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# Environmental Impacts in the Textile Sector: A Life Cycle Assessment Case Study of a Woolen Undershirt

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**Abstract:** The textile industry, known for its significant contribution to global greenhouse gas emissions, is increasingly active in exploring techniques and technologies to improve its environmental performance. The main tool to calculate environmental impacts is the Life Cycle Assessment (LCA) methodology, which is standardized and internationally recognized. Specific guidelines for the impact calculation of textile products are under development (Product Environmental Footprint Category Rules (PEFCRs) for the category of Apparel and Footwear). In this context, this study contributes to the knowledge in the textile sector through the development of a cradle-to-gate LCA of a woolen undershirt produced in Italy. This study shares robust and recent (2021) primary data for the phases of weaving, cutting, and sewing, obtained from an Italian company. Data from previous studies of the authors, as well as secondary data, are also used to complete the inventory. A further analysis is developed to include the use phase as well. The impact on climate change of one undershirt results in 11.7 kg $CO_2$ eq, primarily due to the farming phase of sheep, which accounts for 88% of the total emissions. The impact on climate change of energy used in the wool transformation process has a relatively low impact (11%), also thanks to the partial use of electricity produced by photovoltaic panels, while materials (e.g., chemicals) and transportation have negligible contributions. The farming phase, despite relying on secondary data, is identified as the primary contributor for most of the other indicators. Additionally, it has been found that user habits play a key role in the impact related to one wearing of the undershirt. The findings suggest that further work is necessary in the textile sector and emphasize (i) the need for guidelines, enabling the inclusion of the use phase without compromising the comparability between different LCAs of similar textile products; (ii) the need for improved traceability practices in the textile sector, to enhance inventory data collection on the raw material production (wool fibers in the case under analysis).

**Keywords:** textile sector; weaving; sewing; LCA; environmental impacts



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## 1. Introduction

The textile sector has been identified as the fifth largest global contributor to greenhouse gas emissions [1]. More than 1.2 billion tons of carbon emissions are produced by the textile processing industry each year [2].

Fast fashion, described as "a business model based on offering consumers frequent novelty in the form of low-priced, trend-led products", is also growing rapidly, as a consequence of rising of global population and increasing wealth and purchasing power in developing nations [3,4]. The main environmental concerns of the textile industry are related to the use of raw materials, including water; water pollution; greenhouse gases emissions; and waste disposal. The production of textile fibers can require large amounts of water, energy, and various chemicals, including fertilizers and pesticides for growing crops for natural fibers (e.g., cotton, flax [5]). The issue of water pollution mainly comes from the processes of textile dyeing and finishing, but also from the use phase, with the release of microplastics from synthetic fibers [1]. The problem of increasing textile waste is a global issue, and numerous studies have shown that most of this waste ends up in landfills [6–8]. This consumption will drive up waste generation and subsequently put a strain on landfills [8]. For example, 4.5% of all MSW in landfills in the United States consists of textiles [9].

It is becoming apparent that a reduction in environmental impacts from the textiles sector requires a change toward circularity. The European Commission, in the framework of the circular economy action plan [10], recently presented the EU Strategy for Sustainable and Circular Textiles [11], addressing practical actions to make textiles more durable, repairable, reusable, and recyclable, to tackle the problem of fast fashion and stimulate innovation within the sector.

Textile companies wanting to show particular attention to the environment can use the tool of the EU Ecolabel [12], whose threshold criteria guarantee limited use of harmful substances and reduced water and air pollution. In addition, the European Commission is preparing the Product Environmental Footprint Category Rules (PEFCRs) for the category of Apparel and Footwear, covering 13 sub-categories of products (T-shirts; shirts and blouses; sweaters and mid-layers; jackets and coats; pants and shorts; dresses, skirts, and jumpsuits; leggings, stockings, tights, and socks; underwear; swimwear; apparel accessories; open-toed shoes; closed-toes shoes; boots). PEFCRs are in line with the standardized Life Cycle Assessment (LCA) methodology [13,14] and provide further guidelines for environmental assessment within specific product groups. The goal of the PEFCRs is to enable unambiguous and fair comparisons of products within the same category. The apparel and footwear PEFCRs are currently in the testing phase and their official adoption is expected in 2024. A draft version is already publicly available, however [15]. In Italy, a voluntary labelling scheme called Made Green in Italy (MGI) is available for woven wool [16]; this integrates the PEF method with specific guidelines for the wool sector.

Research activities on techniques and technologies to improve the environmental performance of the textile life cycle are currently supporting this transition toward higher circularity. Environmental evaluations are available for the production of different types of fibers, such as conventional and organic cotton, silk, jute, flax, and polyester [5,17–21] and garments [22–25]. Life cycle assessments (LCAs) have been used in the literature to evaluate potential environmental benefits of standard textile recycling methods based on mechanical, chemical, and thermal processes [21,26–28]. Recently, biological recycling using microorganisms has been developed to recycle textile waste, in the hope that it is somewhat more environmentally friendly than traditional methods.

