ	1,16E+02	3,99E+01	4,13E+01	4,53E+01	4,65E+01	1,06E+02
Resource use, minerals and metals	kg Sb eq	1,54E-04	5,32E-05	4,75E-05	5,28E-05	4,81E-05	8,98E-05
Climate change - Fossil	kg CO² eq	2,57E+01	8,86E+00	8,12E+00	9,06E+00	8,44E+00	1,68E+01
Climate change - Biogenic	kg CO² eq	5,16E+01	1,783+01	1,54E+01	1,74E+01	1,55E+01	2,83E+01
Climate change - Land use and LU change	kg CO² eq	8,36E+00	2,88E+00	2,50E+00	2,82E+00	2,50E+00	4,59E+00
Human toxicity, non-cancer-organics	CTUh	1,39E-07	4,80E-08	4,18E-08	4,70E-08	4,18E-08	7,69E-08
Human toxicity, non-cancer-inorganics	CTUh	1,79E-07	6,15E-08	5,37E-08	6,04E-08	5,39E-08	9,92E-08

IMPACT CATEGORY	UNIT	OPEN TOPS, NOT DYED	Shorter fibers (REVIWOOL®)	Shorter fibers, DYED	CARBONISED REVIWOOL® Shorter fibers	CARBONISED DYED Shorter fibers	SPINNING SOFT WASTE
Human toxicity, non-cancer-metals	CTUh	3,17E-07	1,09E-07	9,68E-08	1,08E-07	9,80E-08	1,84E-07
Human toxicity, cancer-organics	CTUh	1,32E-08	4,54E-09	3,98E-09	4,47E-09	4,00E-09	7,37E-09
Human toxicity, cancer-metals	CTUh	7,78E-09	2,68E-09	4,17E-09	2,97E-09	4,21E-09	7,83E-09
Ecotoxicity, freshwater-organics	CTUe	3,82E+02	1,32E+02	1,15E+02	1,29E+02	1,15E+02	2,10E+02
Ecotoxicity, freshwater-inorganics	CTUe	2,14E+0	7,37E+01	6,50E+01	7,26E+01	6,54E+01	1,20E+02
Ecotoxicity, freshwater-metals	CTUe	7,60E+02	2,62E+02	2,33E+02	2,60E+02	2,36E+02	4,40E+02

