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Life Cycle Assessment (LCA) of Worsted and Woollen processing in wool production: ReviWool® noils and other wool co-products

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ABSTRACT

The textile and fashion industry is becoming increasingly active in measuring its environmental performance. As far as wool is concerned, there is quite abundant literature on environmental impacts available. However, previous studies very rarely distinguish between the different co-products of the wool transformation, and often attribute the same impact to fibers produced from worsted processing (longer and more expensive fibers) and woollen processing (shorter and cheaper fibers). This study firstly provides a detailed mapping of processes and products involved in the wool production chain, from sheep grazing to yarn production, with particular attention to the shorter fibers, which have been mostly neglected in previous literature. Secondly, this study uses the Life Cycle Assessment (LCA) methodology to analyze the environmental impacts of the different intermediate co-products. In particular, when multi-output processes occur, impacts are distributed proportionally to their relative economic value, using therefore an *economic allocation*. This approach enabled the calculation of environmental impacts of fibers used both in the worsted and woollen processing. It results that shorter fibers generally have lower impacts than longer fibers used for the production of fine yarns. Specifically, most short fibers have an impact on climate change ranging from 25 to 30 kg CO_2 eq/kg, while, longer fibers have an impact of 78–97 kg CO_2 eq/kg. The physiological variation in the ratio between worsted and woolen co-products of multi-output processes appears to have little effect on the final impact results. Finally, since the grazing phase is highly variable, impacts on climate change of the analyzed intermediate products have been re-calculated using, for the greasy wool, the lowest and highest values of impact found in literature. Impacts of the analyzed products vary sensibly according to the value considered for the greasy wool, but the relationship between them is rather stable.

This paper contributes with detailed information and easily replicable data which could be used as a basis for the environmental assessment of wool garments and for improving the sustainability in the wool sector.

1. Introduction

Clothing is estimated to account for between 2% and 10% of the environmental impact of EU consumption (European Parliament, 2019). The life cycle of textiles has significant impacts on the environment: it is estimated that this sector is the fourth highest-pressure for the use of primary raw materials (after food, housing and transport), and fifth for greenhouse gas (GHG) emissions (ETC/WMGE, 2019). Recent studies demonstrate that the production and use phases are responsible for the greatest share of impacts (Amicarelli et al., 2022; Şener Fidan et al., 2023). In the production phase, the main impacts are connected to the cultivation and production of natural and man-made fibers. Therefore, this phase can require high amounts of water, energy and chemicals, including fertilizers and pesticides (ETC/CE, 2022; ETC/WMGE, 2021). During the use phase (washing, drying and ironing), electricity, water and detergents are used, with consequent problems connected to wastewater treatment. At the end-of-life, different scenarios are possible, such as the reuse, recycling or incineration, each one associated to different impacts (Amicarelli and Bux, 2022). In this framework, a strategy to enhance the environmental performances of the textile sector plays a key role. The European Commission recently published the EU Strategy for Sustainable and Circular Textiles (European Commission, 2022), which mainly focuses on concrete actions encouraging the production of long-lived and recyclable products. Concurrently, an

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increased interest in the circular economy in both industry and policy, led to the search of solutions able to increase the sustainability of the textile sector. Recent literature studies are available on more sustainable practices for the production of fibers and textile products (de Oliveira et al., 2021; Gomez-Campos et al., 2021; Nguyen et al., 2021; Tourangeau and Sherren, 2020). Other studies focuses on technologies for recycling, reusing or repurposing textiles to reduce the environmental impacts (Juanga-Labayen et al., 2022; Keßler et al., 2021; Martin and Herlaar, 2021; Ribul et al., 2021; Xie et al., 2021).

The potential impacts of fibers and textiles are in most cases calculated following the international and standardized methodology of Life Cycle Assessment (LCA) (The International Standards Organisation, 2020a, 2020b). LCA studies have been developed on fibers and textile products of virgin, recycled and organic cotton (Chen et al., 2021; Fidan et al., 2021; La Rosa and Grammatikos, 2019; Liu et al., 2020; Şener Fidan et al., 2023). Among the natural fibers, the wool has been object of different environmental assessments, focusing on the grazing phase (Bhatt and Abbassi, 2021; Biswas et al., 2010; Brock et al., 2013; Cottle and Cowie, 2016; Gowane et al., 2017; Henry et al., 2015a; Wiedemann et al., 2016), the textile production or the entire life cycle of woolen garments (Henry et al., 2015b; Wiedemann et al., 2020). Also synthetic or semi-synthetic materials used in the textile and clothing chain (such as polyester, nylon, acryl, elastane, viscose) have been analyzed by different authors (Guo et al., 2021; Phan et al., 2023; van der Velden et al., 2014; Yacout et al., 2016).

This study specifically focuses on wool fibers. Globally, 1950 million kg (IWTO, 2022) of greasy wool was produced in 2021, representing a limited share in the global supply of textile fibers. Nevertheless, thanks to the physical properties of the wool (Doyle et al., 2021), this fiber is hardly replaceable by other materials and still play an important role in the textile industry. Wool is produced by long and global value chain, with Australia as the main producer of greasy wool, followed by China and New Zealand (IWTO, 2022).

Despite standards and guidelines for impact calculation being available, a quite high degree of freedom in the setting of LCA studies is still possible. This often leads to difficulty in comparing impact results obtained from different studies. The main issues related to the LCA of wool fibers are detailed in the next paragraph.

In this framework, this paper specifically focuses on the many co-products of the wool production chain and aims to share a methodology as well as detailed inventory and impact results that are expected to be used as a common basis for future assessments and comparisons of wool garments. The scope of this paper is: (i) to share a detailed mapping of the complex wool production chain, with particular attention to the production of shorter fibers, (ii) to provide key information enabling the calculation of environmental impacts of different wool fibers, (iii) to provide environmental impact results of wool co-products. Finally, this paper could help textile companies to choose strategies able to improve the environmental performance of their products.

2. LCA issues related to co-products of the wool production chain

A key point in the LCAs of wool products is the criteria used to calculate impacts of multi-output processes, which are very frequent throughout the wool production chain.

Therefore, almost all 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 characterized by integrated processes, which provide a set of fibers and related products with different characteristics. To give an example, long staple fibers are used to produce highly smooth and lightweight fabrics, such as, for example, next-to-skin baselayers, babywear and gloves. On the other hand, for the production of outerwear, such as jumpers, sweater and scarves it is more suitable to use a bulkier fabric, made with coarser fibers.

