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ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF APPAREL SUPPLY CHAIN: THE CASE OF AN ITALIAN VIRGIN WOOL COAT

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Abstract

An environmental sustainability assessment study was carried out on the entire life cycle of a 100% virgin wool coat, in the framework of the Horizon 2020 TRICK project. Its main goals were to identify environmental hotspots, evaluate possible improvements and assess the application of the European Product Environmental Footprint method to a luxury garment. A broad data collection was performed in the pilot companies, covering all the main life cycle phases of wool coat, from raw material manufacturing up to the assembly phase. Moreover, four alternative scenarios for the coat production and use were analysed to evaluate possible improvement options and to what extent the life cycle results could be affected by some methodological choices made during the study execution. The results show that the most relevant life cycle stage is the “Raw material acquisition and pre-processing”. The most relevant processes are the production of greasy wool, the use of natural gas during fabric production, the use of electricity for fabric production and during coat assembly. The outcomes of the alternative scenarios highlight that both the use of recycled fibres and the increase in the number of coat uses can significantly decrease the product global environmental impacts. Finally, some difficulties and limitations about the application of the Product Environmental Footprint method to the luxury garment were identified. The overall results of the study could support project companies towards a wider application of circularity approaches and a more efficient and sustainable use of resources of the textile sector.

Key words: apparel, coat, environmental sustainability, life cycle assessment, textile

Received: May, 2025; Revised final: August, 2025; Accepted: September, 2025; Published in final edited form: October, 2025

1. Introduction

The textile sector is one of the most important and strategic parts of “Made in Italy,” both in terms of the number of companies, employees and overall revenue (Gilodi and Misani, 2019). Nevertheless, the production, manufacturing, use and disposal of textile products cause several environmental impacts along their supply chain (Watson and Wiedemann, 2019; Piontek and Muller, 2018).

At the European level, the Strategy on sustainable textile products (EC Communication, 2022), as well as the adoption of the Regulation on eco-design for sustainable products (EU Regulation,

2024) aim to support the production and consumption of sustainable and circular textile and apparel products. In this context, the standardised ISO Life Cycle Assessment (LCA) (ISO 14040, 2020; ISO 14044, 2020) method plays a significant role in the assessment of this kind of products environmental performance, with the aim also to plan improvement options along the supply chain and support consumers in making more informed choices.

ISO LCA has therefore been used in the textile industry in different countries to evaluate the potential negative effects of textile products on the environment (Piontek and Muller, 2018), to compare the environmental performance of recycled and virgin

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fibres and products (Liu et al., 2020; Bianco et al., 2022), to evaluate the improvement potential provided by the use of best practices as well as to compare conventional technology with new ones (Hicks and Theis, 2017; Nieminen et al., 2007; Parisi et al., 2015).

Moreover, in the last years, the European Commission has developed the harmonized Product Environmental Footprint (PEF) method (EC Recommendation, 2021), based on ISO LCA, with the aim to assess and communicate to consumers the environmental performances of products throughout their entire life cycle. In addition to the PEF method, the European Commission is preparing specific methodological guidelines for the category Apparel and Footwear, called Product Environmental Footprint Category Rules (PEFCR), which are expected to be published during 2025. The goal of PEFCRs is to enable companies and consumers to compare life cycle performances of products of the same product category in a transparent and reliable way (Bianco et al., 2023). Being the PEFCR still in development, few studies based, at least in part, on the draft of these guidelines, have been published in the last years on cotton and polyester T-shirts or on woolen undershirt (Bianco et al., 2023; Gonçalves et al., 2024; Horn et al., 2023), but, to the best of authors knowledge, no environmental assessment study based on the PEF method, and applied on luxury textile products, was found in literature.

Within this context, the Horizon 2020 TRICK project (Product data traceability from cradle to cradle by blockchains interoperability and sustainability service marketplace), coordinated by Fratelli Piacenza S.p.A. and in which ENEA was a partner, aimed to develop and test a secure blockchain digital platform for collecting and disseminating data along the textile supply chain, supporting the transition to circular and sustainable production systems. Data collection performed by the TRICK platform can also support companies to calculate the environmental profile of their products and pinpoint improvement options.

During the project environmental sustainability assessment, studies were performed on textile products produced during the project pilot phase by project partners. In particular, an LCA study was carried out on the entire life cycle of a luxury garment, i.e. a 100% virgin wool coat produced by project partners in the pilot phase. In order to assure a reliable, comparable, consistent and transparent assessment of the coat environmental performance, the PEF method (EC Recommendation, 2021) and the draft PEFCR for Apparel and Footwear Version 1.2 (Quantis, 2021), which was the draft valid when this study was conducted, were used as methodological guidelines. The aims of the LCA study were therefore: 1) to identify environmental hotspots for the wool coat supply chain with the use of the PEF method and the draft PEFCR; 2) to support companies in the identification of improvement options, which could be used to develop eco-design strategies in the near future; 3) to evaluate the application of the draft PEFCR to a luxury textile product, identifying to what

extent the main methodological rules and parameters provided by the PEFCR for the different product categories can be representative for the studied product, highlighting also the main critical issues, difficulties and limitations.