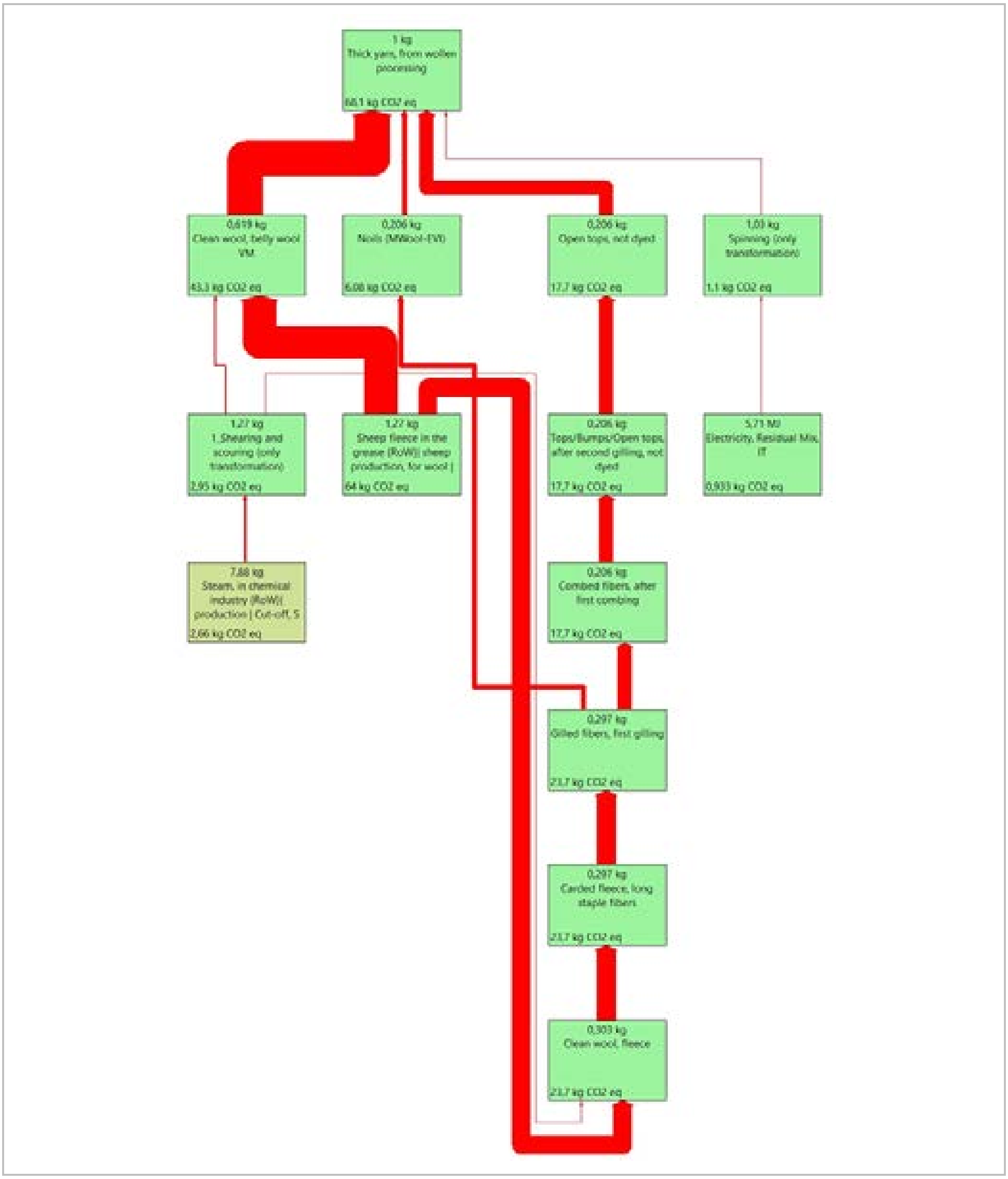
Figure 8 graphically shows the impact on climate change of the different wool fibers generally employed in the woollen processing. As it can be noticed, the fibers having the highest impact are the open tops, the belly wool (with VM or carbonized) and the spinning soft waste. Therefore, these fibers have relatively high economic value if compared with other fibers used in the woollen processing.

Figure 8. Impact on climate change of different fibers from the woollen processing.



Thick yarns are spun with fibers from the woollen processing. **The impact of the yarn depend on its composition. An example is here made for a yarn composed of 60% of belly wool with VM, 20% of Shorter fibers ReviWool® and 20% of not dyed open tops.** Figure 9 graphically shows the impact on climate change of the production of thick yarn, referred to 1 kg. **The total impact results of 68,1 kg CO2 eq/kg and, as expected, a high contribution is given by the belly wool (64%) and open tops fibers (26%), while Shorter fibers account for only 9% of the total impact.**

Figure 9. Impact on climate change of 1 kg of thick yarn, having composition of 60% belly wool with VM, 20% Shorter fibers ReviWool® and 20% not dyed open tops (visualization cut-off of 1%).



As already underlined in the previous report, titled Life Cycle Assessment of MWool® (recycled wool) fibers by Manteco, the impact of the grazing phase has a high uncertainty because of the high variation of flows between farms. The dataset from Ecoinvent database used in this study considers 50 kg CO2/kg of greasy wool. According to a recent review paper (Bhatt and Abbassi, 2021), the range of GHG emission for greasy wool is 20-60 kg CO2 eq./kg. **To have a more complete view, the impact on climate change has been calculated also considering the lowest and highest values of the above-mentioned range (respectively 20 and 60 kg CO2 eq./kg of greasy wool).**

Table 14 lists the impact on climate change for 1 kg of all the intermediate products (both from worsted and woollen processing), calculated using, for greasy wool, (i) the lowest value from literature (20 kg CO2 eq./kg), (ii) the Ecoinvent value (50 kg CO2 eq./kg), (iii) the highest value from literature (60 kg CO2 eq./kg). **As it can be noticed, the impacts of the intermediate products vary sensibly according to the value considered for the greasy wool, but the proportion between them is quite stable.**

Table 14. Impacts on climate change of intermediate products from worsten and woolen processing, calculated considering different impacts of the greasy woo (minimum and maximum values from literature and value from Ecoinvent database).

