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# Uncertainty of Life Cycle Assessment Studies for Blended Textiles

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***Abstract* – Textile fibres are derived from natural and artificial fibres and, in some cases, are blended together to ensure optimum properties. Textiles made from cotton and polyester blends currently hold a significant market share as they are relatively inexpensive, offer excellent performance, and have complementary properties. However, the production and consumption of textiles contribute significantly to environmental degradation and greenhouse gas emissions, but the scale of the impact is uncertain and under debate. This is also the case in studies of cotton and polyester blends, as a detailed life cycle inventory of the production of this material is absent in the scientific literature, thus affecting its environmental impact assessment. Therefore, the study aimed to identify the limitations and assumptions used so far in the environmental assessments of cotton and polyester blends and to assess the uncertainties they may introduce in future environmental assessments. Two methods were used: literature analysis and scenario-based life cycle assessment. The literature analysis summarized five studies and reports that have carried out an environmental assessment of blended textiles and provided inventory data. The results of the life cycle assessment showed that it is not possible to fill the knowledge gap by creating a new life cycle inventory using existing literature data. This is because the uncertainty in results was too high, reaching as much as 772 % difference from the baseline scenario. Nevertheless, this study is a step towards a complete life cycle inventory and can improve the future environmental assessment of textile blends.**

***Keywords* – Cotton; environmental impact; fabric; Life Cycle Inventory (LCI); literature analysis; mixed fibre; polyester.**

## 1. INTRODUCTION

The textile industry has a significant environmental impact due to resource-intensive production and high demand for textile products [1]. In the European Union, textiles are the third largest category regarding land and water use and the fourth largest category regarding negative environmental impact and climate change [2]. This impact will only increase as consumption is expected to grow rapidly under the current business-as-usual approach. The production of textiles is the most impactful part of their life cycle, as it consumes large amounts of energy, water, and chemicals [3], [4]. Overall, these impacts can account for almost 70 % of the total life cycle environmental impacts – fibre production (38 %), yarn

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production (8 %), fabric production (6 %), and wet processing (15 %) [5]. However, this depends on the fibre type, processing methods, and technologies.

Textile production and finishing include a variety of technological phases, depending on the desired properties and specific use case of the final product. The basis for the properties is ensured by various types of fibres – man-made, natural, and artificial which offers different properties and often multiple types of fibres are combined to achieved desired properties for the final product [6]. The most commonly used natural fibre for textile production is cotton, making up 23 % of all fibres produced globally [7]. Cotton production has significant negative environmental and social impacts despite its natural origin. These impacts are caused by the intensive use of land, water, pesticides, and chemicals in the production process [8].

Man-made fibres can be classified by their polymeric origin: natural and synthetic polymers [8]. Polyester is the most widely used synthetic fibre, accounting for 52 % of textile fibres [7]. Environmental concerns are mainly linked to dependence on fossil resources for materials and energy [9]. In the production of polyester textiles, harmful chemicals and dyes are also often derived from fossil resources. Another issue with synthetic textiles is the creation of microplastics during their use and at the end of their life cycle [10].

Blended textiles are commonly used because blending two or more fibre types gives combined and unique characteristics [6]. The most common blended textile on the market is cotton/polyester (CO/PES), used in different proportions. This blend is so popular and widely used in everyday clothing as polyester provides durability, anti-wrinkle properties, fast drying, and shape retention, while cotton offers comfort, moisture control, and breathability of fabric [11]. However, once a blended textile reaches the end of its life cycle, significant challenges arise because the various blends and complex structures make recycling complicated [6], [12]. Cotton and polyester blends are no exception. Moreover, the different percentages of blends prevent a standardized system for their separation and recycling.

The most widely applied method to evaluate the environmental impact of a product is the life cycle assessment (LCA) [13]. The analysis can cover the entire life cycle, from raw material extraction to the end of the life cycle, such as disposal or recycling. The LCA method is also used to evaluate textiles. Numerous LCA studies have been performed to assess textiles, taking into account variables such as fibre, processing methods, and the type of textile product manufactured [14]–[16]. Also, some studies focus specifically on a particular stage of the life cycle, for example, wet processing [17] recycling and reuse [18]

When performing an LCA, uncertainty is one of the main factors affecting the reliability of the LCA results [19]. Uncertainty in LCA arises in several ways and can be divided into nine classes [20]. The most commonly measured and considered type of uncertainty is the parameter uncertainty which includes variability and uncertainty in model input parameters. The two most widely used methods for quantifying uncertainties in this area are the Monte Carlo simulation and sensitivity analysis [19]. Monte Carlo simulation is a numerical propagation of uncertainty that operates by generating random samples for all input variables, inserting these values into the model to obtain results, and analysing the impact on the results [20]. Sensitivity analysis has many definitions and is used in various ways. It can be used in the same way as the previous method, by changing numerical inputs or by changing specific system characteristics [20]. If a system characteristic or set of parameters is changed, a scenario analysis is performed where different scenarios are run and compared with each other. Scenario analysis can be considered as a form of sensitivity analysis [20].

A knowledge gap was identified when looking more closely at the LCA studies on CO/PES blends. Several studies have been carried out on the environmental impact of this material [13], [21]–[23], but they do not cover a detailed life cycle inventory (LCI). Wagner *et al.* also identified this knowledge gap [13]. A literature review is necessary to develop a complete

LCI for CO/PES blends. This will improve the understanding of what has been studied so far, what assumptions have been made in the LCA of blended textiles, and why a comprehensive LCI has not been developed. Therefore, the aim of this study is to review the literature on environmental assessment studies of cotton and polyester blend production and to identify what data assumptions have been made so far and to assess how these data variations can introduce uncertainties in environmental impact assessments using scenario-based life cycle assessment. Textile production and consumption are known to contribute to environmental degradation and greenhouse gas emissions, but the actual size of this impact is still unclear and under debate [4]. Thus, a step closer to a complete life cycle inventory can help assess textiles' environmental impact more accurately, leading to improved knowledge on their sustainability.