In this framework, the distribution of environmental impacts among the different wool co-products can result controversial. For example, the combing process generally produces both *tops* (which will be transformed into a very fine yarn) and *noils* (which will be transformed into a coarser yarn). Therefore, the total impacts connected to the combing process have to be split among tops and noils through an objective allocation criteria. The LCA standards and guidelines are not highly prescriptive on the allocation criteria to be used; this mainly depends on the goal of the study, and it could be, for example, a physical criteria (which, in the case of wool could be based on mass, insulation properties, strength, moisture capacity, resiliency, etc.), an economic criteria or other types of criteria.

Literature on environmental assessments on virgin wool products is not highly abundant, but neither scarce. Most previous LCA studies on wool have mainly focused on the farming phase. For this phase, allocation procedures have been discussed in detail. (Henry, 2012) made a review of 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 impact results, which was confirmed by (Wiedemann et al., 2015), who applied seven methods of allocation to address 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, as well as manure (used as a fertilized replacement) and 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 have also analyzed the phases that follow the farming stage, such as the scouring phase and the transformation of raw wool into textile. During the scouring phase, lanolin is a co-product. In the study of (Bech et al., 2019), however, no allocation was addressed to the lanolin. In the same year, (Wiedemann et al., 2019) suggested using a system expansion approach, meaning that lanolin would have to be considered a product that substitute (and therefore avoids production of) coconut oil.

Regarding the transformation of raw wool into yarn, some authors (Barber and Pellow, 2006; Brent and Hietkamp, 2003) considered also the co-production of wool noils, 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 (considered of higher quality) and 1 kg of short fibers (considered of lower quality). The same approach has been more recently used by (Wiedemann et al., 2020), who analyzed the entire life cycle of a sweater produced with wool long fibers.

In 2016, IWTO published Guidelines for conducting an 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 available for co-productions during farm stage (animal species; meat, wool, milk) and for co-production of wool fibers and lanolin during the processing. On the contrary, it is not specifically mentioned how to deal with co-products in the phase of transformation into wool yarns.

To the best of the authors' knowledge, no LCA study specifically focuses on woollen processing and no allocation procedures different from the mass basis have been employed, probably because of lack of data. This study was developed in collaboration with Manteco Spa and contributes to creating a shared and detailed framework for impact calculation of many different wool co-products. Specifically, its main novelties include: (i) clear mapping system for identifying all relevant co-products occurring in the wool value chain; (ii) proposing an LCA allocation criteria suitable for use within this sector; (iii) environmental assessment conducted on 19 kinds of wool co-products, including

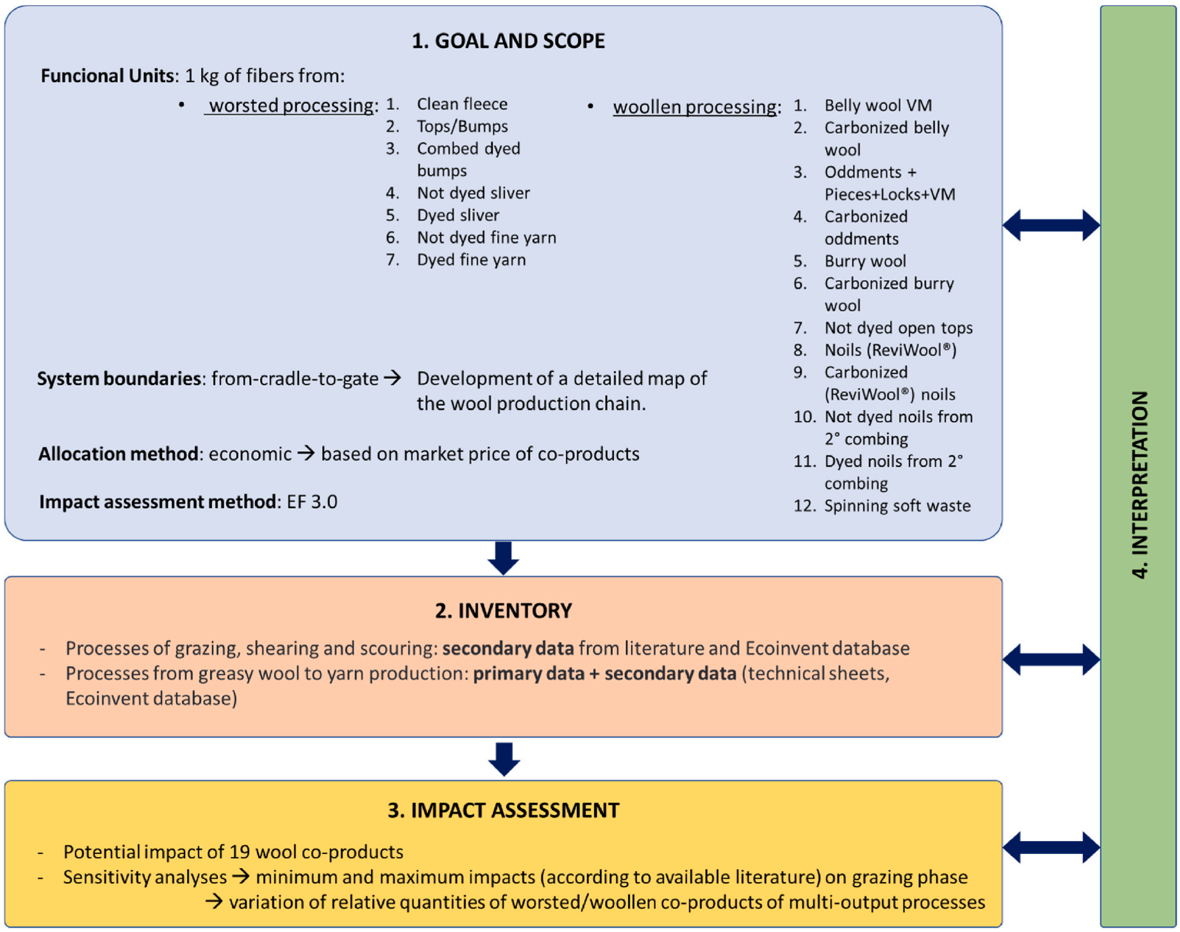

Fig. 1. Scheme of the methodology followed in this study.

shorter fibers, which were mainly neglected in previous literature.

3. Methodology

The LCA methodology is employed to evaluate the potential impacts of 19 wool co-products. The framework of this study is in line with ISO standards and guidelines of the European Commission and the four phases of goal and scope, inventory, life cycle impact assessment and interpretation are covered. Within this well-established scheme, the present paper provides elements of novelty, mainly in the goal and scope phase. Therefore, the system boundaries include both worsted and woollen processing, which are highly interconnected. As detailed in section 2.1, a detailed map of the wool production chain has been developed to overcome the lack of data which probably hindered the assessment of short wool fibers in previous literature. An allocation method with the related parameter has been defined as well (section 2.2). For the inventory phase, primary and secondary data were employed, as detailed in section 2.3 and in the Supplementary Material. Finally, impact results were calculated for 19 wool co-products and two sensitivity analyses were performed (section 3).