D'Adamo et al. [29] examine the topic of the circular economy in the fashion industry. Their work highlights that collection and recycling are not necessarily the best practices for the circular economy. For this to happen, close collaboration between manufacturers and retailers in the value chain is needed to move the industry towards responsibly sustainable production and consumption models. D'Adamo and Colasante [30,31] report on data from an interesting survey to assess consumers' attitudes towards the circular economy and bioeconomy practices with a specific focus on the fashion industry. Kumar et al. [32,33] examine the topic of the circular economy in the textile sector with specific reference to Pakistan.

Environmental research in the textile sector is increasingly recognized as strategically important for achieving carbon neutrality goals. However, there is a lack of precise knowledge regarding textile raw materials, process technologies, and garment users' behaviors, mainly due to the significant variability within the phases of the textile production chain. In this context, the current study specifically centers around a woolen undershirt, chosen as a reference because it represents a basic clothing item. This study aligns with the objectives of the European Commission and seeks to contribute to a more comprehensive understanding of the resources typically employed in common processes within the textile sector. Specifically, this report introduces a significant novelty by incorporating robust and up-to-date (2021) primary data for weaving, cutting and sewing phases. In addition, this report contributes to the evaluation of the significance of the use phase for a textile product. Finally, it aims to reveal the environmental impacts of a woolen undershirt and to identify the main sources of those impacts.

## 2. Materials and Methods

This study is aligned with the Life Cycle Assessment (LCA) methodology, according to the ISO standards 14040-44 [13,14] and to the Product Environmental Footprint Guidelines [34], divided into the phases of goal and scope, inventory, impact results, and discussion, as hereafter detailed.

### 2.1. Goal and Scope

Impact results of LCA studies have to be ascribed to a specific parameter, called the functional unit (FU). The choice of functional unit and system boundaries is a delicate question in LCA; studies of similar products, but developed using different FU and system boundaries, are difficult to compare. Other factors in the LCA study (e.g., choice of dataset, way of modelling the use and end-of-life phases) also largely influence the impact results. In this context, the Product Environmental Footprint guidelines [34] provide a more detailed indication for a standardized way of calculating environmental performance. Additionally, specific product category rules, known as Product Environmental Footprint Category Rules (PEFCRs) are currently being developed or have been recently published for different product categories. However, regarding textile products, specific guidelines are not yet available.

The "Made Green in Italy" guidelines [16] are applicable to semi-finished products in carded wool, suitable for sewing carded garments such as coats and sweaters. Therefore, woolen undershirts, taken as reference in this study, are out of the scope, even though part of the production chain is the same as for other woolen garments. These guidelines indicate the cradle-to-gate system boundaries and use 1 $m^2$ of raw textile as the functional unit. The PEFCRs on apparel and footwear (currently only available in a draft version) suggest the inclusion of the entire life cycle of the analyzed product, including the use and end-of-life phases and considering one wearing as the functional unit. However, indications on criteria and assumptions to be used for the use phase and for the estimation of the lifespan are not yet available. For these reasons, this study was first developed considering the cradle-to-gate system boundaries (Figure 1), i.e., from raw wool production to the finished undershirt at the plant gate. The functional unit chosen is one black women's undershirt made of 100% Merino wool with a net weight equal to 114.5 g. However, a further analysis is carried out to also include the use phase and estimate the potential impact related to the functional unit of one wearing of the analyzed undershirt.

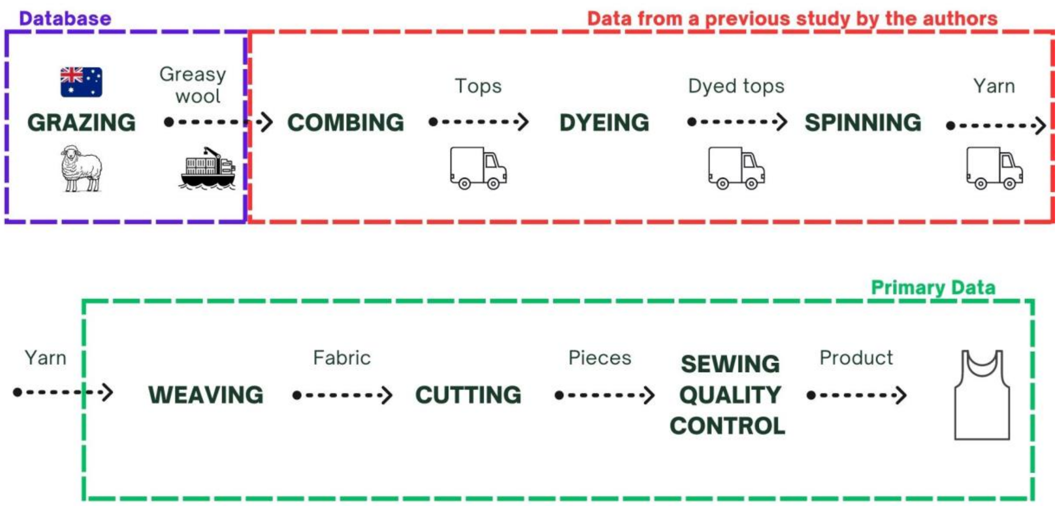


**Figure 1.** System boundaries and source of inventory data for the "cradle-to-gate" analysis.

The inventory includes secondary data from the Ecoinvent 3.7 database (blue outline in Figure 1), data from the authors' previous studies (red outline), and primary data from an Italian company (green outline). It is necessary to emphasize that transportation between steps should also be considered. Transportation in the textile industry can potentially have a high impact, as the textile supply chain is widely geographically dispersed nowadays. In the present case, long-distance transport is necessary to provide Australian wool to the Italian company. For the subsequent steps, however, transports are limited, since the company providing data is highly vertically integrated, with many steps being carried out within the same facility. Additionally, yarn suppliers (and subcontractors) are located in close proximity.