For the study, a broad and complete data collection was carried out in the pilot companies, covering all the main life cycle phases of wool coat. Moreover, four alternative potential scenarios for the coat production and use, were analysed, to evaluate both possible improvement options as well as to what extent the life cycle results could be affected by some specific methodological choices. This paper describes the goal and scope of the LCA study; the primary data collection in TRICK companies and the life cycle inventory; the life cycle results obtained; the alternative scenarios and their results, as well as final considerations about the application of the draft PEFCR to the studied product and possible future developments.

2. Materials and methods

2.1. Goal of the study and target audience

The main goal of the study is to measure and evaluate the life cycle environmental performance of a coat made of 100% virgin wool, produced by TRICK partners, with the aims to identify hotspots in the life cycle of the analysed product and support the identification of potential improvement scenarios. Moreover, the study aims to evaluate the application of the draft PEFCR to a luxury product, providing also some specific considerations about difficulties and limitations for this type of production chain.

2.2. Functional unit and reference flow

The functional unit, according to the draft PEFCR, is 1 day of wear (i.e. 1 use) of 1 coat for men, size 50, made of 100% virgin wool, with a standard duration of service of 100 wears; the coat has an intrinsic quality multiplier of 0.67 (i.e. no performance tests were available or were performed for this product), and a reuse rate of 23%, in line with the draft PEFCR. The reference flow is 1/100 of the coat.

2.3. System boundaries

The entire life cycle (from cradle to grave) of the coat, including the raw material acquisition and pre-processing, manufacturing, distribution, use and end of life were included in the system boundaries (Fig. 1).

2.4. Impact categories and impact assessment methods

The default Environmental Footprint impact category indicators were used, by applying the Environmental Footprint 3.1 impact assessment method, in line with the prescriptions of the PEF method.

2.5. Data quality requirements

Company-specific primary data were collected for each of the following life cycle phases:

- Wool fibre production (LCS1);
- Yarn production (LCS2);
- Fabric production (LCS2);
- Assembly (LCS2).

Collected data refer to 2022 for fabric production and 2017 for wool fibre production; the latter data were the most recent available from the company and, as explained by the company, refer to a well-known and consolidated technology which was therefore still valid during the execution of the LCA study. The other companies provided the most recent and available data about their production processes.

Default data from the draft PEFCR for Apparel and Footwear were used for distribution (LCS3), use (LCS4) and end of life (LCS5) phases, because primary data were not available for those phases.

Ecoinvent 3.9.1 database (Wernet et al., 2016) was used as source of all background data, selecting the most proper datasets for the modelling phase, according to their technological, time and geographical representativeness.

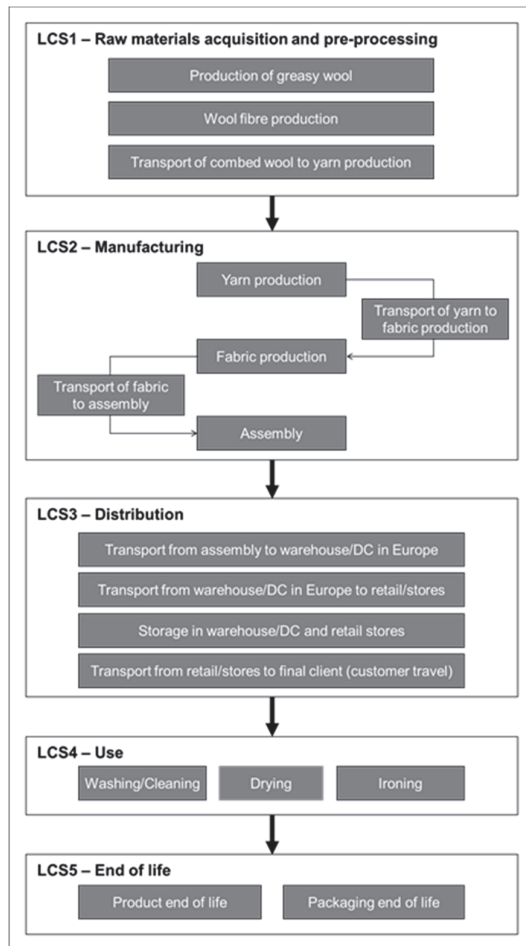


Fig. 1. System boundaries diagram of coat life cycle

2.6. Inventory and data collection

In the following paragraphs, a summary of life cycle data will be presented for each phase; Table 1 shows the inventory data used for the study, referred to the functional unit.

2.6.1. LCS1 – Raw materials acquisition and pre-processing. Wool fibre production

The life cycle of fibre production is divided in 5 sub-phases: scouring, carding, gilling, combing and warehousing. Activity data collected at company level comprises the followings:

- Greasy wool from sheep farms;
- Consumption of auxiliary materials (detergent, sodium carbonate, peroxide, ensimage oil, anti-static);
- Energy consumption (electricity, natural gas, diesel);
- Water and steam consumption;
- Wastewater production;
- Combed wool;
- Packaging for the combed wool;
- Transport of combed wool to yarn producer;
- Waste production;
- Co-products (lanoline, scoured wool for sale, burrs, blouse).

The greasy wool in input to the scouring sub-phase was calculated by subtracting the amount of dirt and soil (considered as a waste) to the total quantity of greasy wool entering the scouring phase.