Fig. 1 summarizes the methodology followed in this study.

3.1. *Goal and scope: system boundaries*

The system boundaries of this study are from-cradle-to-gate and the functional unit is 1 kg of wool product.

A mapping of the wool co-products has been developed thanks to a strong collaboration with the Italian company Manteco SpA, fabrics producer. This map intends to give a general but detailed overview on the wool supply chain. To this goal, data from literature (Carrières et al., 2022; Di Girolamo, 2018; International Wool Textile Organisation (IWTO), 2020) have been also analyzed. It has to be noticed that this sector is highly fragmented, and, as a consequence, the identified stages can slightly differ from a company to another. This mapping can however be considered representative of the wool sector in general, since the used techniques and the technologies are similar all over the world. Fig. 2 summarizes the mapping of the wool production chain, hereafter described.

The first passages are the **grazing, shearing and scouring** to obtain wool cleaned from grease and dirt. Specifically, from this phase is generally 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 (about 12% in mass), the clean oddments, pieces and locks (lower quality parts, about 10% in mass), the wool grease (i.e. lanolin, about 7% in mass) and wastes (about 21% in mass). In some cases, for belly wool and oddments, a subsequent **carbonization** process is required as well to eliminate vegetable matters (VM). The carbonization involves a treatment with sulphuric acid, which attaches to the VM, followed by a drying process that makes the VM brittle and easier to remove. With the passages of scouring and eventual carbonization are obtained clean fleece, and clean (or carbonized) belly wool and oddments, pieces and locks. Clean fleece (having longer and finer fibers) will be transformed into very fine yarn through the *worsted processing system*. On the other hand, clean/carbonized belly wool and oddments, together with other fibers discarded from the worsted processing system, will be transformed into coarser yarns though the *woollen processing system*. In both worsted and woollen processing, fibers firstly undergo a process of **carding**. This is a mechanical process that

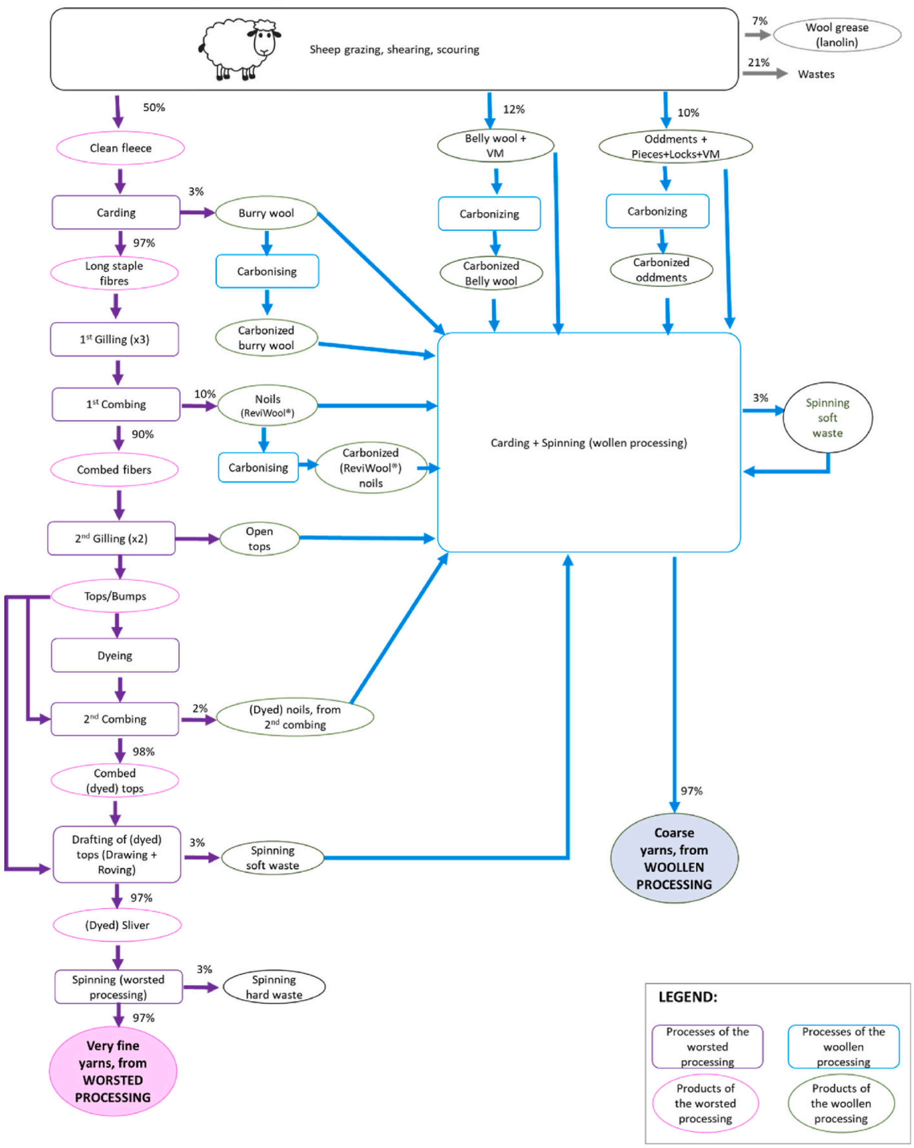

Fig. 2. Flow chart of the wool production chain. Purple boxes and pink circles respectively identify processes and products of the worsted processing; blue boxes and green circles respectively identify processes and products of the woollen processing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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 fibers in a parallel direction and produce a sliver with a more uniform weight. The combing process further straightens the fibers and removes short fibers and foreign matter. The short fibers, called noils, 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.

When the **dyeing** is required, this operation is generally made on bumps. Subsequently the sliver undergoes a second combing, where short fibers still present (about 2%) are removed and sent to the woollen processing. Subsequently, the worsted processing continues with the **drafting**, a mechanical process that reduces the top thickness, and transform the top into the so called sliver. The drafting is composed by two consecutive passages, called drawing and roving. Discarded fibers from the drafting process take the name of spinning soft waste and are generally sent to the woollen processing. Finally, the sliver undergoes the **spinning** process and is transformed into a very fine yarn. Fibers discarded from this process are about the 3% in mass and are called spinning hard waste, which are, generally, recycled (Bianco et al., 2022).