The impact assessment has been developed with the EF 3.0 method, in line with the most recent guidelines from the European Commission. For the sake of completeness and to facilitate future comparisons, impacts are provided for 16 impact categories.

### *2.2. Inventory Data*

The first part of the production chain (from sheep grazing to yarn production) is not under the control of the company involved in this study. For these processes, Ecoinvent background datasets and previous studies of the authors [35] have been used to allow better alignment with the available literature and to facilitate future comparison with other studies.

Primary data were used for the processes ranging from weaving to the creation of the finished product. Regarding electrical and thermal energy, data referring to the year 2021 were taken directly from the meters. In addition, referring to the electrical energy, the company is equipped with photovoltaic panels which allow the harnessing of solar energy. Thanks to these panels, 27% of the electrical energy is self-produced, while the remaining 73% comes from plants powered exclusively by renewable energy sources.

The main consumption of thermal energy is linked to the weaving phase, due to the presence of a calender, and to the sewing and quality-control phases with reference to the ironing process that the garment undergoes before being packaged. As concerns the water consumption, the production process is mainly dry, and water is only used in the stabilization phase during weaving. From the total water consumption in 2021 and the number of garments produced in the same year, it was possible to calculate the water consumption in relation to production. The derived value in $m^3$ per garment was averaged across the entire production because it was not possible to obtain the precise value for the individual garment under examination. The production encompasses a variety of garments, ranging from underwear, with significantly lower weight, to outerwear characterized by accessories such as lace, buttons, and zippers, with significantly higher weight. Given these considerations, it was reasonable to choose an indicative average weight for the entire production of the knitwear. The derived value is 0.0049 $m^3$/item.

Lastly, textile waste is only present during the cutting phase. The cutting process is carried out with precision and care, minimizing waste as much as possible. The total textile waste for the year 2021 is a value directly derived from the company's receipt and dispatch register. Considering the total production in 2021, the percentage of waste relative to production was calculated. By multiplying this percentage with the weight of the garment under examination, the waste related to the production of the specific product amounted to 0.0054 kg.

As far as transports are concerned, all commercial transports between Australia and Europe use the Suez Canal route, and the distance travelled by the ship is set at 21,928 km. The road transport from the port to the city where the combing phase company is located is 200 km.

Table 1 summarizes the inventory for the phases of weaving, cutting, and sewing of one undershirt.

**Table 1.** Inventory data for the processes of weaving, cutting, and sewing for one undershirt.

| **Weaving** | | | |
|---|---|---|---|
| **Input Flows** | **Measuring Unit** | **Quantity** | **Ecoinvent Dataset** |
| Woolen yarn | g | 106 | Fine yarn, dyed, from worsted processing (from [35]) |
| Electricity (Italian grid mix) | MJ | $2.5 \times 10^{-3}$ | Electricity, medium voltage {IT} \| market for \| Cut-off, S |
| Electricity (from PV panels) | MJ | $6.8 \times 10^{-3}$ | Electricity, low voltage {IT} \| electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted \| Cut-off, S |
| Heat | MJ | 0.46 | Heat, from steam, in chemical industry {RER} \| market for heat, from steam, in chemical industry \| Cut-off, S |
| Water | kg | 0.52 | Tap water {Europe without Switzerland} \| market for \| Cut-off, S |
| Transport with 16–32 t lorry | kgkm | 21.2 | Transport, freight, lorry 16–32 metric ton, euro6 {RER} \| market for transport, freight, lorry 16–32 metric ton, EURO6 \| Cut-off, S |
| Transport with small lorry | kgkm | 10.6 | Transport, freight, lorry 3.5–7.5 metric ton, euro6 {RER} \| market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 \| Cut-off, S |
| **Output flow** | **Measuring unit** | **Quantity** | |
| Raw fabric, after weaving | g | 106 | |
| **Cutting** | | | |
| **Input flows** | **Measuring unit** | **Quantity** | **Ecoinvent dataset** |
| Raw fabric, after weaving | g | 111 | |
| Transport with small lorry | kgkm | $1.2 \times 10^{-2}$ | Transport, freight, lorry 3.5–7.5 metric ton, euro6 {RER} \| market for transport, freight, lorry 3.5–7.5 metric ton, EURO6 \| Cut-off, S |
| Electricity (Italian grid mix) | MJ | $1.2 \times 10^{-4}$ | Electricity, medium voltage {IT} \| market for \| Cut-off, S |
| Electricity (from PV panels) | MJ | $3.0 \times 10^{-4}$ | Electricity, low voltage {IT} \| electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted \| Cut-off, S |
| **Output flows** | **Measuring unit** | **Quantity** | **Ecoinvent dataset** |
| Undershirt, after cutting | g | 106 | |
| **Finishing** | | | |
| **Input flows** | **Measuring unit** | **Quantity** | **Ecoinvent dataset** |
| Undershirt, after cutting | g | 106 | |
| Woolen yarn | g | 8.5 | Fine yarn, dyed, from worsted processing (from [35]) |