Allocation of the environmental impacts at each sub-phase related to combed wool was performed by applying mass allocation, considering the total mass of scoured wool, carded wool, gilled wool, combed wool and the total mass of the co-products of each sub-phase. Since the sheep breeding phase and the subsequent greasy wool production were not included in the primary data collection, due to the absence of sheep breeders and greasy wool producers in TRICK partnership, an Ecoinvent dataset was used for the modelling (Table 1).

The Argentinian high voltage electricity mix from grid was used in the study, as declared by the company producing combed wool. Since the company did not specify the composition of both the ensimage oil, which is a lubricant, and the anti-static, a proxy dataset available in Ecoinvent, i.e. lubricant oil, was used for their production. This dataset was selected on the basis of its technological, time and geographical representativeness; moreover, other public national guidelines were investigated and followed to evaluate the better choice for the modelling of these products (Confindustria Toscana Nord, 2021; Sistema Moda Italia, 2018).

For the transport of combed wool to yarn production, primary data were used, considering that the combed wool is transported from Argentina to Germany with a ship. Moreover, the transport distance (by truck) from Germany to Italy was considered.

2.6.2. LCS2 – Manufacturing

2.6.2.1 Yarn production

Activity data collected at company level comprises the followings:

- Combed wool from fibre producer;
- Electricity consumption;
- Water consumption;
- Wastewater production;
- Wool yarn;
- Packaging for the wool yarn;
- Waste production (textile powder);
- Co-product (mixed fibre).

The quantity of combed wool used by the yarn producer was calculated considering the weight of yarn, mixed fibre and powder produced by the process. Allocation of the environmental impacts related to wool yarn was performed by applying mass allocation, considering the mass of yarn and the mass of the co-product (mixed fibre). The yarn yield during spinning was equal to 95%. It was considered, according to primary data provided by the company, that 51.4% of total electricity consumption comes from photovoltaic panels, whereas the remaining 48.6% comes from medium voltage Italian electricity mix.

The waste powder was assumed to be incinerated; finally, the transport of packed yarn (by truck) to fabric producer was taken into account.

2.6.2.2 Fabric production

Activity data collected at company level comprise the following inputs and outputs:

- Wool yarn from yarn producer;
- Energy consumption (electricity from grid, cogeneration plant and photovoltaic panels; natural gas);
- Water consumption from river and from wells;
- Wastewater production;
- Dyes and dyeing auxiliaries (acetic acid, sodium sulfate, ammonium sulfate, anti-felting and air-reducer products);
- Fabric production;
- Packaging for the fabric;
- Waste production (packaging materials, sludge, textile waste);
- Co-product (other types of fabrics produced by the company).

Allocation of the environmental impacts related to wool fabric used for the production of the coat was performed by applying mass allocation, considering the mass of fabric used for the coat production and the mass of all fabrics produced by the company. The yield of weaving was considered equal to 97% and that for dyeing and finishing operations to 85%, as provided by the company.

Due to the lack of specific Ecoinvent datasets to model dyes and dyeing auxiliaries, a proxy dataset was used for the production of all these products, representing the production of organic chemicals (Table 1). It should be noticed that this dataset was chosen on the basis of its technological, time and geographical representativeness as well as on similar

choices made in other public national guidelines for the modelling of dyes and dyeing auxiliaries (Confindustria Toscana Nord, 2021; Sistema Moda Italia, 2018). The different types of electricity used by the company were included in the study, i.e. Italian medium voltage electricity mix, electricity from a cogeneration plant fed with natural gas, electricity from photovoltaic panels.

Specific waste treatments were included for each waste stream, according to the data provided by the company. Finally, the transport of packed fabric to the assembly company was considered to be by truck.

2.6.2.3. Assembly

The final weight of the coat (1,700 g) was considered, together with the amount of fabric needed to obtain 1 coat and the bill of materials of any other textile and non-textile component (e.g. buttons, lining, pockets, shoulder pads, brand tag). For each of these components, the related material and weight were considered, on the basis of primary data. Moreover, the final packaging of the coat was considered (i.e. nylon bag, paper tag, polystyrene hanger). The amount of fabric waste during assembly was calculated by subtracting the total weight of the components to the weight of the fabric in input (i.e. the fabric needed to obtain 1 coat); the fabric waste was assumed to be incinerated, similarly to the fabric waste obtained during fabric production.

Finally, photovoltaic electricity was used for the coat assembly phase (primary data from the company).

2.6.3. LCS3 – Distribution

Default data provided by the draft PEFCR were used for the distribution phase since primary data were not available from the project companies, considering the retail/in-store scenario, which goes from the factory to the final client. For the transport of the coat, the total weight of the product (coat, accessories, such as brand tag, shoulder pads, and packaging) was considered. The impacts from consumer travel (allocation of the car impact) and during storage were based on the volume, in line with the draft PEFCR.

Moreover, the default storage capacity and energy consumption for warehouse/distribution centre and retail/stores provided by the draft PEFCR were used. Finally, distribution losses of 1% and product returns of 10% were included in the study, in line with the draft PEFCR.