The woollen process is also suitable for the use of shorter fibers and generally produces a coarser yarn than the worsted processing. To obtain acceptable yarn strength, when very short fibers are processed, the blending with longer natural fibers or man-made fibers is needed. As already mentioned, in the woollen process belly wool and oddments of the sheep fleece can be used, eventually carbonized. In addition, the woollen processing receives the short fibers discarded from the worsted processing: burs (eventually carbonized), open tops, noils (eventually carbonized) and spinning soft waste. These fibers only undergo the processes of **carding** and **spinning**, using almost the same principles as the process undertaken for worsted spinning. Discarded fibers (spinning soft waste, around 3% in mass) re-enter in the woollen process. The quality of wool by-products necessarily depend on the original wool quality. ReviWool® are the Manteco selected noils obtained after the first combing, which can have the presence of vegetal matters or can be carbonized.

3.2. Goal and scope: allocation criteria for wool co-products

Based on the map of the wool production chain, a method is proposed to attribute environmental impacts to the identified wool co-products.

The most recent European standards and guidelines on LCA methodology (European Commission, 2013, 2018; The International Standards Organisation, 2020a; 2020b), report that systems involving multi-functionality of processes should be modelled following a decision hierarchy. Specifically, whenever possible, allocation should be avoided through subdivision or system expansion. Subdivision means that input/output flows must be separated and associated to each co-product, while system expansion means that the analysis includes the different co-products and results are given for the expanded system as a whole rather than for individual co-products. However, in the case under analysis, subdivision is not a viable solution because co-products derive from exactly the same processes. The system expansion goes against of the goal of this study, which tries to clearly define the individual environmental impacts of the different wool co-products.

According to the LCA standards and guidelines, in case subdivision or system expansion cannot be applied, it should be used a physical allocation: the inputs and outputs of the system should be divided between the co-products proportionally to relevant underlying physical relationships between them. However, in the case of wool co-products, 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 coarser yarn (from the woollen processing). In other words, with a mass allocation it result that the valorization of the discarded short fibers have the same impact of long fibers. According to the authors of this study, an allocation based on mass is not 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 coarser yarn. In addition, when a mass allocation is used, the comparability of textiles could be questionable: for example, it probably results that the final impact of a sweater produced with fine fibers (lighter, often more prestigious and expensive) is inferior than a (heavier and often cheaper) sweater of the same size produced with shorter fibers. Other physical relationships between the wool co-products could be the average thickness of the fiber or the average length. However, this type of allocation would result hardly implementable. Therefore, the thickness of the fibers is highly variable, depending, for example, on the breed and age of the sheep and on the type of pasture. Also the length of the fibers has a high variability, mainly depending on the part of the sheep body from which the fibers come from.

Where the previous solutions for assessing multifunctional process cannot be used, the LCA standards and guidelines indicate that other relationships can be employed to allocate inputs and outputs.

This study proposes to use an economic allocation, which associate impacts to the different co-products proportionally to their relative market price. 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 other words, the economic allocation reflects the fact that the use of materials and resources (and their consequent impacts) is driven to a greater extent by the products providing larger profits. In addition, the economic allocation is one recognized way of systematically executing allocation in LCA (Guinée et al., 2004). 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 relatively stable for wool co-products since, as confirmed also by (Australian Wool Exchange Ltd, 2013), the price of wool is often based on the expected processing outcome, rather than the actual wool characteristics.

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

Process	Outputs 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	0.12	8.50	15.9
	Oddments + Pieces + Locks + VM	0.10	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
	Noils	0.1	6.20	3.7
2nd combing (1 kg)	Combed dyed tops	0.98	21	99.4
	Noils	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

The economic allocation is based on average market values estimated from the experience of Manteco SpA and from data publicly available. Specifically, information on open cry auctions published on the website of AWEX (https://www.awex.com.au/) have been consulted for defining the market prices of greasy wool. Therefore, greasy wool is mainly sold through auctions, even though minor quantities are sold also directly from woolgrowers or from wool selling brokers.

Table 1 lists the processes where an allocation has been necessary, the mass quantities of each economic outputs, their average market price and the allocation expressed in percentage. 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 assumed, since these products are not generally sold. No allocation has been necessary for the process of second gilling because the price of outputs (tops, bumps) is the same (18 €/kg) and the quantities produced depend on the request of the market.

Even though the economic values can change over time, their ratio generally has a minor variability. However, also in the case their ratio will sensibly change in the next future, the reader can easily reproduce the LCA model of the wool production chain, starting from data provided in this paper and in the related Supplementary Material.

3.3. Inventory

For each process defined in the map of Fig. 1, input/output flows of resources, materials, energy, waste and emissions have been quantified. Inventory quantities, specific datasets and details on flows are available in the Supplementary Material.

The grazing, shearing and scouring processes take place in many farms located in different countries. Since authors and the company Manteco SpA have no access to details on these processes, the related datasets employed for the LCA process refer to average global production. On the contrary, for the processes related to the transformation of raw wool into fibers (operated by Manteco SpA and its network of

Table 2
Percentage ratios of worsted and woollen co-products for each multi-output process. Values of Scenario A (minimum percentage of woollen co-product) and Scenario B (maximum percentage of woollen co-product) are employed in the sensitivity analysis.

Multi-output process	Wool co-products	Reference value	Scenario A (MINIMUM % of short fibers)		Scenario B (MAXIMUM % of short fibers)	
			Value	Source	Value	Source
Sheep grazing, shearing, scouring	Cleen fleece	69%	80%	de Beer (2020)	60%	Manteco experience
	Belly wool	17%	10%		22%	
	Oddments + Pieces + Locks + VM	14%	10%		18%	
Carding	Long staple fibers	97%	98%	Manteco experience	95%	Manteco experience
	Burry wool	3%	2%	Manteco experience	5%	Manteco experience
1st combing (1 kg)	Combed fibers	90%	93%	Manteco experience	87%	Manteco experience
	Noils	10%	7%	Manteco experience	13%	Manteco experience
2nd combing (1 kg)	Combed dyed tops	98%	99.5%	Manteco experience	97%	Manteco experience
	Noils	2%	0.5%	Manteco experience	3%	Manteco experience
Drafting of not dyed tops (1 kg)	Sliver	97%	98%	Cottle and Wood (2012)	96.5%	Cottle and Wood (2012)
	Spinning soft waste	3%	2%	Cottle and Wood (2012)	3.5%	Cottle and Wood (2012)
Drafting of dyed tops (1 kg)	Dyed sliver	97%	98%)	Cottle and Wood (2012)	96.5%	Cottle and Wood (2012)
	Spinning soft waste	3%	2%	Cottle and Wood (2012)	3.5%	Cottle and Wood (2012)

collaborating companies) primary data integrated with data from technical sheets of machineries are employed. For these processes, electricity is modelled according to the Italian Residual mix declared in the report of the Association of issuing bodies (AIB).