97.2 kg CO2 eq/kg of fine yarn, dyed--> 97.2*(0.0085+0.106) = 11.13 kg CO2 eq/undershirt (solo per la lana, esclusi weaving, cutting, finishing)

**Table 1.** *Cont.*

| | | | |
|---|---|---|---|
| Electricity (Italian grid mix) | MJ | $7.9 \times 10^{-3}$ | Electricity, medium voltage {IT} \| market for \| Cut-off, S |
| Electricity (from PV panels) | MJ | $2.9 \times 10^{-3}$ | Electricity, low voltage {IT} \| electricity production, photovoltaic, 3 kWp slanted-roof installation, multi-Si, panel, mounted \| Cut-off, S |
| Heat | MJ | 0.10 | Heat, from steam, in chemical industry {RER} \| market for heat, from steam, in chemical industry \| Cut-off, S |
| **Output flows** | **Measuring unit** | **Quantity** | **Ecoinvent dataset** |
| Finished undershirt | Item | 1 | |

A second analysis has been conducted, which incorporates the use phase of the woolen undershirt. The use phase is highly variable as it depends on the individual user's habits. To address this variability, a default scenario has been established as a reference point. Additionally, three sensitivity analyses have been performed to identify the variables that can have a more significant impact on the overall results. The default scenario considers the following assumptions:

- a woolen undershirt is worn an average of 3 times before washing [36];
- the wearing frequency of a single next-to-skin garment is 8.3 wearings/month [36];
- a woolen undershirt is used for 6 months/year;
- a woolen undershirt is used for 3 years before disposing of it [36];
- the energy used to wash 1 kg of wool with a washing machine is 0.23 kWh [36], and an Italian energy mix is used in the inventory;
- the water used to wash 1 kg of wool with a washing machine is 17.9 L [36];
- the detergent used to wash 1 kg of wool is 6.38 g [16], and a non-ionic surfactant is used as a proxy for the inventory.

Impact results were calculated for one wearing of the woolen undershirt under the above-mentioned conditions.

A sensitivity analysis was carried out to analyze how the impacts changed as a function of (i) the number of years before disposal (ranging from 1 to 10 years); (ii) the number of wearings before washing (ranging from 1 to 10 days); (iii) the wearing frequency (ranging from 4 to 15 wearings/month). In this sensitivity analysis, one variable is changed at a time, while keeping the other variables fixed. This approach allows readers to understand the individual impact of each variable on the overall results without their interactions influencing the outcome. By systematically altering one variable at a time, the study is able to pinpoint the specific factors that have the most significant effect on the results.

## 3. Results

The impact assessment was conducted with the method EF 3.0, in line with the Product Environmental Footprint (PEF) framework. Table 2 presents the results of the impact assessment for the production of one undershirt, considering cradle-to-gate boundaries.

A contribution analysis has been developed to identify the main sources of environmental impacts within the product life cycle, as shown in Figure 2. It was found that for almost all the impact categories, the main contribution to the total impact of the analyzed undershirt is the farming phase. For the climate change indicator, the grazing phase accounts for 82% of the overall impact.

11.7-11.3 = 0.4 kg CO2 eq per weaving, cutting, finishing di 1 canotta

**Table 2.** Potential environmental impacts of one woolen undershirt.

| Impact Category | Unit | Potential Impact |
|---|---|---|
| Climate change | kg $CO_2$ eq | $1.17 \times 10^{1}$ |
| Ozone depletion | kg CFC11 eq | $2.49 \times 10^{-7}$ |
| Ionizing radiation | kBq U-235 eq | $1.53 \times 10^{-1}$ |
| Photochemical ozone formation | kg NMVOC eq | $1.14 \times 10^{-2}$ |
| Particulate matter | disease inc. | $1.76 \times 10^{-6}$ |
| Human toxicity, non-cancer | CTUh | $8.45 \times 10^{-8}$ |
| Human toxicity, cancer | CTUh | $3.62 \times 10^{-9}$ |
| Acidification | mol $H^{+}$ eq | $2.50 \times 10^{-1}$ |
| Eutrophication, freshwater | kg P eq | $2.81 \times 10^{-3}$ |
| Eutrophication, marine | kg N eq | $4.30 \times 10^{-2}$ |
| Eutrophication, terrestrial | mol N eq | 1.10 |
| Ecotoxicity, freshwater | CTUe | $1.81 \times 10^{2}$ |
| Land use | Pt | $1.14 \times 10^{3}$ |
| Water use | $m^3$ depriv. | 2.15 |
| Resource use, fossils | MJ | $2.78 \times 10^{1}$ |
| Resource use, minerals and metals | kg Sb eq | $2.13 \times 10^{-5}$ |