2.6.4. LCS4 – Use

In accordance with the draft PEFCR for Apparel and Footwear, the use stage for apparel considers impacts related to washing and cleaning, drying, ironing and steaming. Due to the lack of primary data about the type and frequency of washing, the type of drying and ironing, default data from the draft PEFCR were used.

The washing frequency was set to 20 uses (=20 days of wear) prior to washing, in line with the draft PEFCR.

2.6.5. LCS5 - End of life

In accordance with the draft PEFCR for Apparel and Footwear, the end of life of textile components (wool, cotton and cupro fabrics, as well as cotton ribbons) was considered, using the general post-consumer scenario rates provided by the draft PEFCR, since primary data were not available within the project.

To model the end of life of other components of the coat and its packaging, directions from Annex C of the PEF method were followed (Zampori and Pant, 2019), creating dedicated scenarios based on the Circular Footprint Formula (CFF). The values for each parameter of the CFF were based on the default application-specific and material-specific values of the PEF method (Zampori and Pant, 2019).

Table 1. Inventory Table for LCS1, LCS2, LCS3 and LCS4

<i>Process</i>	<i>Dataset</i>	<i>Amount</i>	<i>UoM</i>
Greasy wool	Sheep fleece in the grease {GLO} market for sheep fleece in the grease Cut-off, U	3.51E-02	kg
Detergent	Soap {GLO} market for soap Cut-off, U	7.60E-04	kg
Sodium carbonate	Sodium bicarbonate {RoW} market for sodium bicarbonate Cut-off, U	2.01E-04	kg
Peroxide	Hydrogen peroxide, without water, in 50% solution state {RoW} market for hydrogen peroxide, without water, in 50% solution state Cut-off, U	2.24E-04	kg
Ensimage and antistatic	Lubricating oil {RoW} market for lubricating oil Cut-off, U	2.45E-04	kg
Sodium sulfate	Sodium sulfate, anhydrite {RER} market for sodium sulfate, anhydrite Cut-off, U	2.83E-03	kg
Ammonium sulfate	Ammonium sulfate {RER} market for ammonium sulfate Cut-off, U	1.12E-03	kg
Acetic acid	Acetic acid, without water, in 98% solution state {GLO} market for acetic acid, without water, in 98% solution state Cut-off, U	5.62E-04	kg
Dyes and dyeing auxiliaries	Chemical, organic {GLO} market for chemical, organic Cut-off, U	3.45E-03	kg
Lining	Fibre, viscose {GLO} market for fibre, viscose Cut-off, U	1.33E-03	kg
Pockets	Textile, woven cotton {GLO} market for textile, woven cotton Cut-off, U	6.92E-04	kg
Label	Packaging film, low density polyethylene {GLO} market for packaging film, low density polyethylene Cut-off, U	8.05E-04	kg
Reinforcing tape	Textile, nonwoven polyester {GLO} market for textile, nonwoven polyester Cut-off, U	1.66E-04	kg
Shoulder pads	Polyurethane, flexible foam {RER} market for polyurethane, flexible foam Cut-off, U	2.23E-04	kg
Counter buttons	Polyethylene terephthalate, granulate, amorphous {Europe without Switzerland} polyethylene terephthalate, granulate, amorphous, recycled to generic market for amorphous PET granulate Cut-off, U	4.85E-06	kg
Ribbons	Textile, woven cotton {GLO} market for textile, woven cotton Cut-off, U	4.77E-04	kg
Size label, brand label, bag	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	6.93E-04	kg
Hanger	Polystyrene, general purpose {GLO} market for polystyrene, general purpose Cut-off, U	1.14E-03	kg
Tag	Solid bleached and unbleached board carton {RER} market for solid bleached and unbleached board carton Cut-off, U	4.13E-05	kg
Buttons	Polyethylene terephthalate, granulate, amorphous {Europe without Switzerland} polyethylene terephthalate, granulate, amorphous, recycled to generic market for amorphous PET granulate Cut-off, U	4.54E-04	kg
Electricity - Medium voltage from grid	Electricity, medium voltage {IT} market for electricity, medium voltage Cut-off, U	9.93E-02	kWh
Electricity - High voltage from grid	Electricity, high voltage {AR} market for electricity, high voltage Cut-off, U	4.71E-02	kWh
Electricity - Photovoltaic	Electricity, low voltage {IT} electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted Cut-off, U	9.33E+01	kWh
Electricity - Co-generation	Electricity, low voltage {Europe without Switzerland} heat and power co-generation, natural gas, 160kW electrical, lambda=1 Cut-off, U	1.14E-01	kWh
Natural gas	Heat, district or industrial, natural gas {Europe without Switzerland} heat production, natural gas, at industrial furnace >100kW Cut-off, U	1.05E+00	MJ
Natural gas - Wool treatment	Heat, district or industrial, natural gas {RoW} heat production, natural gas, at boiler modulating >100kW Cut-off, U	3.66E-01	MJ
Diesel	Diesel, burned in building machine {GLO} market for diesel, burned in building machine Cut-off, U	4.45E-03	MJ
Steam	Steam, in chemical industry {RoW} market for steam, in chemical industry Cut-off, U	1.41E-04	t
Water - From well	Water, well, IT	3.19E-03	m ³
Water - From river	Water, river, IT	5.12E-03	m ³