The information available in the Supplementary Material enables readers to easily reproduce or modify parts of this study. For example, they can change the source of energy employed in the inventory according to the geographical location where transformation processes take place.

The provided inventory can be considered representative of global-level wool sector processes. Therefore, as already mentioned, this sector has a global value chain and technologies for processing greasy wool into fibers and yarns are mostly similar over the world.

3.4. Life cycle impact assessment (LCIA) and sensitivity analyses

The potential environmental impacts of the identified 19 wool co-products have been calculated using the allocation criteria previously detailed and the EF 3.0 method, developed by the European Commission (Fazio et al., 2018). For completeness and to facilitate future comparisons, 16 impact categories were selected: climate change, ozone depletion, ionising radiation, photochemical ozone formation, particulate matter, human toxicity (cancer; non-cancer), acidification, eutrophication (freshwater; marine; terrestrial), land use, water use, resource use (fossil; minerals and metals). It should be noticed that the calculation methods to assess the potential impact of different indicators have different levels of scientific robustness, as specified in the report of the European Commission (Fazio et al., 2018). The potential impacts are provided for:

- 5 co-products of the worsted processing: clean fleece with vegetable matters (VM); top/bumps; combed dyed tops; not dyed sliver; dyed sliver; very fine yarn (not dyed); very fine yarn (dyed);
- 12 co-products of the woollen processing: belly wool + vegetable matter; carbonized belly wool; oddments + pieces + locks + vegetable matter; carbonized oddments + pieces + locks; burry wool; carbonized burry wool; open tops; noils (ReviWool®); carbonized (ReviWool®) noils; not dyed noils; dyed noils; spinning soft waste.

Two sensitivity analyses have been developed to understand how much impact results are influenced by the main variables of the study. A first sensitivity analysis concerns the grazing phase, whose impacts are highly variable, as discussed in recent literature (Bech et al., 2019; Bhatt and Abbassi, 2021; Biswas et al., 2010; Brock et al., 2013; Dougherty, 2018; Eady et al., 2012; Wiedemann et al., 2016). This variability is due both to LCA methodological aspects and to the wide differences in farming practices and production efficiencies, as already discussed in the previous work of the authors (Bianco et al., 2022). Impact results on climate change have been re-calculated considering the lowest and highest values found in literature for 1 kg of greasy wool, which are 10.4

Table 3
Potential impacts of 1 kg of the intermediate products of the worsted processing.

Impact category	Unit	Clean fleece VM	Tops/ Bumps	Combed dyed bumps	Sliver, not dyed	Sliver, dyed	Fine yarn, not dyed	Fine yarn, dye
Climate change	kg CO2 eq	7.82E+01	8.57E+01	8.83E+01	9.02E+01	9.31E+01	9.42E+01	9.72E+01
Ozone depletion	kg CFC11 eq	9.21E-07	1.04E-06	1.27E-06	1.54E-06	1.77E-06	1.71E-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	8.77E-02	9.18E-02
Particulate matter	disease 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
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

Table 4
Potential impacts of 1 kg of the intermediate products of the woollen processing.

Impact category	Unit	Belly wool VM	Carbonized belly wool	Oddments + Pieces + Locks + VM	Carbonized Oddments + Pieces + Locks	Burry wool	Carbonized burry wool
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	disease 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
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

Impact category	Unit	Open tops, not dyed	Noils (ReviWool®)	Carbonized (ReviWool®) noils	Noils, from 2nd combing, not dyed	Noils, from 2nd combing, dyed	Spinning soft waste
Climate change	kg CO2 eq	8.57E+01	2.95E+01	2.98E+01	2.57E+01	2.61E+01	4.97E+01
Ozone depletion	kg CFC11 eq	1.04E-06	3.57E-07	4.02E-07	3.15E-07	3.74E-07	9.46E-07
Ionising radiation	kBq U-235 eq	4.60E-01	1.58E-01	1.83E-01	1.43E-01	1.57E-01	5.68E-01
Photochemical ozone formation	kg NMVOC eq	7.44E-02	2.56E-02	2.61E-02	2.23E-02	2.30E-02	4.62E-02
Particulate matter	disease inc.	1.37E-05	4.73E-06	4.74E-06	4.11E-06	4.12E-06	7.57E-06
Human toxicity. non-cancer	CTUh	6.34E-07	2.18E-07	2.20E-07	1.90E-07	1.92E-07	3.59E-07
Human toxicity. cancer	CTUh	2.10E-08	7.22E-09	7.28E-09	6.28E-09	8.14E-09	1.52E-08
Acidification	mol H+ eq	1.94E+00	6.68E-01	6.69E-01	5.81E-01	5.81E-01	1.07E+00
Eutrophication. freshwater	kg P eq	2.09E-02	7.21E-03	7.25E-03	6.28E-03	6.31E-03	1.20E-02
Eutrophication. marine	kg N eq	3.32E-01	1.14E-01	1.15E-01	9.95E-02	9.99E-02	1.84E-01
Eutrophication. terrestrial	mol N eq	8.56E+00	2.95E+00	2.95E+00	2.56E+00	2.57E+00	4.71E+00
Ecotoxicity. freshwater	CTUe	1.36E+03	4.67E+02	4.70E+02	4.06E+02	4.12E+02	7.71E+02
Land use	Pt	8.95E+03	3.08E+03	3.08E+03	2.68E+03	2.68E+03	4.92E+03
Water use	m3 depriv.	1.55E+01	5.35E+00	5.42E+00	4.65E+00	4.77E+00	8.93E+00
Resource use. fossils	MJ	1.16E+02	3.99E+01	4.51E+01	3.53E+01	4.13E+01	1.06E+02
Resource use. minerals and metals	kg Sb eq	1.54E-04	5.32E-05	5.37E-05	4.63E-05	4.75E-05	8.98E-05

kg CO_2 eq. (Dougherty, 2018) and 69.8 kg CO_2 eq. (Bech et al., 2019) respectively.

A second sensitivity analysis has been developed to consider the typical variability of the ratios between the co-products of a same process. For each multi-output process, a range of variability has been defined, based on literature data and decades of field experience from Manteco SpA company. The minimum and maximum percentage of short fibers (woollen co-products) respectively define the Scenario A and B. Table 2 lists the reference data used throughout the study, as well as the values employed for the sensitivity analysis and their source.