		Impact on climate change (kg CO_2 eq/kg)		
	Product (1 kg)	Greasy Wool: Literature Min	Greasy Wool: Database	Greasy Wool: Literature Max
Wrosted processing	Clean fleece	18,8	78,2	106,7
	Tops/Bumps	20,8	85,7	116,9
	Combed dyed bumps	22,5	88,3	120,0
	Sliver, not dyed	24,6	90,2	121,8
	Sliver, dyed	26,4	93,1	125,2
	Fine yarn, not dyed	26,5	94,1	126,7
	Fine yarn, dyed	26,5	97,1	130,2
Woollen processing				

8 Conclusions

Life cycle assessment on ReviWool® fibers

8 Conclusions

From the mapping of the wool production chain carried out in this study, it emerges that the wool sector is highly efficient. Therefore, fibers discarded at different stages of the main stream (the so called worsted processing), generally flows into the woollen processing for the production of thicker yarn. Despite literature on environmental analyses of wool production chain is relatively abundant, detailed studies that distinguish between fine and thick yarns (and consequent products) are currently scarcely available.

This study contributes to fill this gap though a Life Cycle Assessment that considers the integration between worsten and woollen processing and their relative intermediate products. In most cases, processes of the production chain are multi-outputs (generally, the longest fibers, destinated to the worsted processing + discarded shorter fibers addressed to the woollen processing). When multi-outputs process occur, it is necessary to find an allocation criteria to distribute the impact of the process among its different outputs. **In literature, when this has been considered, allocation by mass was used, disregarding the fact that shorter fibers are discarded from the worsted processing and, in the textile sector, are considered of lower value than longest fibers. According to the authors of this study the ratio between the prices of the different wool (intermediate) products is indicative of the driver(s) of the processes along the production chain.** In addition, the economic allocation is one recognised way of systematically executing allocation in LCA (Guinée et al., 2004). **This LCA study considers therefore the prices of the wool products to allocate impacts of multi-outputs processes.** This approach enabled the calculation of environmental impacts of the different fibers used both in the worsted and woollen processing.

It results that shorter fibers, used in the woollen processing, generally have lower impacts than longest fibers addressed to the production of fine yarns. Specifically, **most part of short fibers have an impact on climate change ranging from 25 to 30 kg CO2 eq/kg, with exception of spinning soft waste (50 kg CO2 eq/kg) and belly wool fibers (70 kg CO2 eq/kg). Specifically, the product ReviWool® of Manteco results having an impact of 29,5 kg CO2 eq/kg. As a term of comparison, the impact of 1 kg of not dyed sliver (which is the input of fine yarn spinning) is of 85,7 CO2 eq/kg.**

The major contributor to the impacts of wool products is the sheep grazing phase. However, this phase is characterized by the higher uncertainty, due to the high variability among different farms. Since Manteco has no access to data on the grazing phase of its production chain, dataset from Ecoinvent database is used (which consider an impact of greasy wool of 50 kg CO2 eq/kg). **A sensitivity analysis is developed through the re-calculation of impacts on climate change using the lowest and highest values found in literature for the grasy wool (respectively 20 and 60 kg CO2 eq/kg).**
Impacts of the analysed products vary sensibly according to the value considered for the greasy wool. However, the relationship between them is highly stable. **This study can be used as a basis to calculate the impact of yarns with different fibers composition. An example is showed for a yarn composed for the 60% of belly wool fibers, 20 % of ReviWool® Shorter fibers and 20% of open tops. The impact of this specific yarn results of 68,1 kg CO2 eq/kg. It is evident that a yarn composed by a higher percentage of fibers characterized by the lowest impacts will increase its environmental performances.**

References

-Barber, A., Pellow, G., 2006. LCA: New Zealand merino wool total energy use, in: 5th Australian Life Cycle Assessment Society (ALCAS) Conference, Melbourne. pp. 22–24.

