

ENVIRONMENTAL AND ECONOMIC ANALYSIS OF OPERATING ROOM TEXTILES

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC)

ebli Ente bilaterale

EBLI is the Bilateral Body of the industrial laundry sector, sterilization centers and related medical services, made up of

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EXECUTIVE SUMMARY

Ebli, the Bilateral Body of the Integrated Industrial System for Textile Goods and Services and Related Medical Products, commissioned Ambiente Italia to carry out a study providing a detailed comparison of the environmental and economic impacts of fabrics used in operating rooms within the healthcare sector. The study and the contents of this report were developed with the collaboration of Assosistema and several associated companies, as well as selected organizations from the National Health System representing contracting authorities, and some companies from the textile supply chain.

The analysis compares disposable solutions (nonwoven fabrics, TNT) with Reusable Technical Textiles (TTR), including, for both options, the sterilization phase. The main objective of the study is to provide technical information to industrial laundry companies, textile suppliers, and contracting authorities responsible for laundry and sterilization services in hospitals, highlighting the overall benefits and costs—both environmental and economic—of the two solutions under comparison.

The study is conducted using Life Cycle Assessment (LCA), an approach that covers the entire life cycle of products, from production and use to end of life, and enables the evaluation of global impacts in terms of resource consumption and pollutant emissions.

The LCA is based on ISO 14040 and ISO 14044 standards. Environmental impact assessment was carried out using the European Product Environmental Footprint (PEF) methodology. For Life Cycle Costing (LCC), reference was made to methodologies available in scientific literature. Environmental impact results are presented in terms of Global Warming Potential (GWP) and a single aggregated indicator representing the remaining environmental impact categories. The economic assessment highlights direct costs related to material procurement and washing treatments, costs associated with end-of-life management, and the benefits derived from reduced raw material consumption in the reusable solution compared to the disposable one.

In the healthcare sector, numerous types of textiles are used, such as surgical drapes, gowns (surgical and non-surgical), and bed linen (sheets, pillowcases, etc.); however, this study focuses on the analysis of medical products used in operating rooms. The product type selected for analysis is the one that best represents the activity. The functional unit considered in the study is one item (represented by a specific article, gown, or drape) made of specific fabrics suitable for use in operating rooms, included or not in a dedicated or standard kit, reused 60 times, while maintaining the required fabric characteristics and without significant signs of wear that would prevent its use.

The end-of-life phase of the products coincides with the point at which they lose the qualities that make them suitable for their intended function: for disposable products, this occurs after a single use, while for reusable textile products, items undergo a defined number of washing cycles before being discarded.

System boundaries define the process units to be included in the LCA and LCC studies and the types of input and/or output data that may be excluded from the system. In the analyzed system, foreground processes (defined by the PEF guidance as processes for which direct access to information is possible) include washing activities and the production of TTR products and TNT products. All other product life-cycle stages for which specific data were not available are classified as background processes, including textile and packaging production, transport processes, and product end-of-life management. The life-cycle boundaries extend from resource extraction and raw material production to the point at which the product becomes waste. Within these boundaries, both product manufacturing and washing activities (for reusable products) are included. All transport processes required throughout the

production cycle are considered, as well as the production of auxiliaries and packaging, and waste flows generated over the entire life cycle.

For the development of the LCA study, both specific (primary) data provided by the companies involved, and generic (secondary) data derived from databases and scientific literature were used, referring to technologically, geographically, and temporally equivalent systems. Data collection involved a representative sample of companies from the textile supply chain and healthcare services sector (industrial laundries), through questionnaires and telephone interviews. Data validation was carried out by comparison with published studies, international databases (Ecoinvent 3.10), and scientific literature. The study considered environmental impacts across all sixteen impact categories foreseen by the PEF methodology.

The results highlight that the adoption of reusable TTR solutions leads to a lower environmental impact compared to disposable TNT solutions. Considering the worst-case scenario represented by the landfilling of TTR products, the single-score indicator (which, according to the PEF methodology, synthesizes the environmental impacts of one item) shows that, for gowns, the environmental impact of reusable products is lower than that of disposable ones by a percentage ranging from 48% to 51%, depending on whether the gown is reinforced and on its size.

With regard to Global Warming Potential (GWP), a disposable reinforced XL gown generates 23 kg CO_2 eq per item, compared to 15 kg CO_2 eq per item for the reusable option (–34%), which further decreases to 14.8 kg CO_2 eq per item (–35%) under the mechanical recycling scenario. An even greater advantage is observed for surgical drapes (of various types), where the single-score indicator shows that the environmental impact of reusable drapes is 45% to 55% lower than that of disposable alternatives. In terms of GWP, a disposable TNT head drape generates 39 kg CO_2 eq per item, whereas the same drape made of TTR results in 27 kg CO_2 eq per item (–32%).

The economic analysis, conducted using the Life Cycle Costing (LCC) approach, also highlights significant differences between reusable and disposable solutions. The comparison shows that the total LCC of TTR products is 20% to 50% lower than that of TNT products, with the exception of reusable pillowcases and drapes. Detailed data analysis emphasizes the weight of the raw material component (fabric production), which represents the predominant share of total costs, as well as washing and sterilization services (for TTR only), and various end-of-life scenarios for all textile types.