## 2. METHODOLOGY

When developing new technologies for recycling processes, their environmental impact needs to be assessed in comparison with existing technologies on the market [18]. Recycling technologies for textiles are currently under active research. In order to compare the environmental impact of blended textile recycling processes with that of virgin textile production, an environmental impact assessment is necessary. Thus, the final objective is to carry out a life cycle assessment of the production and recycling of the polyester and cotton blend. However, in order to do so, a complete LCI is needed. Hence, an algorithm was developed to understand the steps to be taken to reach the final goal (see Fig. 1).

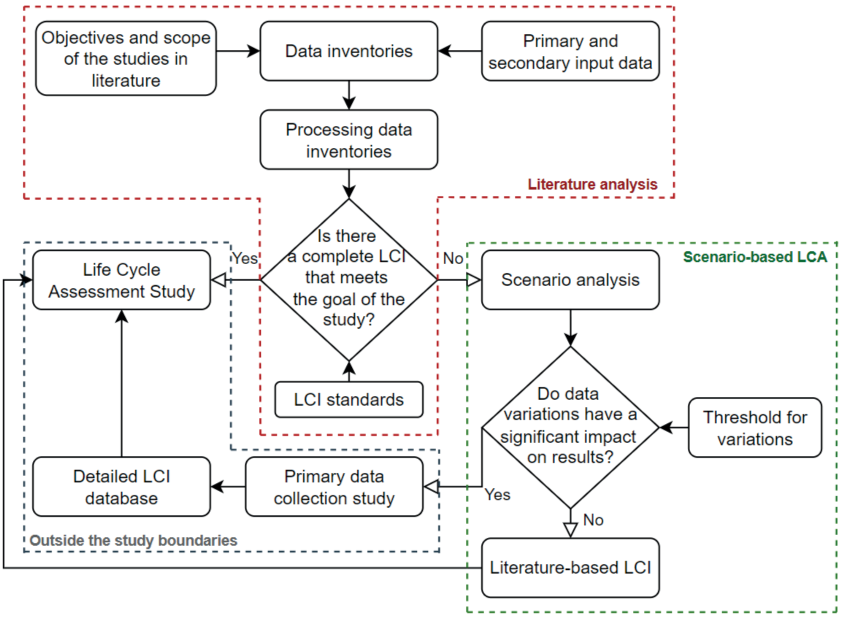


Fig. 1. Algorithm for the methodology.

Initially, a literature analysis should be carried out to obtain a complete LCI for blended textiles. To determine whether the LCI obtained from the literature is complete, the inventory standards for the specific product should be analysed. If a complete LCI is already available in the literature, it can be used as the LCI base for the LCA study. Certainly, minor adaptations should be made to make it more suitable for the specific product under investigation. On the other hand, if a complete LCI is not available in the literature, further analysis will be needed to determine whether a complete LCI can be developed from the data available in the literature.

The aim of the further analysis is to investigate the impact on the life cycle assessment if the LCI were to be created from the inventories found in the literature. It is therefore necessary to choose a base inventory that is the most relevant to the scope of the study and the most complete inventory. The analysis can be carried out using Monte Carlo simulation or sensitivity analysis by varying a number of input parameters based on data found in the literature. In this case, several parameters would be changed separately and the impact on the system of a particular parameter would be measured. However, the parameters are interrelated, e.g., hydrogen peroxide and sodium hydroxide depend on each other [24], so this relationship would be ignored. It is therefore better to carry out a scenario analysis in which several parameters can be changed simultaneously.

Scenario analysis is most often used to develop and test future scenarios or best and worst case scenarios [20], for example future-oriented LCA with qualitative scenarios for agri-food sector [25], scenario-based LCA to evaluate future impacts of offshore wind [26] and scenario-based LCA for best and worst case end-of-life scenarios for renewable energy systems [27]. To our knowledge, the use of scenario-based LCA to test data variations and the resulting uncertainties has not been used so far. However, the methodology is suitable for such a study.

In scenario-based LCA each scenario will be based on the baseline scenario and the variable parameters will come from inventories found in the literature. The analysis will result in variations that will be compared to a threshold value to determine whether they are significant or not. If they are not significant, a LCI for the product will be created from the literature data. However, if significant, further research will be needed to obtain primary data to build a new LCI database for blended textiles.

### *2.1. Literature Analysis*

The literature analysis started with a bibliometric analysis to gain an overview of the research area and to identify the main keywords for further use. Bibliometric analysis is a quantitative method used to assess the current state of a research field by looking at the interrelationships between scientific publications in that field [28]. The analysis is based on a large number of scientific publications, which are analysed using software that uses statistical and network tools. *VOSviewer* software was used in this study.

The aim was to gain insight into research on the environmental impact of blended textiles, particularly CO/PES blends. For bibliometric analysis, Scopus or Web of Science databases are recommended [29]. The Web of Science database was used in this study, as 381 results were found for the given keywords, while 211 results were found in the Scopus database. The keywords were combinations between environmental impact and environmental assessment and between mixed textiles, blended textiles, and cotton-polyester blends, for example, environmental impact mixed textiles. In total, six keywords were created and separated by "OR".

After the first analysis, a number of words were identified and changed in the original file as they had the same meaning but different spellings, e.g., LCA and life-cycle assessment were replaced by life cycle assessment. After that, a threshold was chosen. The number of keyword occurrences above 12 was selected because logical clusters were formed, and the number of words was not too high.

Using the identified keywords, further literature analysis was carried out to summarize studies on the environmental assessment of CO/PES blend production. To do this, keywords from the life cycle assessment cluster were used mainly, but occasionally, keywords from other clusters, like wastewater and toxicity, were used. In addition to the existing keywords, authors also searched for studies on specific stages of textile production – yarn sizing, weaving, pre-treatment, dyeing, and finishing. Three databases were used – Web of Science, Google Scholar, and Scopus. The studies were qualitatively assessed, and only those with sufficient quantitative data were selected for further analysis.