-Bech, N.M., Birkved, M., Charnley, F., Laumann Kjaer, L., Pigosso, D.C.A., Hauschild, M.Z., McAloone, T.C., Moreno, M., 2019. Evaluating the Environmental Performance of a Product/Service-System Business Model for Merino Wool Next-to-Skin Garments: The Case of Armadillo Merino®. Sustain. . https://doi.org/10.3390/su11205854

-Bhatt, A., Abbassi, B., 2021. Review of environmental performance of sheep farming using life cycle assessment. J. Clean. Prod. 293, 126192. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.126192

-Brent, A.C., Hietkamp, S., 2003. Comparative evaluation of Life Cycle Impact assessment methods with a South African case study. Int. J. Life Cycle Assess. 8, 27–38. https://doi.org/10.1007/BF02978746

-Confindustria Toscana Nord, 2021. Schema nazionale volontario "Made Green in Italy". Regole di categoria di prodotto (RCP): Tessuti in lana cardata o peli fini cardati. Italy.

-Eady, S., Carre, A., Grant, T., 2012. Life cycle assessment modelling of complex agricultural systems with multiple food and fibre co-products. J. Clean. Prod. 28, 143–149. https://doi.org/https://doi.org/10.1016/j.jclepro.2011.10.005

-EC-JRC, 2012. Product Environmental Footprint (PEF) Guide. Eropean Commision Jt. Res. Cent. 154.
European Commission-Joint Research Center, 2010. ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance, Constraints. https://doi.org/10.2788/38479

-European Commission, 2013. Product Environmental Footprint (PEF) Guide, Recommendation 2013/179/EU of the European Commission of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

-Guinée, J.B., Heijungs, R., Huppes, G., 2004. Economic allocation: examples and derived decision tree. Int. J. life cycle Assess. 9, 23–33.

-Henry, B., 2012. Understanding the environmental impacts of wool: A review of life cycle assessment studies.

-International Wool Textile Organisation (IWTO), 2016. Guidelines for conducting a life cycle assessment of the environmental performance of wool textiles.

-The International Standards Organisation, 2006a. Environmental management — Life cycle assessment — Principles and framework. Iso 14040 2006, 1–28. https://doi.org/10.1136/bmj.332.7550.1107

-The International Standards Organisation, 2006b. Environmental management — Life cycle assessment — Requirements and guidelines. ISO 14044 2006, 652–668. https://doi.org/10.1007/s11367-011-0297-3

-Wiedemann, S., Ledgard, S., Henry, B.K., Yan, M.-J., Mao, N., Russell, S., 2015. Application of life cycle assessment to sheep production systems: Investigating co-production of wool and meat using case studies from major global producers. Int. J. Life Cycle Assess. 20, 463–476. https://doi.org/10.1007/s11367-015-0849-z

-Wiedemann, S., Simmons, A., Watson, K., Biggs, L., 2019. Effect of methodological choice on the estimated impacts of wool production and the significance for LCA-based rating systems. Int. J. Life Cycle Assess. 24. https://doi.org/10.1007/s11367-018-1538-5

-Wiedemann, S.G., Biggs, L., Nebel, B., Bauch, K., Laitala, K., Klepp, I.G., Swan, P.G., Watson, K., 2020. Environmental impacts associated with the production, use, and end-of-life of a woollen garment. Int. J. Life Cycle Assess. 25, 1486–1499. https://doi.org/10.1007/s11367-020-01766-0

Authors of the study

Dr. Giuseppe Picerno
Prof. Gian Andrea Blengini
PhD Isabella Bianco

Organisations involved

MANTECO
MANTELLASSI COMPAGNIA TESSILE

Politecnico di Torino