Packaging - Plastic film	Packaging film, low density polyethylene {GLO} market for packaging film, low density polyethylene Cut-off, U	6.22E-04	kg
Packaging - Plastic straps	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U	1.04E-05	kg
Packaging - Wood pallet	EUR-flat pallet {RER} market for EUR-flat pallet Cut-off, U	8.94E-05	p
Packaging - Paper	Corrugated board box {RER} market for corrugated board box Cut-off, U	2.62E-04	kg
Packaging - Plastic cones	Polypropylene, granulate {GLO} market for polypropylene, granulate Cut-off, U	9.90E-04	kg
Packaging - Metal clips	Aluminium alloy, AlMg3 {GLO} market for aluminium alloy, AlMg3 Cut-off, U	8.32E-06	kg
Packaging - Cardboard tubes	Core board {GLO} market for core board Cut-off, U	6.24E-03	kg
Transport - By container ship	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, U	6.74E+02	kgkm
Transport - By lorry >32 metric ton	Transport, freight, lorry >32 metric ton, EURO4 {RER} market for transport, freight, lorry >32 metric ton, EURO4 Cut-off, U	8.12E+01	kgkm
Transport - By lorry 16-32 metric ton	Transport, freight, lorry 16-32 metric ton, EURO4 {RER} market for transport, freight, lorry 16-32 metric ton, EURO4 Cut-off, U	2.45E+00	kgkm
Transport - By barge	Transport, freight, inland waterways, barge {RER} market for transport, freight, inland waterways, barge Cut-off, U	5.39E-01	kgkm
Transport - By train	Transport, freight train {Europe without Switzerland} market for transport, freight train Cut-off, U	1.25E+01	kgkm
Transport - By cargo plane	Transport, freight, aircraft, long haul {GLO} market for transport, freight, aircraft, long haul Cut-off, U	2.27E+01	kgkm
Transport - By car	Transport, passenger car {RER} market for transport, passenger car Cut-off, U	2.67E-03	km
Transport - By van	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER} market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 Cut-off, U	6.67E-03	kgkm
Washing, drying and ironing	Washing, drying and finishing laundry {GLO} market for washing, drying and finishing laundry Cut-off, U	1.03E-01	kg
Waste treatment - Textile	Waste textile, soiled {GLO} treatment of waste textile, soiled, municipal incineration Cut-off, U	1.19E-02	kg
Waste treatment - Paper and cardboard	Waste paper, sorted {GLO} market for waste paper, sorted Cut-off, U	1.04E-03	kg
Waste treatment - Wood	Wood chipping, industrial residual wood, stationary electric chipper {GLO} market for wood chipping, industrial residual wood, stationary electric chipper Cut-off, U	2.91E-04	kg
Waste treatment - Mixed material	Municipal solid waste {IT} treatment of municipal solid waste, municipal incineration Cut-off, U	1.29E-03	kg
Wastewater treatment	Wastewater, average {Europe without Switzerland} treatment of wastewater, average, wastewater treatment Cut-off, U	7.54E-03	m ³
End of life treatment - Fabric	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	2.65E-02	kg
End of life treatment - Plastic components	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	1.21E-03	kg
End of life treatment - Buttons	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	4.17E-04	kg
End of life treatment - PS packaging	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	1.14E-03	kg
End of life treatment - PA (Nylon) packaging	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	6.80E-04	kg
End of life treatment - Paper packaging	For this waste treatment, dedicated scenario was developed on the basis of CFF parameters and Ecoinvent datasets	4.13E-05	kg

3. Results and discussion

3.1. Characterization, normalization and weighting results

Results of the characterization, normalization and weighting phases are presented from Tables 2 - 4 in relation to the functional unit, i.e. one use of the wool coat.

3.2. Most relevant impact categories, life cycle stages, processes and elementary flows

Table 5 and Table 6) present, according to the specific rules of the PEF method:

- the most relevant impact categories (Table 5);
- the most relevant life cycle stages (Table 5);
- the most relevant processes (Table 6);
- the most relevant elementary flows (Table 6).

Moreover, a detailed interpretation of the results is presented in the next paragraphs. The results show that the most significant impact categories (i.e. those cumulatively contributing at least 80% of the total impact of the coat) of 1 day of wear of the coat are *Climate change*; *Acidification*; *Particulate matter*; *Eutrophication, terrestrial*; *Land use*; *Resource use, fossils* and *Eutrophication, marine* (Fig. 2). The most relevant life cycle stage is the “Raw material acquisition and pre-processing”, contributing to 77%-99% of the impact in many of the most relevant impact categories, with the exception of Resource use, fossils, where the “Manufacturing” phase (i.e. spinning, weaving and assembly) contributes to 55% of the total impact (Table 5).

The most relevant processes are the production of greasy wool (Fig. 3), which includes also sheep breeding, whose contribution varies from 19% in Resource use, fossils to 99% in Land use; the use of natural gas burned in boilers and stenters during fabric production, which accounts for 16% in Resource use, fossils and 5% in Climate Change; the use of electricity produced with co-generation for fabric production, which contributes to 12% of the Resource

use, fossils impact; the use of electricity during coat assembly, which accounts for 11% in Resource use, fossils (Table 6). Other types of energy consumption, i.e. steam used during wool fibre production, electricity from grid used at spinning, natural gas burned for both wool fibre production and coat washing, drying and ironing, provide a contribution ranging from 3% to 8% in Resource use, fossils (Table 6). For Climate change, the main elementary flows are methane and dinitrogen monoxide airborne emissions during the production of greasy wool and airborne carbon dioxide emissions due to the use of electricity and natural gas (Table 6).