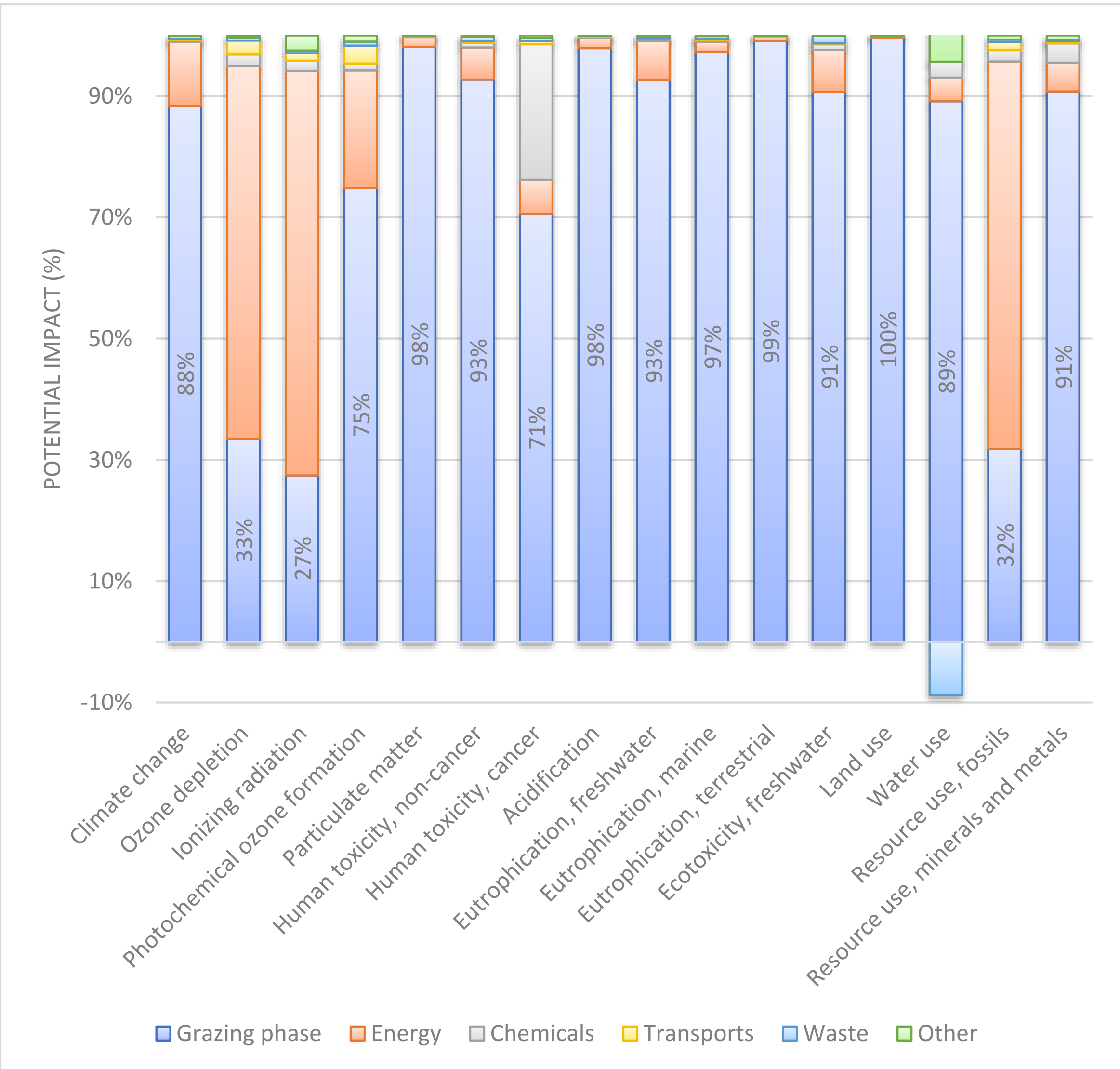


**Figure 2.** Contribution of grazing phase, energy, chemicals, transportation, waste, and other (mainly materials) to the overall impact of the analyzed undershirt.

The energy (electricity and heat) consumed throughout the value chain was found to have varying impacts ranging from 0.2% to 66.7%. The impact of energy is significant for the indicators of ionizing radiation (66.7%, mainly due to nuclear energy imported from France), fossil resource use (63.9%), and ozone depletion (61.5%). As far as the climate change indicator is concerned, energy accounts for only 10% of the total impact, also thanks to the adoption of photovoltaic panels by the company producing the undershirt. Starting from the inventory data, the reader is able to eventually assess and compare the same processes but with different energy mixes. The impacts of chemicals, mainly from textile dyeing, result in significant effects only for the indicator of human toxicity (cancer), which, however, is not yet a robust LCA indicator.

Transports from Australia (where raw lanolin-containing wool is produced) to Italy produce a limited share of the overall impact of the analyzed undershirt. The transportation impact was found to be lower than 3% of all impact categories, indicating a relatively minor contribution.

Considering also the use phase, impacts are provided for one wearing for each impact category of the EF 3.0 method (Table 3).