4. Results

4.1. Impact assessment of wool co-products

Table 3 lists the overall potential impacts of 1 kg of the following intermediate products of the worsted processing: clean fleece with vegetable matters (VM), top/bumps, combed dyed tops, not dyed sliver, dyed sliver, very fine yarn (not dyed), very fine yarn (dyed).

As it can be noticed, the dyed fine yarn has the higher potential impacts, since it is the final product of the worsted processing. The total impact results of 97.2 kg CO_2 eq/kg. The main contribution is the grazing phase, accounting for 89% of the total impact. All other transformations together (shearing and scouring, carding, gilling, combing, dying, drafting and spinning) account for the 11% of the total impact. For this phase, the Ecoinvent dataset "Sheep fleece in the grease {RoW}|sheep production, for wool|Cut-off" has been used, which shows a carbon footprint of 50 kg CO_2 eq/kg. As already discussed, a high variability characterizes the sheep farming phase, and the sensitivity analysis provided in Section 3.2 identifies how impacts of analyzed co-products vary according to the impact associated to this phase.

Table 4 lists potential impacts of 1 kg of following intermediate products of wollen processing: belly wool + vegetable matter, carbonized belly wool, oddments + pieces + locks + vegetable matter, carbonized oddments + pieces + locks, burry wool, carbonized burry wool, open tops, noils (ReviWool®), carbonized (ReviWool®) noils, not dyed noils, dyed noils, spinning soft waste.

Results show that, generally, the production of woollen products has lower potential impacts than the production of worsted products, although in some cases the difference is not particularly high. However,

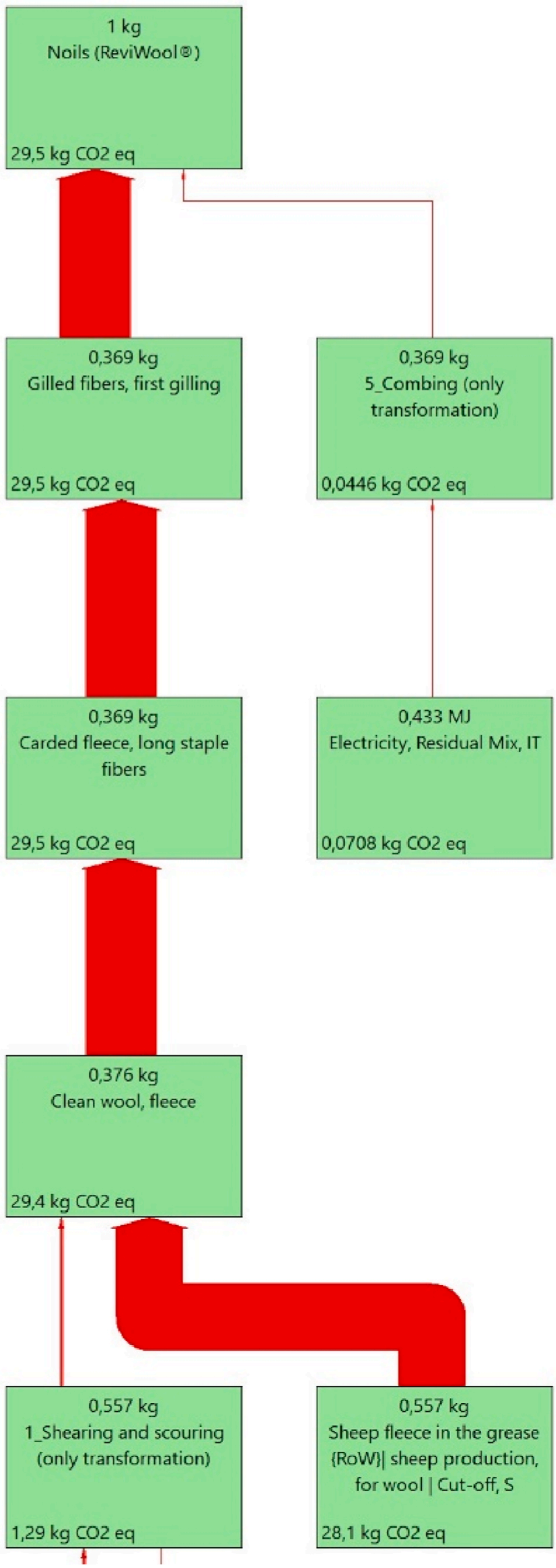

Fig. 3. Impact on climate change of 1 kg of ReviWool® noils (visualization cut-off of 0.1%).

it has to be highlighted that these results have not to be considered a comparison between fine and coarse fibers, since they generally have different final uses, but rather a detailed starting point for the assessment of different wool garments. As can be seen, open tops, belly wool (with VM or carbonized) and spinning soft waste have the highest potential impacts. Therefore, these fibers have relatively high economic value if compared with other fibers used in the woollen processing. To better understand the results, a contribution analysis has been developed on a woollen product: the ReviWool® noils (a co-product of the first combing employed for producing coarse yarns). In the chart of Fig. 3, the cumulative impact on climate change indicator can be read in the box and thicker arrows correspond to higher impacts. As it can be noticed, also in this case the grazing phase is responsible of the highest share of impacts (95% of the total). However, if compared with combed fibers (co-product of the ReviWool® noils, produced by the same combing process), its impact is significantly lower (about the 66% less). Results appears reasonable, since they reflect the fact that the wool sector (and thus materials and resources employed in the supply chain) is mainly driven by the worsten products, which provide larger share of profit.

Coarser yarns are spun with fibers from the woollen processing and their final impact depend on their composition. An example is provided here for a yarn composed of 60% belly wool with VM, 20% noils ReviWool® and 20% undyed open tops. Fig. 4 graphically shows, for all the analyzed indicators, the relative contribution of the fibers and of the spinning process into yarn. The total impact results of 68.1 kg CO_2 eq/kg and, as expected, a high contribution is given by the fibers of belly wool (45%–65% of the total impact, according to the indicator) and open tops (20%–26%), while noils account for only 7%–9% of the total impact.

4.2. Sensitivity analyses

Since the grazing phase gives a significant contribution to the total impact of the analyzed products and is highly variable, a sensitivity analysis has been developed. Table 5 lists the carbon footprint of the co-products analyzed in this study, considering respectively the lowest value, the value from the Ecoinvent dataset and the maximum value for greasy wool. As expected, the final impact of the analyzed fibers change significantly because the grazing phase is one of the main contributors of the impact on climate change. However the ratio between impacts of the analyzed products remains rather stable.