For Acidification, Particulate matter and Eutrophication terrestrial, ammonia airborne emissions, due to the production of greasy wool, is the main elementary flow (95%-97% of the total impact for each category) (Table 6). The occupation of land for greasy wool production is the main elementary flow for Land use (86%); the consumption of natural gas, hard coal and crude oil for the production of electricity and heat used during wool fibre production, weaving, spinning and assembly are the most relevant elementary flows in Resource use, fossils (Table 6).

Table 2. Results of the characterization phase in relation to 1 use of the wool coat

<i>Impact category</i>	<i>Unit</i>	<i>Total</i>
Acidification	mol H ⁺ eq	3.61E-02
Climate change	kg CO ₂ eq	1.79E+00
Ecotoxicity, freshwater	CTUe	2.62E+01
Particulate matter	disease incidence	2.59E-07
Eutrophication, marine	kg N eq	6.66E-03
Eutrophication, freshwater	kg P eq	4.64E-04
Eutrophication, terrestrial	mol N eq	1.56E-01
Human toxicity, cancer	CTUh	2.97E-09
Human toxicity, non-cancer	CTUh	1.02E-08
Ionising radiation	kBq U-235 eq	2.66E-02
Land use	Pt	1.63E+02
Ozone depletion	kg CFC-11 eq	2.17E-08
Photochemical ozone formation	kg NMVOC eq	3.10E-03
Resource use, fossils	MJ	8.93E+00
Resource use, minerals and metals	kg Sb eq	7.94E-06
Water use	m ³ depriv.	1.07E+00

Table 3. Results of the normalization phase in relation to 1 use of the wool coat

<i>Impact category</i>	<i>Total</i>
Acidification	6.50E-04
Climate change	2.37E-04
Ecotoxicity, freshwater	4.62E-04
Particulate matter	4.36E-04
Eutrophication, marine	3.41E-04
Eutrophication, freshwater	2.89E-04
Eutrophication, terrestrial	8.81E-04
Human toxicity, cancer	1.72E-04
Human toxicity, non-cancer	7.93E-05
Ionising radiation	6.31E-06
Land use	1.99E-04
Ozone depletion	4.15E-07
Photochemical ozone formation	7.58E-05
Resource use, fossils	1.37E-04
Resource use, minerals and metals	1.25E-04
Water use	9.29E-05

Table 4. Results of the weighting phase in relation to 1 use of the wool coat

<i>Impact category</i>	<i>Unit</i>	<i>Total</i>
Total	μPt	2.43E+02
Acidification	μPt	4.03E+01
Climate change	μPt	5.00E+01
Ecotoxicity, freshwater	μPt	8.88E+00
Particulate matter	μPt	3.90E+01
Eutrophication, marine	μPt	1.01E+01
Eutrophication, freshwater	μPt	8.09E+00
Eutrophication, terrestrial	μPt	3.27E+01
Human toxicity, cancer	μPt	3.66E+00
Human toxicity, non-cancer	μPt	1.46E+00
Ionising radiation	μPt	3.16E-01
Land use	μPt	1.58E+01
Ozone depletion	μPt	2.62E-02
Photochemical ozone formation	μPt	3.62E+00
Resource use, fossils	μPt	1.14E+01
Resource use, minerals and metals	μPt	9.42E+00

Table 5. Most relevant impact categories and Life Cycle Stages

<i>Most relevant impact category</i>	<i>[%]</i>	<i>Most relevant life cycle stages</i>	<i>[%]</i>
Climate change	21	LCS1 – Raw materials acquisition and pre-processing	77
		LCS2 – Manufacturing	19
Acidification	17	LCS1 – Raw materials acquisition and pre-processing	96
Particulate matter	16	LCS1 – Raw materials acquisition and pre-processing	95
Eutrophication, terrestrial	13	LCS1 – Raw materials acquisition and pre-processing	97
Land use	7	LCS1 – Raw materials acquisition and pre-processing	99
Resource use, fossils	5	LCS2 – Manufacturing	55
		LCS1 – Raw materials acquisition and pre-processing	36
Eutrophication, marine	4	LCS1 – Raw materials acquisition and pre-processing	89