**Table 3.** Potential environmental impacts of one wearing of the analyzed woolen undershirt (default scenario).

| Impact Category | Unit | Potential Impact |
|---|---|---|
| Climate change | kg $CO_2$ eq | $8.34 \times 10^{-2}$ |
| Ozone depletion | kg CFC11 eq | $2.21 \times 10^{-9}$ |
| Ionizing radiation | kBq U-235 eq | $1.58 \times 10^{-3}$ |
| Photochemical ozone formation | kg NMVOC eq | $8.93 \times 10^{-5}$ |
| Particulate matter | disease inc. | $1.19 \times 10^{-8}$ |
| Human toxicity, non-cancer | CTUh | $6.09 \times 10^{-10}$ |
| Human toxicity, cancer | CTUh | $2.75 \times 10^{-11}$ |
| Acidification | mol $H^+$ eq | $1.69 \times 10^{-3}$ |
| Eutrophication, freshwater | kg P eq | $2.00 \times 10^{-5}$ |
| Eutrophication, marine | kg N eq | $2.94 \times 10^{-4}$ |
| Eutrophication, terrestrial | mol N eq | $7.38 \times 10^{-3}$ |
| Ecotoxicity, freshwater | CTUe | 1.29 |
| Land use | Pt | 7.69 |
| Water use | $m^3$ depriv. | $1.82 \times 10^{-2}$ |
| Resource use, fossils | MJ | $2.58 \times 10^{-1}$ |
| Resource use, minerals and metals | kg Sb eq | $1.88 \times 10^{-7}$ |

Results of the sensitivity analysis show that habits related to the use phase have a significant influence on the impact result. Graphs visually show the relative impacts of the analyzed undershirt at varying numbers of years before disposal (Figure 3), numbers of wearings before washing (Figure 4), and wearing frequency (Figure 5).

As it can be noticed from the graphs, the number of years before disposal has the highest influence on the impact results; 5 and 10 years of usage of the woolen undershirt reduce the impact on climate change by 78% and 88%, respectively, compared with one year of usage. On the other hand, the number of wearings before washing has a minor effect on the final impact; as far as climate change is concerned, a 10-day usage interval lowers the impact by only 14% compared with a 1-day usage and by only 4% compared with a 3-day usage (default scenario). The wearing frequency has a significant effect on the reduction in impacts; the use of a single undershirt for 15 days/month lowers the impact on climate change by 71% compared to using it for only 4 days per month.

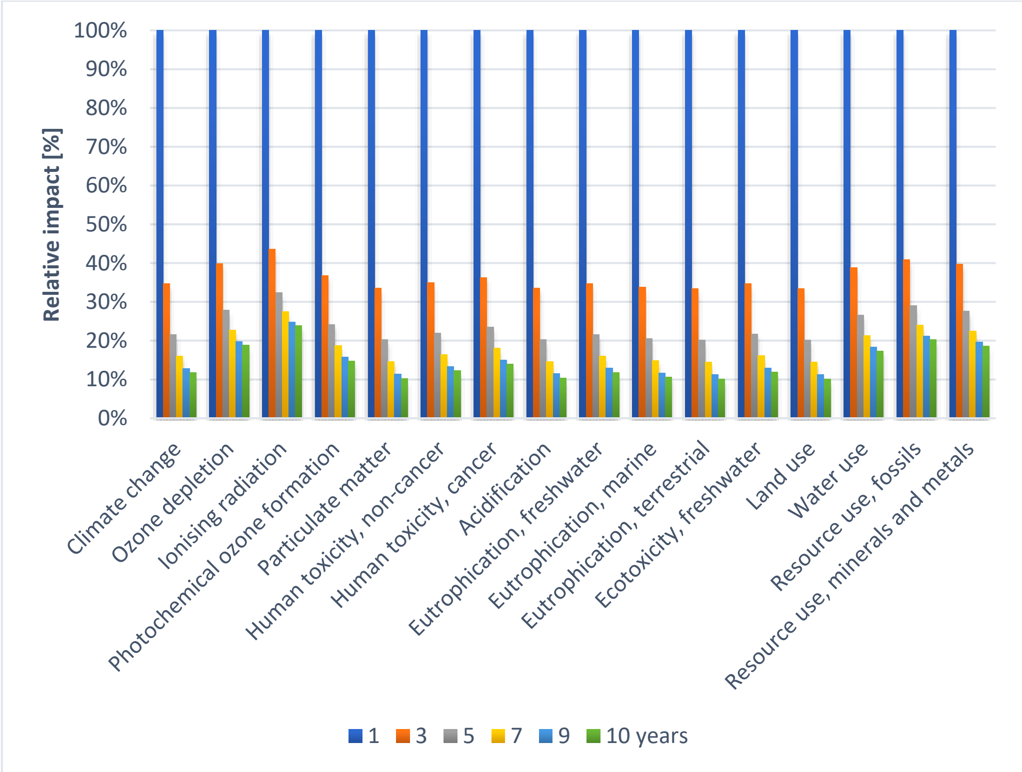


**Figure 3.** Relative impact results of one wear of the analyzed undershirt for varying numbers of years before disposal (from 1 to 10 years).