After the literature review, the *Ecoinvent* database was also explored as it will be used in further analysis. The database contains datasets on various sectors, such as energy production, transport, and materials. It contains more than 20 000 interlinked datasets [30]. Therefore, it was examined whether the database includes processes for the production of CO/PES blends.

Also, the Product Category Rules (PCR) were reviewed to get an idea of what a complete LCI should look like. PCRs have been developed for specific products or product groups to be followed when carrying out an LCA for an Environmental Product Declaration (EPD) [31]. They provide guidance on things like system boundaries, functional units and LCI. To determine the threshold of potential uncertainty, LCA standards [32]–[34] and methodology study [20] were reviewed.

### *2.2. Scenario-Based Life Cycle Assessment*

LCA method was used to analyse the data from the literature review. The aim of the analysis was to evaluate the potential uncertainties on the environmental assessments of CO/PES blended textiles due to differences in available data and assumptions made in the literature. When comparing scenarios against each other, it is not the value of the impact score that matters, but the difference or ratio between the impact scores. Thus, absolute values are irrelevant when assessing uncertainty [20]. The results of the LCA scenarios will therefore be presented as ratios. It is important to note that each study on which the scenarios are based has different inputs and processes with various technologies. It is also one of the sources of uncertainty in LCA. The literature review shows that studies often use data from the literature that are close to the target but do not come from exactly the same technological processes as the specific case [13], [23]. This is done in the absence of specific data. Therefore, the current analysis does not take into account the variety of technologies in order to consider their impact on uncertainty.

The scope of the LCA was based on the study on which the baseline scenario is based [13]. The functional unit in the reviewed study is woven doctor's trousers (unisex) in white with two side pockets and two back pockets with material parameters cotton-polyester yarn (35/65), 470 dtex [13]. However, the material parameters are only relevant at the beginning of yarn production, as all other production processes have been adopted from cotton production [35]. In the current study, only fabric production is considered, so the functional unit is 1 kg of cotton and polyester blended textile with the same material parameters. The unit of weight was used because the reviewed study inventory was attributed to 1 kg of fabric [13].

LCA from cradle to gate was applied and covers the following processes: fibre extraction, yarn production, weaving preparation (sizing), weaving, pre-treatment, continuous dyeing, and fabric finishing. A more detailed description of the processes is given in the study by V. Wagner *et al.* [13]. The LCA was performed according to ISO 14040/14044 standards. The *SimaPro* 9.5 software was used for the analysis. Input datasets were taken from the *Ecoinvent* 3.8 database. The *ReCiPe* Midpoint (H) V1.08 life cycle impact assessment method was chosen [13].

## 3. Results

### *3.1. Literature Analysis on Blended Textile Environmental Impact Assessment*

#### *3.1.1. Bibliometric Analysis*

As a result, 31 keywords were identified that occurred 12 or more times. The keywords were linked by 278 links and formed four clusters. The keywords and their links are shown in Fig. 2. The most popular keyword was waste (36 occurrences), followed by textile (35 occurrences), and next came life cycle assessment and wastewater (34 occurrences). Looking at the total link strength, the order was similar, except for the second strongest connection, shown by sustainability, indicating a high correlation with other words, although occurring less than other words.

The largest cluster was around the keyword wastewater and degradation, indicating that much of the research in this area deals with textile wastewater and textile end-of-life. The next cluster in size was around the keywords waste and textiles, linking words such as mechanical performance, showing that research is also being done on the technical side of blended textiles. The last cluster, which was of considerable size, was around the keyword life cycle assessment, meaning that studies are carried out on the environmental impact of blended textiles over their whole life cycle, taking into account sustainability and circular economy aspects.

An important finding was that life cycle assessment is not closely linked to wastewater, as it is not linked to terms such as wastewater, toxicity, and heavy metals. This suggests that existing LCA studies on blended textiles are likely to pay little attention to the wastewater and its toxic effects. Also, keywords related to greenhouse gas emissions do not appear, which means that this aspect has not been sufficiently researched or may not be relevant when considering the environmental impact of a blended textile.

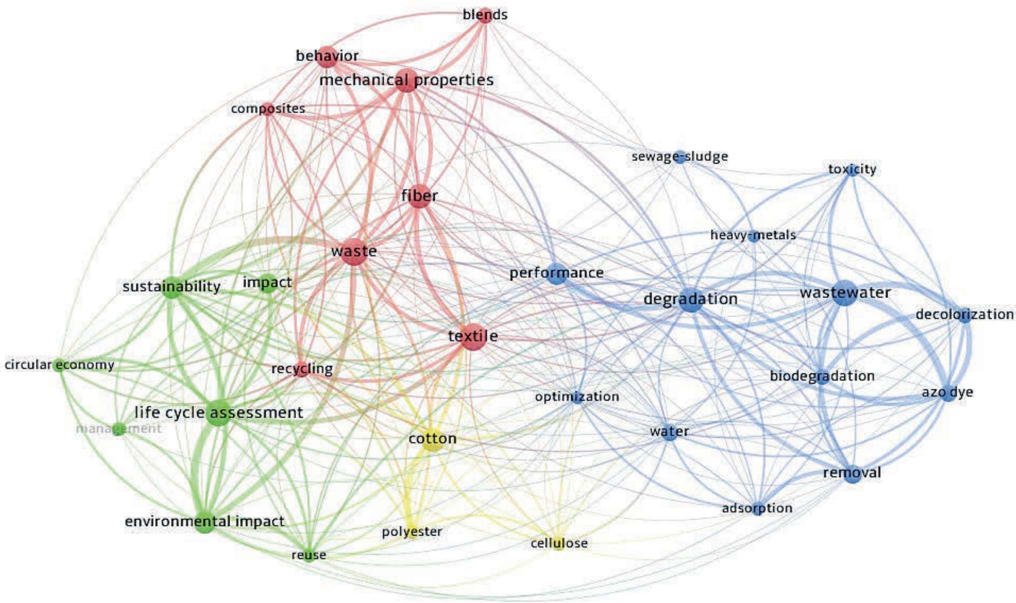


Fig. 2. Keyword co-occurrence with a threshold of at least 12 occurrences.