This suggests that: (i) companies that want to calculate the impact of specific wool products should identify the source(s) of the greasy wool and the impacts of the related grazing phase; (ii) studies on wool products should refer to the same LCA methodological aspects (allocation criteria, system boundaries, etc.), with particular attention to the grazing phase; (iii) if the source of the wool is unknown, different studies on wool are (partially) comparable only if the same average dataset on greasy wool is considered.

As explained in Section 2.3, the relative quantities of worsted/woollen co-products derived from the same multi-output process can vary. To understand how this variability can affect the impact results, a second sensitivity analysis is developed considering a Scenario A, having the minimum percentage of short fibers, and a Scenario B, having the maximum percentage of short fibers. The graphs in Figs. 5 and 6 shows the impact on climate change in the reference scenario, in Scenario A and in Scenario B, respectively for the products of worsted and woollen processing.

From this analysis, it results that the physiological variations in the ratio of the co-products have a limited influence on the final impact. For worsted products, the impact on climate change averages between −6% (scenario A) and +7% (scenario B), while for woollen products it averages between −5% (scenario A) and +6% (scenario B). As expected, it emerges that for both longer and shorter fibers, the best environmental performances are obtained when the yield of long fibers is maximized (scenario A).

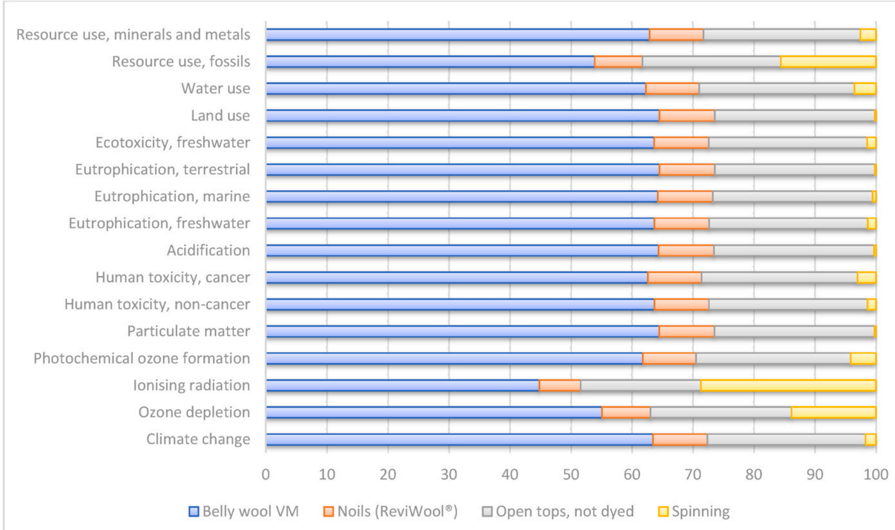

Fig. 4. Relative contribution of fibers and of the spinning process to the total impact of a coarse yarn composed by 60% of belly wool with VM, 20% of noils ReviWool® and 20% of not dyed open tops.

Table 5
Impacts on climate change of intermediate products from worsted and woolen processing, calculated considering different impacts of the greasy woo (minimum and maximum values from literature and value from Ecoinvent database).

	Product (1 kg)	Impact on climate change (kg CO_2 eq/kg)		
		Greasy Wool: Literature Min	Greasy Wool: Ecoinvent Database	Greasy Wool: Literature Max
Worsted products	**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	26.6	94.2	126.7
	Fine yarn, dye	28.4	97.2	130.3
Woollen products	**Belly wool VM**	16.8	69.9	95.5
	Carbonized belly wool	17.2	70.3	95.8
	Oddments + Pieces + Locks + VM	5.9	24.7	33.7
	Carbonized Oddments + Pieces + Locks	6.3	25.0	34.0
	Burry wool	5.9	24.6	33.6
	Carbonized burry wool	6.3	24.9	33.9
	Open tops, not dyed	20.8	85.7	116.9
	Noils (ReviWool®)	7.2	29.5	40.3
	Carbonized (ReviWool®) noils	7.5	29.8	40.6
	Noils, from 2nd combing, not dyed	6.3	25.7	35.0
	Noils, from 2nd combing, dyed	6.7	26.1	35.4
	Spinning soft waste	14.1	49.7	66.8

5. Discussion

The results of this study provide information and indications that address the current main issues for assessing wool garments, and as a consequence, could contribute to achieve a higher level of sustainability in the textile sector. As already known from previous literature (Gomez-Campos et al., 2021; Henry et al., 2015b; Nguyen et al., 2021), the wool production is responsible of major impacts when compared with the production of other natural or synthetic fibers. Therefore, the wool production chain deserves detailed studies to identify strategies that can improve its sustainability. To the best of the authors' knowledge, no previous study has defined a systematic method to quantify the impacts of short fibers, despite their widespread use in the production of wool garments. The main novel contribution of this paper is in filling this gap through the integration of detailed information from the wool industry and the implementation of LCA methodology with guidelines that fit the textile sector. The map of the production chain provided in this paper, which considers the complementarity of worsted and woollen processing, is a necessary first step to evaluate and differentiate the impact of the different wool co-products. The allocation criteria to be used in the LCA is a delicate question, and in the case of the wool production chain, plays a key role due to the high number of multi-output processes. Allocation on a mass basis has various weak points as already discussed, while an economic criterion appears to be more appropriate to reflect the main drivers of the wool sector. The problem of the volatility of prices is mitigated by the fact that their ratio results relatively stable in the wool sector. Starting from these settings, impact results show that producing fine fibers (from the worsted processing) has higher impacts than producing coarser fibers. However, these results should not to be considered a comparison since fine and coarse fibers often have different final uses. In addition, even when the final garments produced with fine/coarse wool is similar (eg. sweater), other relevant variables should be considered before comparing them. For example, it should be evaluated if the type of wool could influence expected lifetime or recyclability of the garment.

Another consideration, emerged from this study and in line with previous literature (Bhatt and Abbassi, 2021; Wiedemann et al., 2016), concerns grazing phase of wool production chain. This phase has highly

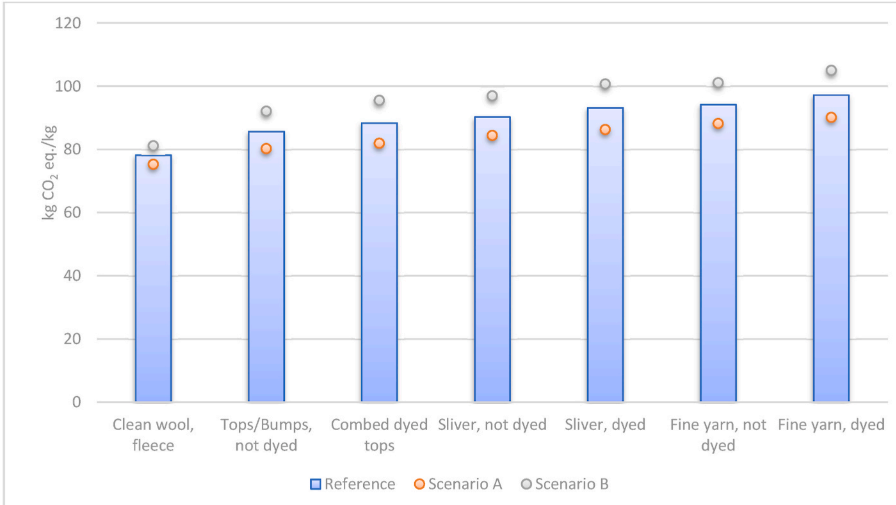

Fig. 5. Potential impacts on climate change of wool products from the worsted processing, in the reference scenario, Scenario A and Scenario B.