Table 6. Most relevant processes and elementary flows

<i>Most relevant impact category</i>	<i>[%]</i>	<i>Most relevant processes</i>	<i>[%]</i>	<i>Most relevant elementary flows</i>	<i>[%]</i>
Climate change	21	Greasy wool production, including sheep breeding	71	Methane in air	57
				Dinitrogen monoxide in air	21
				Carbon dioxide (land transformation) in air	11
		Natural gas burned in boilers and stenters at fabric production	5	Carbon dioxide (fossil) in air	89
		Electricity used during fabric production and assembly	4	Carbon dioxide (fossil) in air	86
Acidification	17	Greasy wool production, including sheep breeding	95	Ammonia in air	97
Particulate matter	16	Greasy wool production, including sheep breeding	94	Ammonia in air	95
Eutrophication, terrestrial	13	Greasy wool production, including sheep breeding	97	Ammonia in air	98
Land use	7	Greasy wool production, including sheep breeding	99	Occupation pasture, man made	86
Resource use, fossils	5	Greasy wool production, including sheep breeding	19	Crude oil	40
				Natural gas	29
				Hard coal	25
		Natural gas burned in boilers and stenters at fabric production	16	Natural gas	97
		Electricity produced with co-generation used for fabric production	12	Natural gas	97
		Electricity used at assembly	11	Hard coal	37
				Natural gas	28
				Crude oil	18
		Steam used at wool fibre production	8	Natural gas	49
				Crude oil	30
				Hard coal	19
		Electricity from grid used at yarn production	7	Natural gas	66
Eutrophication, marine	4	Greasy wool production, including sheep breeding	87	Uranium	14
				Natural gas	97
				Natural gas	97
				Nitrate in water	77
				Ammonia in air	17

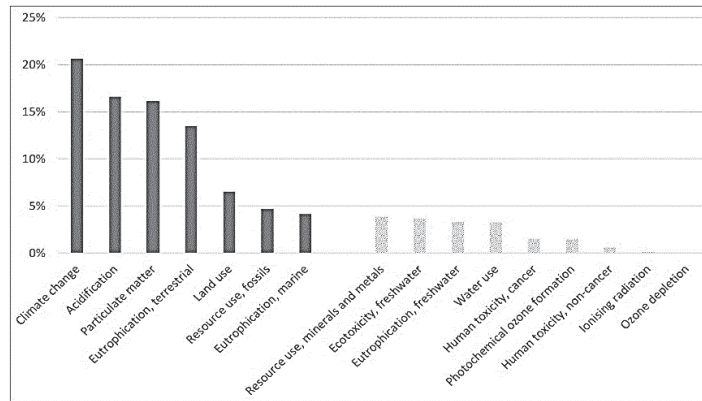


Fig. 2. Most relevant impact categories (weighted results) of 1 use of the wool coat

Finally, the nitrate waterborne emissions during greasy wool production are the main elementary flow in Eutrophication, marine (77% of the total impact of this category) (Table 6).

3.3. Alternative scenarios

Some alternative scenarios for the wool coat life cycle were analyzed, to verify possible improvement actions for the environmental performance of the product life cycle as well as test the effect of some default data provided by the draft PEFCR on the study results.

More in detail, the following scenarios were considered:

1. Scenario 1 (20% recycled wool – short distance): a coat made of 20% recycled wool and 80% virgin wool, considering a transport distance of 100 km via truck for the transport of the coat at the end of its life to the recycling facility;

2. Scenario 2 (20% recycled wool – long distance): a coat made of 20% recycled wool and 80% virgin wool, considering reverse logistics for the transport of the coat at the end of its life to the recycling facility. In this case, the reverse logistics was modelled with the same distances and means of transport used in the “Distribution” phase;

3. Scenario 3 (More renewable electricity): a

coat made of 100% virgin wool, considering that all electricity from grid originally used at factory level, i.e. during wool fibre production, yarn production, fabric production and assembly, is replaced with electricity from photovoltaic panels;

4. Scenario 4 (Higher number of uses): a coat made of 100% virgin wool, considering that its overall lifetime is 1,000 uses.

The comparison between the environmental impacts of the Baseline Scenario and those of the alternative scenarios are shown in Fig. 4, considering the weighted life cycle values. While the use of renewable energy for the coat production at factory level (Scenario 3) provides a minor improvement to the environmental performance (-1%, considering weighted results; it should be considered that most of the TRICK companies already used electricity from renewable energy systems in their production processes and therefore this improvement is rather low), the use of 20% recycled wool fibres in addition to 80% virgin fibres reduces the weighted impacts by 16% in both Scenarios 1 and 2.

Finally, the increase in the number of uses of the coat during its lifetime (Scenario 4) has a significant effect on the reduction of the total environmental impact (-89%), because it affects the quantity of wool statistically used for each wear of the coat.

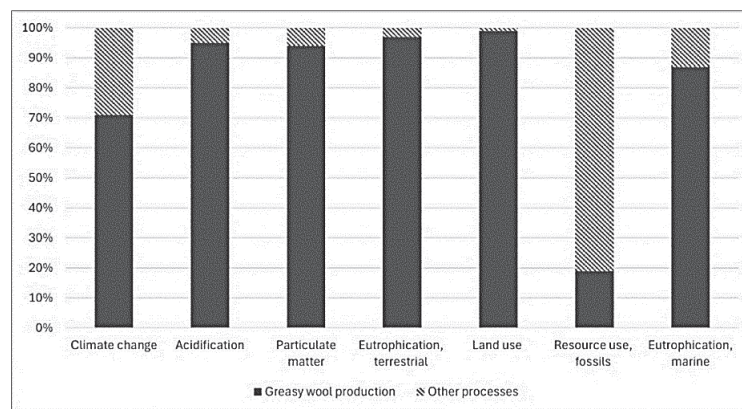


Fig. 3. Results of the most relevant processes: contribution of greasy wool production in the most relevant impact categories