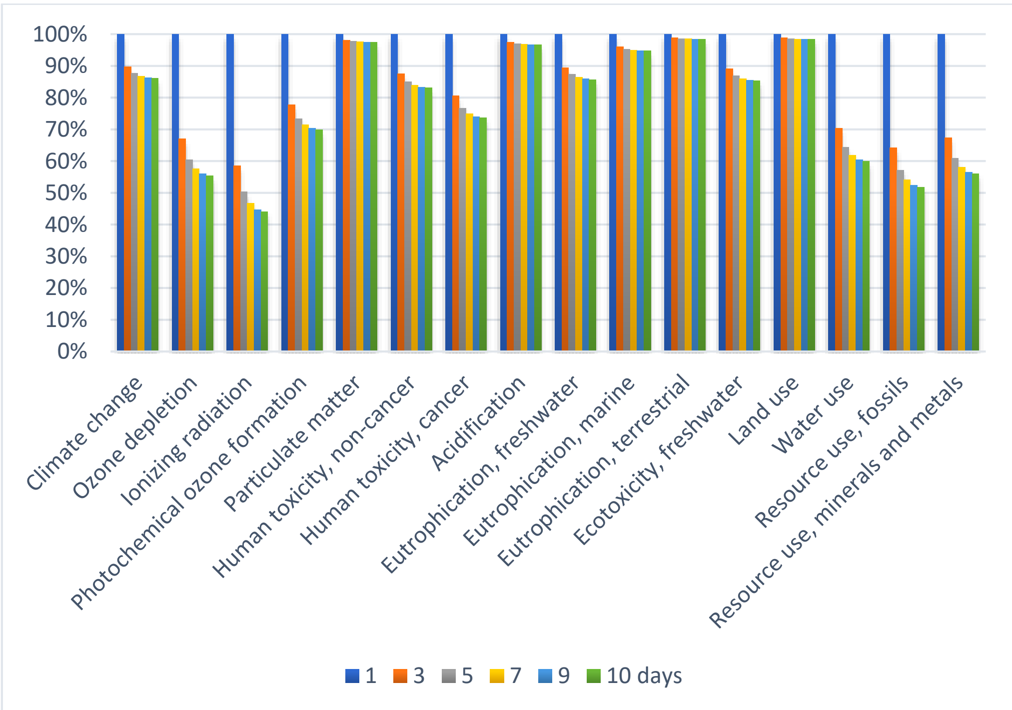


**Figure 4.** Relative impact results of one wear of the analyzed undershirt for varying numbers of days before washing (from 1 to 10 days).

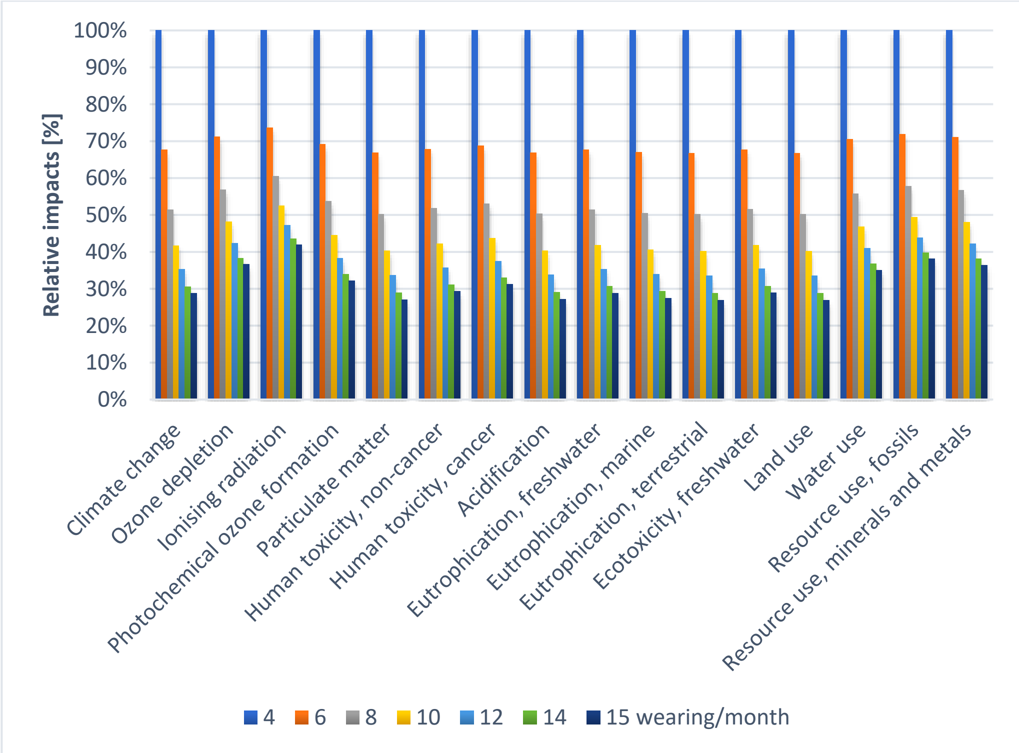


**Figure 5.** Relative impact results of wearing the analyzed undershirt at varying frequencies (from 4 to 15 wearing/month).