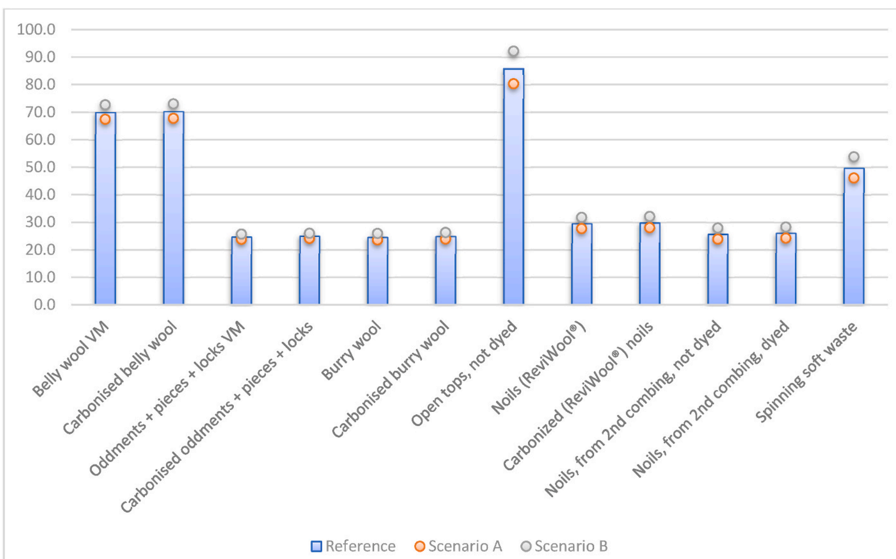

Fig. 6. Potential impacts on climate change of wool products from the woollen processing, in the reference scenario, Scenario A and Scenario B.

variable impacts and is generally responsible for significant contributions to climate change impact. As a consequence, companies wanting to assess impacts of specific wool products should know origin of the greasy wool and assess impact of its grazing phase (or at least one with similar characteristics). However, this goal is generally hard to achieve because currently the traceability for wool is scarce, as well as information on specific farms. In addition, the LCA methodology used for evaluating grazing phase should converge on specific rules that limit arbitrariness in some key settings of the study (system boundaries, allocation method, etc).

6. Conclusions

The wool sector has traditionally been engaged in environmental studies and strived to understand and improve the environmental profile of related products, so the scientific literature on this topic is relatively abundant. Nevertheless detailed environmental studies that clearly distinguish between fine and coarse yarns (and consequent products) are scarcely available. This study contributes to fill this gap through a general mapping of the processes involved in the production chain of wool yarns and a related Life Cycle Assessment. In such a mapping exercise some simplifications were necessarily introduced to overcome the unnecessary complexity of such a highly fragmented sector. However, the level of detail of this analysis is significantly higher in comparison to previous literature and it can be considered as a representative step towards a more comprehensive knowledge of the wool sector.

The wool supply chain can be considered highly efficient, since fibers discarded at different stages of the main stream (the *worsted processing*) generally flow into the *woollen processing* for the production of coarser yarns. Based on the map, this study applies the LCA methodology to calculate environmental impacts on the different wool co-products, considering the integration between worsted and woollen processing. In most cases, processes in the production chain are multi-outputs (generally, longest fibers destinated to the worsted processing + shorter fibers addressed to 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.

Based on the outcomes of this study, the ratio between prices of different wool (intermediate) products is indicative of the driver(s) of the processes along the production chain. Moreover, the economic allocation appeared to be the most appropriate, as well as in line with other LCAs in this sector. Therefore, this LCA study considers and provides the prices of the wool products to allocate impacts of multi-outputs processes. The inventory data for this study is provided in the Supplementary Material, to enable the reader to easily replicate the study (and eventually adapt it to similar supply chains).

From the analysis it results that, as expected, products deriving from the worsted processing have higher impacts than the products deriving from the woollen processing. 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), belly wool fibers (70 kg CO_2 eq/kg) and open tops (85.7 kg CO_2 eq/kg). The product ReviWool® of Manteco SpA results having an impact of 29.5 kg CO_2 eq/kg. Products from the worsted process have an impact on climate change ranging from 78 to 97 kg CO_2 eq/kg. For all the analyzed products, a significant contribution to the impact is due to the grazing phase, producing the greasy wool. Since this phase is highly variable, 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 greasy wool (respectively 10.4 and 69.8 kg CO_2 eq/kg). It results that impacts of the analyzed products vary sensibly according to the value considered for the greasy wool. However, the relationship between them is rather stable.

The typical variation in the percentage ratio of worsted/woollen co-products appears to have little influence on the final result (from −6% to +7%), as demonstrated by a second sensitivity analysis.

This study can also 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® and 20% of open tops. The impact of this specific yarn results of 68.1 kg CO_2 eq/kg. It is evident that a yarn composed by a higher percentage of fibers characterized by the lowest impacts (such as oddments, burry wool and noils) will increase its environmental performances.

Some assumptions have been introduced in the study, mainly to provide a comprehensive but simplified map of the wool supply chain. Other assumptions concern the market values of long staple fibers and combed fibers that are intermediate products generally not sold and the quantities of some inputs included int the Life Cycle Inventory (as specified in the Supplementary Material). Nevertheless, all the above assumptions can be considered fairly representative of the investigated supply chain, and so the obtain environmental impact results. This study could be further fine-tuned with additional data from companies of the wool supply chain.

This article is expected to become a methodological and applicative reference for future calculations of environmental impacts in the textile sector.

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CRediT authorship contribution statement

Isabella Bianco: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Giuseppe Picerno:** Validation, Investigation, Resources, Writing – review & editing, Funding acquisition, Project administration. **Gian Andrea Blengini:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data have been shared in the article and in the Supplementary Materials

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137877.

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