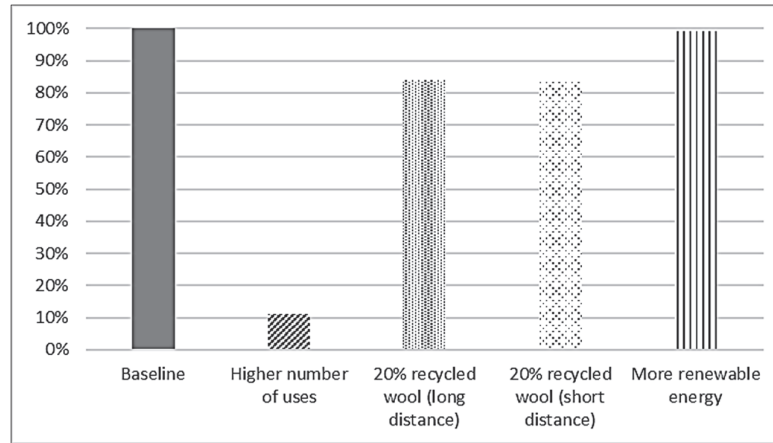


Fig. 4. Results of the alternative scenarios

4. Conclusions

This LCA study was performed on the entire supply chain of the TRICK wool coat, involving all pilot companies of the project in an extensive primary data collection. The study was carried out following the methodological rules of both the PEF method and the draft PEFCR for apparel and footwear, in order to guarantee transparency, reproducibility and comparability. The results highlighted the main hotspots and possible improvements, which are detailed here below.

Considering improvement at the life cycle phase level and the main hotspots for the wool coat, since the most relevant process in the “Raw material acquisition and pre-processing” is the production of greasy wool, TRICK companies should collect primary data also for the sheep breeding phase, to further improve the robustness of the study results and their representativeness of the actual situation as well as to better guide the identification of improvement potentials and measure their effectiveness. Considering the whole life cycle of the coat, the substitution of part of the virgin fibres with recycled ones (alternative Scenarios 1 and 2) lowers the global environmental impact of the product. The benefits are evident also when a complex system is used by producers to directly collect used coats (Scenario 2); in this case, the quality of the recycled material is improved, affecting the quantity of virgin fibre to be produced, which is the main hotspot for most impact categories. The limit of this option is related to the maximum share of coat’s recycled content which is acceptable from a technological and commercial point of view: this point should be studied in detail by companies to obtain a recycled garment with both the best environmental performance and the best technical characteristics. Moreover, the actual number of wears of coats produced with a quota of recycled fibres should be carefully investigated, since it could be quite different from the number of wears of coats made only by virgin fibres. As shown by the alternative Scenario 4, the increase in the number of coat uses leads to a

remarkable decrease in the total environmental impact, because it indirectly affects the quantity of wool statistically used for each wear of the coat. In this context, companies could adopt some design options to reduce the overall impact of the product by the extension of its lifetime, for example they could offer maintenance and repair services or develop a tailoring service to adapt the product (e.g. size adjustments) to specific customer needs or fashion evolution.

As regards the applicability of the draft PEFCR for apparel and footwear to the luxury coat, some critical issues and limitations have been identified.

Firstly, data collection for the study was rather difficult and time-consuming, especially for companies which do not have any experience with LCA. During the coat study, difficulties were found while collecting some primary data, especially when a specific production phase was carried out by an external supplier, and to the calculation of yields, waste and scraps, mainly when the company did not have an accounting system for the collection of this type of data.

Moreover, the draft PEFCR contains unrealistic default parameters which do not reflect the peculiarities of the specific luxury coat, e.g. number of total uses during the lifetime of the garment (100 uses during its lifetime), washing frequency (20 uses prior to washing), type of washing (hand washing and washing machine, in addition to dry cleaning), size of the product (size 50 for men coat, which is quite small; moreover it was not clear if the draft PEFCR refers to European sizes or to other types of sizes).

Finally, the representative product for the coat and jacket category described in the draft PEFCR is not very representative for the luxury coat, because it includes, in addition to overcoats, several types of jackets for different uses. Furthermore, its weight is 950 g (almost half the weight of the TRICK coat) and it is made of different types of materials, such as polyester and other synthetics (35%), polyamide (15%), cotton (15%), acrylic (11%), wool (9%). The wool quantity in the representative product is therefore very low if compared to the TRICK coat, made of

100% wool. It is therefore clear that, since the characteristics of the two products are quite different, life cycle results of the TRICK coat and the representative product can be rather different.

All these considerations can be useful to policy makers, European Commission and industries which participate to the development of the final PEFCR, in order to better improve the guideline and to consider also other types of markets and products (i.e. luxury one) in the PEFCR.

Despite the highlighted difficulties and limitations, the present work can support companies of the TRICK partnership to evaluate potential eco-design strategies to be applied in the near future, towards a wider application of circularity approaches and a more efficient and sustainable use of resources in the textile sector. When the final PEFCR will be published, hopefully taking into account also the peculiarities of luxury markets, TRICK companies could apply them with the final goal to communicate reliable environmental information of their garment and therefore contribute to improve the competitiveness and innovation for the entire supply chain.

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