### 3.1.2. Environmental Assessment of the Production of Cotton and Polyester Blends

Many review and research studies were reviewed before it was possible to compile studies on the environmental impacts of CO/PES production relevant to this study. Most of the reviewed research does not directly address the CO/PES blend production [15], [36], use generic data [23], use pre-built processes from databases such as *Ecoinvent* [37], or do not give detailed input data [22]. It was confirmed that no complete LCI on CO/PES production is available in the literature. However, several studies and reports were found with data partially covering production, see Table 1.

TABLE 1. STUDIES AND REPORTS THAT PARTIALLY COVER DATA ON THE ENVIRONMENTAL IMPACT OF CO/PES PRODUCTION

| Product | Material | Functional unit | Processes covered | Data covered | General assumption | Publication year | Source |
|---|---|---|---|---|---|---|---|
| **Medical workwear** | CO/PES | woven doctor's trousers in white with cotton-polyester yarn (35/65), 470 dtex | yarn spinning, sizing, weaving, pre-treatment, dyeing and finishing | Input: Energy, water, chemicals.<br>Output: water emissions, waste | All data taken from cotton production except for yarn spinning | 2023 | [13] |
| **Fabric** | CO/PES | 2 tons of polyester-cotton product | pre-treatment, dyeing and finishing | Input: Energy, water, chemicals.<br>Output: water emissions, air emissions | Data were obtained from commercial companies, but it is not specified what, if any, assumptions were made | 2018 | [38] |
| **Hospital uniform** | CO/PES | hospital uniform, cotton-polyester weave | yarn spinning, weaving, dyeing and finishing | Input: Energy, water, chemicals<br>Output: water emissions, air emissions, waste | Excluding sizing and de-sizing, and only dyeing is specifically for CO/PES | 2019 | [21] |
| **Fabric** | CO/PES | 100 kg of cotton-polyester fabric | pre-treatment, dyeing | Input: Energy, water, chemicals<br>Output: water emissions | The data is from a company report, but potentially outdated | 2003 | [39] |
| **Fabric (BAT)** | CO and CO blends | n/a | pre-treatment, dyeing and finishing | Input: Energy, water, chemicals | Cotton and cotton blends are assumed to have the same input parameters, except at the finishing stage | 2023 | [40] |

The most complete LCI on CO/PES production was included in the Wagner *et al*. LCA study [13]. It includes data on primary inputs such as energy and water, which are included in several studies reviewed. Still, it also provides a detailed list of chemicals used and the wastewater characteristics for each process. For complete data, there is a lack of data on air emissions. However, the main problem is that all data are taken for cotton production [35], as the authors found that no data on CO/PES production were available in the literature.

A literature review led to a study on CO/PES fabrics, which included LCI [38]. The data for the study are collected from companies and include data on pre-treatment, dyeing, and finishing. The LCI provides air emissions that were not covered by the previously discussed research, but input parameters and water emissions are limited. Only lye (NaOH) and dyes are listed as input chemicals as they are one of the most important inputs in the production process. The data acquisition and assumptions are also not described, only the fact that the data were obtained from commercial businesses.

The lack of data in the literature on textile input chemicals was also recognized by Roos *et al.* who carried out a study to develop a nomenclature system for textile-related chemicals, that was used to create a generic chemical inventory for use in LCA of textiles [21]. LCI data for several key textile manufacturing processes were collected and compiled into LCI datasets. In addition, LCA was also carried out for some textile products using the established LCI. One was a hospital uniform made of a CO/PES blend. However, the study only looked at one process specifically for the CO/PES mixture – dyeing. Also, the sizing and de-sizing, which uses many chemicals in the pre-weaving and pre-treatment process [13], was not included.

As no other studies were available in the scientific literature that included the required data, various reports were reviewed. For further analysis, the B05 company report and the Best Available Techniques (BAT) for the textile industry report were selected [39], [40]. For company B05, the environmental impact of CO/PES fabric production was reported [39]. Only two processes were reported, and no detailed emission data are available. Furthermore, the report was prepared in 2003, and production technologies have evolved since then, so the data may be outdated.

Unlike the previous case, the BAT report summarizes all current developments in the textile industry [40]. However, this was not an exception, as relatively little attention was paid to textile blends, and in several cases, cotton and cotton blends were assumed to have the same processing and production processes. This may be correct in some cases, but incorrect in others, for instance the dyeing process requires an additional dyeing stage to colour the PES part of the blend in order to obtain a dark colour [41]. This needs to be clarified in order to avoid the assumption that in all cases the same raw materials and processes can be adopted for the production of CO blends as for the production of CO. Emissions from textile production were also considered more qualitatively, and no specific data was compiled to provide insight into the reference values for water and air emissions in the textile industry.

To better understand the differences between the studies, the process-specific data from each study were analysed, and then the values of the shared parameters were summarized in Table 2 and Table 3. It should be noted that these are only the shared parameters, and the tables do not show the other input parameters for each case.

Table 2 summarizes the overlapping input chemicals for three processes – pre-treatment, dyeing, and finishing. Data for the other processes are not included as they were only listed in one study [13]. A switch to the same units of measurement was made to allow the values to be compared with each other. Comparing the input values, it can be observed that inputs like enzymes have quite small variations, on the other hand, some inputs such as sodium dithionite and sodium hydroxide vary considerably. This variation might be driven by the desired properties of the final product – its colour, fastness, etc. [42]. Also are likely due to the different treatment steps and technologies involved in the main processes in each situation, as well as the exclusion of other input chemicals that could smooth out the overall difference. It should also be noted that there are no completely overlapping parameters, indicating that there are no essential chemicals used in all variations of the process and included in the LCI.