## 4. Discussion

From the environmental assessment of the analyzed woolen undershirt, it emerges that for most indicators, a large share of the impact is attributable to the grazing phase, confirming results of previous scientific studies [37–41]. However, it has to be emphasized that for this phase, secondary data from the Ecoinvent database were used in the analysis, because of the unavailability of information about the origin of the wool and, as a consequence, on the inventory of any specific farm. This is a common issue in the textile sector, since tracing the provenance of wool is currently still challenging because of the complexity of supply chains and limited adoption of traceability practices. This critical point hinders the comparability of different woolen textile products and suggests that, in case of unavailability of primary data for the grazing phase, comparisons between different studies can be relevant only if the same dataset for the raw wool is used. Also, for this reason, specific guidelines in the textile sector (currently under development) are necessary for enabling fair comparisons between products of the same category.

Regarding the company under study, the results indicate that the weaving, cutting, and sewing phases have limited environmental impacts compared to other stages of the product life cycle. This result is in line with the previous literature, which highlighted that the transformation of the wool is generally responsible for lower impacts [39,42]. It has to be noticed that the use of a different energy mix could modify the impact results. The overall impact of the analyzed underwear is an interesting result, especially considering that it represents a basic clothing item. Impact results of the same order of magnitude were obtained by Bech et al. [24]. However, generally, comparability with other similar studies remains challenging due to several reasons: (i) different clothing items (e.g., underwear and sweaters) are not directly comparable, as their functions can vary significantly; (ii) even items that are similar, like underwear, but produced with different fibers may not always be comparable due to the distinct properties and functions of each material (woolen undershirts could not be substitutes for cotton undershirts); (iii) variation in the settings of the LCA study, such as different functional units (FUs) and system boundaries, further complicates the comparability of studies. Given these complexities, it is crucial to interpret the results of the study within the specific context of the woolen undershirt and avoid making direct comparisons with other dissimilar products or studies. Specific information about this product (such as the weight of one underwear item) is provided in the methodology section to allow for the possibility of converting impacts into other functional units and to facilitate eventual comparisons with other textile products. In addition, the chosen functional unit will probably be the most suitable for future alignment with the PEFCRs on apparel and footwear (subcategory of underwear), as soon as these guidelines become available. According to the current draft of the PEFCRs [15] the functional unit could be a day of wear of one piece of the analyzed apparel product.

*Contribution of This Study*

This study contributes to knowledge, practice, and managerial implications. Firstly, the inclusion of robust and recent primary data for the phases of weaving, cutting, and sewing enhances the body of knowledge on textile impact assessment. The calculation of impacts on different indicators provides a deeper understanding of the environmental impacts associated with different phases of the undershirt's life cycle, from raw material production to manufacturing and use. In addition, the research highlights the role of user habits in the impact of clothes. These aspects, beyond being valuable for further research, raise awareness among industry stakeholders about the significance of production and use phases in the garments' life cycle. This awareness can lead to more informed decision making and the adoption of eco-friendly practices by companies, policymakers and users. Furthermore, this study emphasizes the need for guidelines that standardize and improve the accuracy of environmental impact assessments in the textile sector. Lastly, since environmental research in the textile sector plays a strategic role in achieving carbon neutrality goals, this study underscores the urgency and importance of incorporating sustainable practices in the industry's operations.

## 5. Conclusions and Recommendations

A life cycle assessment of a black woolen undershirt has been developed in this study. The functional unit chosen for the "cradle-to-gate" analysis was one black undershirt for women (medium size) [15]. This study has also extended the system boundaries until the use phase by introducing assumptions about users' habits. Through a sensitivity analysis, it has become evident that these habits can significantly influence the impact results of the woolen undershirt. The sensitivity analysis has been instrumental in identifying critical aspects that require attention to effectively reduce the environmental impact of the product. Notably, the sensitivity analysis revealed the following key findings. (i) The number of days of usage before washing has a limited influence on the potential environmental impacts; (ii) on the other hand, both the frequency of usage and the number of years before disposal play pivotal roles in determining the overall environmental impact of the woolen undershirt.

From this study, it is clear that common rules for the assessment of the use phase are necessary to estimate the lifetime impact of a piece of underwear. Therefore, the average number of times a woolen undershirt is worn can vary highly, depending on several factors, including individual preferences, care practices, and the quality of the garment. Typically, woolen garments, including undershirts, are known for their durability and ability to resist odors. Wool fibers have natural properties that make them resistant to microbial growth and moisture absorption, which can contribute to a longer lifespan and multiple uses before washing. Wool also has good elasticity, allowing it to retain its shape even after frequent use. These considerations suggest that the high impact due to the sheep grazing phase could be mitigated by a longer typical lifespan for this kind of product.

As discussed, the main limitations of this study are the lack of primary data for the sheep grazing phase and the variability of the use phase due to consumer habits.

Once guidelines become available, the present work will be further developed, extending the system boundaries to include the end-of-life phases and aligning the assumptions made for the use phase.

It is expected that this report, together with current and future studies on environmental performances of garments, will provide crucial information to the textile sector to help it reach the ambitious goal of carbon net zero.

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