TABLE 2. COMPILATION OF OVERLAPPING DATA FROM SELECTED STUDIES AND REPORTS (CHEMICALS)

| | **CO (Medical workwear) [13], [35]** | **CO and CO/PES (BAT)* [40]** | **CO/PES (Hospital uniform) [21]** | **CO/PES (Fabric, B05 company)** [39]** | **CO/PES (Fabric) [38]** |
|---|---|---|---|---|---|
| **Pre-treatment** | | | | | |
| **Enzymes, g kg$^{-1}$** | 4.8 | 5 | – | – | – |
| **Hydrogen peroxide ($H_2O_2$), g kg$^{-1}$** | 35.4 | 10 | – | 65 | – |
| **Non-ionic and ionic surfactant/ Wetting agents, g kg$^{-1}$** | 0.05 | 23.5 | – | – | – |
| **Sodium hydroxide (NaOH), g kg$^{-1}$** | 472.5 | 452 | – | 20 | 7000 |
| **Stabilizing agent, g kg$^{-1}$** | – | 5 | – | 25.3 | – |
| **Sodium silicate/Detergent, g kg$^{-1}$** | – | 14 | – | 48 | – |
| **Dyeing** | | | | | |
| **Sodium dithionite/Sodium hydrosulphite, g kg$^{-1}$** | 2.4 | – | – | 3472 | – |
| **Hydrogen peroxide ($H_2O_2$), g kg$^{-1}$** | – | – | 10 | 19.5 | – |
| **Non–ionic and ionic surfactant/ Wetting agents, g kg$^{-1}$** | 0.02 | 108 | 4 | – | – |
| **Sodium hydroxide (NaOH), g kg$^{-1}$** | 65.3 | – | 12 | 42.5 | – |
| **Sequestering agents, g kg$^{-1}$** | – | 144 | 6 | – | – |
| **Anti-migration agent, g kg$^{-1}$** | – | 900 | – | 198.4 | – |
| **Acetic acid/Vinegar, g kg$^{-1}$** | 5 | 57.6 | 52 | – | – |
| **Vat dye, g kg$^{-1}$** | – | – | 20 | 520.8 | 33 |
| **Reactive dye, g kg$^{-1}$** | – | – | 20 | – | – |
| **Disperse dye, g kg$^{-1}$** | – | – | – | 54.6 | – |
| **Finishing** | | | | | |
| **Softener, g kg$^{-1}$** | 16.2 | 920 | – | – | – |
| **Acid/Acetic acid, g kg$^{-1}$** | 5.1 | 11.5 | – | – | – |

* In some cases, the chemicals were given as g L$^{-1}$ water but no water consumption was provided, so to get g kg$^{-1}$ water consumption was taken from V. Wagner *et al*. study [13].
** In the study, several input chemicals were given as mL kg$^{-1}$, which were converted to g kg$^{-1}$ using density.

Energy and water data were compiled the same way as for chemicals (see Table 3). It can again be observed that there are cases where the differences are minimal, such as water consumption in finishing, and there are also very significant variations, such as water and wastewater in pre-treatment. The least data are available for thermal energy. Zhang *et al.* included in their inventory the amount of coal used, which was most likely used for heating but due to insufficient information, this was not included [38]. The BAT report provides only general data on energy and water consumption in the textile industry but no data on specific materials and processes, except for water consumption in pre-treatment [40].

TABLE 3. COMPILATION OF OVERLAPPING DATA FROM SELECTED STUDIES AND REPORTS (ENERGY AND WATER)

| | **CO (Medical workwear) [13], [35]** | **CO and CO/PES (BAT) [40]** | **CO/PES (Hospital uniform) [21]** | **CO/PES (Fabric, B05 company) [39]** | **CO/PES (Fabric) [38]** |
|---|---|---|---|---|---|
| **Pretreatment** | | | | | |
| **Electricity, kWh kg$^{-1}$** | 0.036 | – | – | 0.049 | 3.55 |
| **Water, L kg$^{-1}$** | – | 23 | – | 23.24 | 615.50 |
| **Wastewater, L kg$^{-1}$** | 15.10 | – | – | 20.40 | 350 |
| **Heat, kWh kg$^{-1}$** | 0.16 | – | – | – | – |
| **Dyeing** | | | | | |
| **Electricity, kWh kg$^{-1}$** | 0.19 | – | 0.70 | 0.014 | 0.45 |
| **Water, L kg$^{-1}$** | 72.72 | – | 75 | 24.80 | 12 |
| **Wastewater, L kg$^{-1}$** | 33.35 | – | – | 19.50 | – |
| **Heat, kWh kg$^{-1}$** | 1.84 | – | 8.33 | – | – |
| **Finishing** | | | | | |
| **Electricity, kWh kg$^{-1}$** | 0.16 | – | – | – | 0.31 |
| **Water, L kg$^{-1}$** | 23.30 | – | – | – | 22.90 |
| **Wastewater, L kg$^{-1}$** | 8.35 | – | – | – | 19.75 |
| **Heat, kWh kg$^{-1}$** | 0.56 | – | – | – | – |

The least included data in the reviewed environmental assessments are water and air emissions. This is consistent with the conclusion of the bibliometric analysis that LCAs and wastewater show no connection. This should not be the case because when it comes to the environmental impact of textile production, much focus is on the toxicity of wastewater [43]. Therefore, LCA studies should also include this aspect to assess blended textiles' environmental impact fully. Only the study about medical workwear includes a detailed composition of the textile wastewater but it is taken from the cotton production [13]. Other studies only include the Chemical Oxygen Demand (COD) [21], [38], [39], which is the most significant component by weight [43]. Therefore, one of the objectives of the following analysis is to find out whether the exclusion of wastewater significantly impacts the results.

It is not possible to develop a comprehensive LCI for CO/PES blended textiles using the data from the literature analysis because some data are unavailable, the differences in the available data are too large, and the assumptions on processes and technologies are not fully clear. Therefore, scenario-based LCA was carried out to see how the differences in available data affect the environmental impact results for CO/PES blends.

### *3.1.3. Ecoinvent Processes*

Following the literature review, the *Ecoinvent* database was checked to assess whether built-in CO/PES production datasets are available. The database includes a textile category in materials and process sections, which contains datasets on textiles and the processes used in their production and use. The materials did not include CO/PES textile material, from which it would have been possible to see input data for its production. Cotton and polyester fibres were available and were used further in the LCA modelling.

Also, in terms of processes, there were no built-in processes specifically for the CO/PES blend. Still, there were various processes for cotton and polyester separately, although not all of them. For example, data on the sizing process was again missing. Processes that could be used for CO/PES modelling with assumptions are synthetic fibre weaving, cotton fibre continuous dyeing, and finishing cotton woven textiles.

#### *3.1.4. Product Category Rules and Uncertainty Threshold*

Several textile related PCRs were considered. According to the United Nations Central Product Classification, the most appropriate PCR was selected, being PCR 2022:04 Fabrics [44]. The guidelines cover system boundaries, data quality requirements, allocation and other key aspects of LCA. However, there is no mention of waste water and its composition or direct emissions to the air. For input parameters, a 1 % cut-off rule is included, which means that 99 % of input variables should be included in the inventory according to their influence on impact categories, mass and energy. These guidelines are mandatory for the development of EPDs, not for research, but they provide an overview of what a complete LCI should look like.

The review of the standards and the study revealed that there is no strict and universal threshold that can be used to assess the uncertainty of results in impact categories [20], [32]–[34]. It was therefore decided to assess the uncertainties qualitatively, based on their potential impact on the ability to establish the LCI and perform the LCA for the CO/PES blended textile.

### ***3.2. Uncertainty Identification through Scenario-Based Life Cycle Assessment***

The LCA study on the medical workwear [13], having the most detailed LCI, was used as the baseline model. It is also the only study to include all manufacturing processes. See Tables 2 and 3 for all input parameter values. Scenarios were created for all studies and reports, summarized in Table 1. The scenarios were built by changing the parameters outlined in Table 2 and Table 3 that were shared with the baseline scenario study. In addition, it was decided to make an exception and add water consumption in the pre-treatment process to the scenarios, although it is not included in the baseline scenario. This was done because it was found in all studies that looked at this process except the baseline case. The changed parameters are shown in Table 4.

TABLE 4. SCENARIOS CREATED AND PARAMETERS CHANGED IN THE PROCESSES

| **Processes** | **Scenario 2 (BAT) [40]** | **Scenario 3 (hospital uniform) [21]** | **Scenario 4 (B05 company) [39]** | **Scenario 5 (fabric) [38]** |
|---|---|---|---|---|
| **Pretreatment** | Enzymes;<br>Hydrogen peroxide;<br>Non-ionic and ionic surfactant/Wetting agents;<br>Sodium Hydroxide;<br>Water | – | Hydrogen peroxide;<br>Sodium Hydroxide;<br>Electricity;<br>Water;<br>Wastewater | Sodium Hydroxide;<br>Electricity;<br>Water;<br>Wastewater |
| **Dyeing** | Non-ionic and ionic surfactant/Wetting agents | Non-ionic and ionic surfactant/Wetting agents;<br>Sodium Hydroxide;<br>Acetic acid/Vinegar;<br>Electricity;<br>Water;<br>Heat | Sodium dithionite/Sodium hydrosulphite;<br>Sodium Hydroxide;<br>Electricity;<br>Water;<br>Wastewater | Electricity;<br>Water |
| **Finishing** | Softener;<br>Acid/Acetic acid | – | – | Electricity;<br>Water;<br>Wastewater |

The scenarios were built without water emissions, as water emissions were only included in the baseline scenario study, so there are no shared parameters to change. However, when carrying out an LCA for textiles, water emissions should be included. In this case, they can be excluded as uncertainty will be assessed rather than specific environmental impacts.

In addition, a scenario was created using built-in *Ecoinvent* processes – the weaving of synthetic fibres, continuous dyeing of cotton fibres, and finishing of cotton woven textiles. For built-in processes, emissions are kept in as the *Ecoinvent* processes include not only direct emissions but also indirect emissions. The reason for this is that it is modelled using inputs from nature rather than from the techno sphere, as the authors of the process have to manually align the emissions. Therefore, it is not possible without in-depth research to distinguish which emissions are direct in order to remove them.

### *3.2.1. Impact Categories and Production Processes*

First, the baseline scenario was analysed, looking specifically at the distribution of the impact of production processes. Life cycle impact assessment provides results for several impact categories. The chosen method has 18 impact categories, each with a corresponding unit of measurement. However, to compare the categories, switching to a common unit of measurement is necessary. This is achieved through normalization. It is the process of normalizing the impact categories to a single dimension and presenting the results in a broader context that indicates the impact of each category in relation to the overall environmental impact [45]. The normalized values for the baseline scenario are shown in Fig. 3. All categories with normalized values greater than 0.0020 are included in the graph, except for global warming (0.0016), which was also included as a widely used category in environmental impact assessments. It should be noted that the results are not original, as the model is based on an existing study [13]. However, the results are not presented and analysed this way, so the following observations are original.

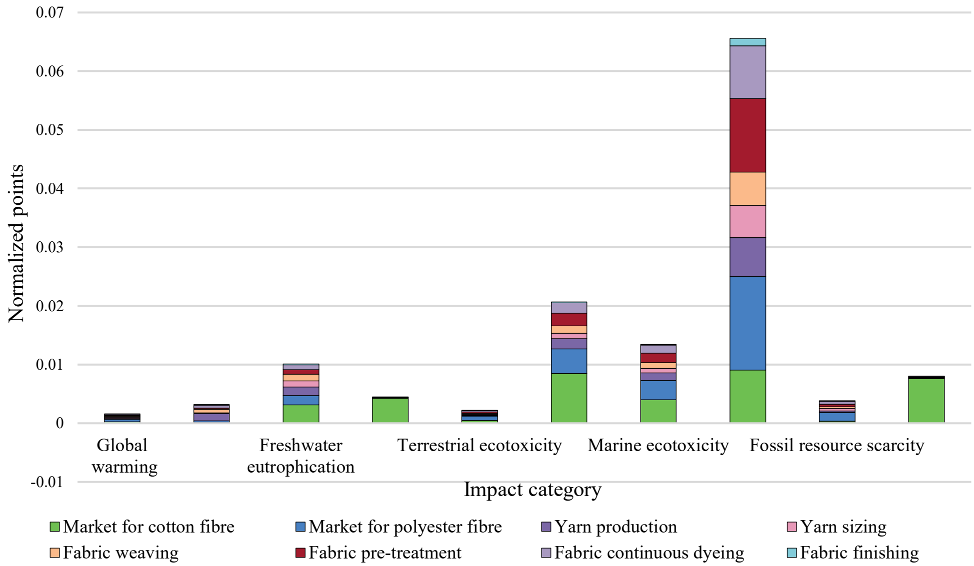


Fig. 3. Normalised results by impact categories for the baseline scenario of cotton and polyester blend production.

It can be observed that the main impact categories are related to toxicity – human carcinogenic toxicity, marine ecotoxicity, and freshwater ecotoxicity. This underlines the importance of having a complete LCI with chemicals, as they are a major source of toxicity. Of the input chemicals, sodium hydroxide had the highest impact, which is explained by the quantity used, as sodium dithionite has the highest impact in Scenario 4, which is based on data from company B05. It is also important to note that the global warming category has a relatively small impact on overall environmental impact. This should be taken into account when analysing the environmental performance of textiles.

Looking at the breakdown of the processes involved, the extraction of raw materials - cotton and polyester fibres - has the highest environmental impact, followed by pre-treatment. Note that this is for the baseline scenario, as the distribution of impact changes when looking at other scenarios. The reference study shows similar results [13], as the second largest impact was related to the extraction of raw materials, while the first was related to the use phase, which is outside this study's scope.

### *3.2.2. Wastewater Importance*

One of the objectives of the analysis was to find out whether the exclusion of water emissions from the LCI significantly changes the results. Therefore, two baseline scenarios were developed – with and without water emissions. The results were then compared with each other, and it was found that 12 of the 18 impact categories had the same results. The results differed significantly in the six categories shown in Fig. 4. These categories have the highest environmental impact compared to the rest, as depicted in Fig. 2, except the human non-carcinogenic toxicity, which shows the highest variation but is not as influential as the others. In contrast, the 10 % difference is shown by human carcinogenic toxicity, which has the highest environmental impact of all categories. Overall, these results show that detailed water emissions are justified to be included in the LCI as they affect the main environmental impact categories in the context of blended textile production.

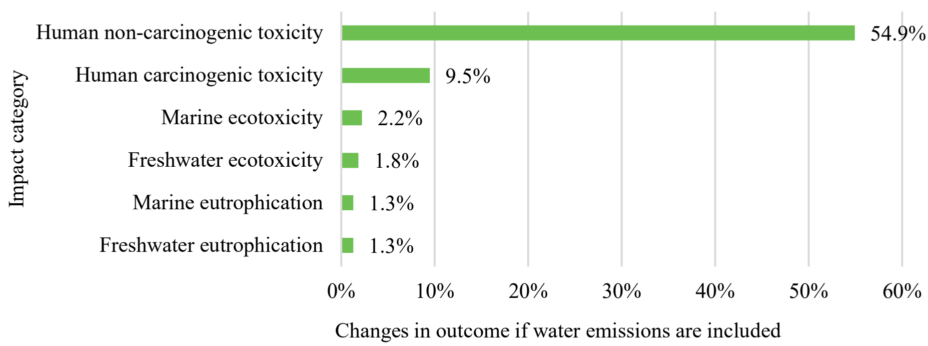


Fig. 4. Variation of results by including detailed water emissions in the production of cotton and polyester blends.

### *3.2.3. Comparison of Scenarios*

As mentioned previously, the aim of this study is not to obtain specific quantitative results but to look at the differences in results. Therefore, the results obtained for each scenario were compared with the baseline scenarios without water emissions and expressed as percentage differences. Fig. 5 summarizes the results obtained in the scenarios for all impact categories.

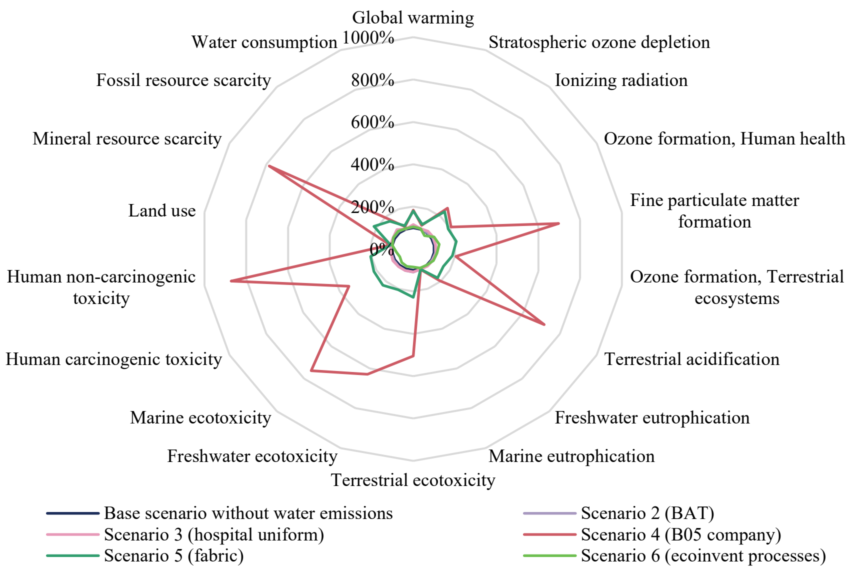


Fig. 5. Comparison of the results by impact categories, using the baseline scenario without water emissions as reference.

Scenarios 2 and 3 show the lowest differences from literature-based scenarios compared to the baseline scenario without water emissions, with average differences of 6 % and 8 %, respectively. These scenarios are based on a BAT and hospital uniform study [21], [40]. The slight difference could be explained by the fact that the sources provide the least data on energy and water, which underlines the importance of these data, and the Scenario 3 study only had data on one of the three processes. The graph also shows that none of the literature-based scenarios have lower environmental impacts than the baseline scenario. This means that the baseline scenario is the best-case scenario regarding environmental impact, at least according to the data available in the literature. However, it is mainly based on cotton production, so it cannot be considered the best option in all cases for the assessment of blended textiles. Although in this specific case it might be that only cotton is treated with dye, yielding a light colour for the final textile, this outcome would not be desirable for all use cases, therefor the same LCI would not be applicable.

Scenario 6 with *Ecoinvent* processes showed, on average, only a 1 % difference from the baseline, but the environmental impacts were lower in some categories. Yet the outcome shows that there is no need to make bigger assumptions and make the model more general by using the built-in processes of *Ecoinvent*.

The most significant changes are found in scenarios 4 and 5, with an average of 288 % and 81 %, respectively. Scenario 5 is based on the Zhang *et al.* study [38], which specifically looked at a blend of CO/PES but used limited input data. In this scenario, only two chemicals were altered, but almost all water and energy inputs were changed, indicating that the water and energy data were most likely responsible for the large changes. Not all processes for producing CO/PES materials are the same, and the choice of process depends largely on the type of finished material and its end use. Consequently, water and energy consumption will vary depending on applied processes and used technologies. On the other hand, it is better to compare parameters for similar end products, such as hospital uniforms in Scenario 3 and in the baseline scenario, as the production processes are more likely to match. In Scenario 5, as in Scenario 4, only four categories are relatively consistent with the baseline scenario – stratospheric ozone depletion, marine eutrophication, land use, and water consumption. The water consumption category does not change significantly, although water consumption increases in Scenario 5, as the impact of this category is mainly driven by cotton extraction.

In the scenario 4, the variation ranges from 3 % to 772 %. This scenario has the most changes in input parameters. Sodium dithionite has the greatest impact as it is used in very high quantities compared to the baseline scenario. Considering that the data for this scenario is from 2003 [39], it is also possible that outdated technologies are causing major changes in results. The graph shows strong peaks for eight categories, exceeding a difference of 350 %. Five of these categories have relatively significant environmental impacts, as shown in Fig. 3. Scenarios 4 and 5 show that results can vary significantly based on the data available in the literature and underline the need for a specific LCI for CO/PES blends.

## 4. Conclusion

A review of the environmental impact assessment studies on CO/PES blends revealed a knowledge gap: several studies have been carried out on the environmental impact of this material, but they do not include a comprehensive LCI. Therefore, the aim of the study was to conduct a literature review on the environmental assessment of the production of CO/PES blends and to identify what assumptions have been made so far and how these assumptions might affect the environmental assessment. A literature analysis was carried out to achieve the objective, including a bibliometric analysis and a review of the scientific literature and the *Ecoinvent* database. The results were used for scenario-based LCA to determine the possible effects of assumptions and data variations on environmental impacts.

A bibliometric analysis of the environmental impact of blended textiles revealed that studies fall into three main groups, covering textile wastewater and end-of-life, the technical side and life cycle assessments. A key finding was that existing LCA studies on blended textiles are unlikely to cover the effects and toxicity of wastewater. Greenhouse gases also appear to be understudied or possibly irrelevant in assessing blended textiles' environmental impacts. This was confirmed by further literature review.

Most of the environmental impact studies on blended textiles do not directly address the production of CO/PES blends, use generic data, or do not provide detailed input data. However, it was possible to summarize five studies and reports that provide some relevant data to move toward a complete LCI. They revealed that the environmental impacts of the sizing process, as well as water and air emissions, are mostly overlooked. Overall, it can be concluded that it is not possible to develop a comprehensive LCI for the CO/PES blend using the data available in the literature. Nevertheless, scenario-based LCA was performed to see what would happen if one tried to establish a complete LCI using the available data.

The scenario-based LCA highlighted the importance of considering input chemicals when addressing blended textiles, something that is often overlooked in practice. These chemicals lead to toxic environmental impacts. Furthermore, while comparing and evaluating blended textiles, it is crucial to concentrate on toxicity categories, such as human carcinogenic toxicity, rather than global warming indicators, as they are more influential for the environmental impact. It is also essential to include a detailed composition of the wastewater as it affects the main environmental impact categories. Finally, the LCA showed that differences in the data available in the literature can lead to considerable uncertainties in results, sometimes as much as eight times more different results. The resulting uncertainties suggests that assumptions and data sources need to be carefully evaluated before use and should be standardized to produce reliable results. Thus, a more detailed database is needed to develop product-specific LCIs for blended textiles in order to avoid such significant uncertainties in future environmental assessments.

The final product and its required properties influence the production processes and technologies chosen, which in turn have an impact on the consumption of chemicals, water and electricity. The main process that determines the chemicals used in textile production is dying. When dyeing blended textiles, there are cases where only CO can be dyed if a light colour is desired. On the other hand, if a darker and brighter colour is desired, both components of the mixture must be dyed; either in one bath or two bath processes. This indicates that there are times when the processes for producing cotton and CO/PES blends may overlap. However, there are cases where the input parameters for a CO/PES blend cannot be considered to be the same as for CO. This largely depends on the colour fastness to washing and/or rubbing as well the other required end characteristics. Thus, when performing an LCA on a blended textile, it is necessary to assess these factors to know which input data to choose. This leads back to the functional unit that describes the amount with defined functions and properties, allowing later comparison of the impact of products providing the same functionality.

The results of this study can be used to understand better what has been done so far and what is missing in the literature. Identified knowledge gaps can be further explored and improved. The main objective was to highlight the impact of knowledge gaps on future research in this area. Further, a primary data collection study is needed to achieve the final goal, which is a life cycle assessment for a blended CO/PES textile. It should be noted that the scenario-based LCA made many assumptions, so the results cannot be used quantitatively and separately and can only be used in the context intended by this study.

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