The calculation also accounts for the benefits derived from raw material savings attributable to the use of TTR solutions. Externality costs were not monetized, as these are clearly addressed in the environmental assessment, thereby avoiding duplication of comparative results. Finally, qualitative considerations were developed to describe additional benefits associated with the use of TTR instead of TNT during the use phase.

1. INTRODUCTION

This document constitutes the complete report of the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) study of textiles used in operating rooms, comparing the purchasing and management services of disposable solutions (TNT) with the rental, washing, and management services of Reusable Technical Textiles (TTR). The study was commissioned by Ebli and carried out by Ambiente Italia S.r.l.

The LCA methodology consists of compiling and evaluating, throughout the entire life cycle, the input and output flows as well as the potential environmental impacts of a product system (definition taken from the international standard UNI EN ISO 14040).

The study was conducted in compliance with the requirements of the following standards:

- ISO 14040:06 Environmental management – Life cycle assessment – Principles and framework.
- ISO 14044:06 Environmental management – Life cycle assessment – Requirements and guidelines, including goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation.

The results are expressed for all environmental impact categories proposed by Commission Recommendation (EU) 2021/9332 of 16 December 2021, concerning the use of common methodologies to measure and communicate the environmental performance of products over their life cycle, as integrated and/or updated in accordance with official documents subsequently published by the Joint Research Centre (JRC).

The Life Cycle Costing (LCC) economic analysis method constitutes the basis upon which Life Cycle Cost Analysis (LCCA) is generally performed. The methodologies adopted are based on guidelines developed by the United States Department of Defense (mid-1960s), originally used to support procurement-related decision-making. In subsequent years, the methodology has been applied across various sectors, leading to the development of multiple definitions and guidelines. Provided for under European public procurement legislation, life cycle cost analysis is ultimately included in Annex II.5 – Technical specifications and labeling of the Italian Public Procurement Code (Legislative Decree No. 36/2023).

1.1. Presentation of the Organization

EBLI is the Bilateral Body of the Integrated Industrial System for Textile Services and Related Medical Products. It was established in 1999 by Assosistema and the trade union organizations most representative of the sector: FEMCA-CISL, FILCTEM-CGIL (formerly FILTEA), and UILTA-UIL. Since its establishment, EBLI has been distinguished by its commitment to creating one of the first bilateral entities in Italy dedicated to analyzing the factors influencing the reference market and the working conditions of employees.

The ambitious and stimulating role undertaken by EBLI is to define—through research, knowledge development, in-depth analysis, and innovation—how actors in industrial relations can contribute both to increasing the competitiveness of the sector and, at the same time, to employment growth and the enhancement of workers' professional skills. As a privileged center for the analysis of the relationship between industrial relations and governance, EBLI also serves as a forum for discussing the link between collective bargaining and social dialogue, as well as the interaction between industrial relations stakeholders and national labor and employment policies.

Assosistema represents companies involved in the production, distribution, and maintenance of individual and collective protective equipment, as well as providers of sanitation and sterilization services for textile and medical devices used in hospitals, nursing homes, private clinics, hotels, restaurants, industrial facilities, and confined environments. Its statutory objectives include the protection, promotion, and development of sector activities, as

well as the safeguarding and coordination of the needs and interests of its member companies. A direct member of Confindustria, Assosistema is affiliated at the European level with ETSA (European Textile Services Association) and ESF (European Safety Federation).

Assosistema represents the entirety of medium- and large-sized companies in the sector, accounting for approximately 63% of the workforce and the majority of the turnover of a sector worth about € 4.2 billion in Italy. The workforce profile (over 35,000 employees) is characterized by high employment stability, with 93% employed on permanent contracts. Companies are located throughout Italy, predominantly in the North (59%), followed by the Center (28%) and the South and Islands (13%). Companies associated with Assosistema share the use of technologically advanced facilities, efficient organizational models, and qualified personnel. They deliver services in compliance with European and national regulations, ensuring the safety and quality of the products used.

The services provided by member companies include:

- INTEGRATED HEALTHCARE SERVICES: Supply, sanitation, and sterilization of reusable textile devices and surgical instruments; product traceability and integrated management of logistics and wardrobe services. The main markets served are hospitals, clinics, and private nursing homes.
- INTEGRATED SERVICES: Supply, sanitation, and integrated management of warehouses and wardrobe services. The main markets served are tourism and hospitality facilities, including hotels, guesthouses, resorts, residences, bed & breakfasts, spa facilities, restaurants, catering services, and corporate canteens.
- OCCUPATIONAL SAFETY: Production and distribution of Individual Protective Equipment (PPE) and Collective Protective Equipment (CPE), as well as occupational safety systems; supply, rental, reconditioning, and maintenance of PPE and CPE in efficient working conditions. The main markets served include healthcare, industry, commerce, agriculture, construction, services, logistics, and law enforcement.
- WORKWEAR: Companies in this segment provide integrated services for the rental, washing, inspection, and maintenance of workwear and personal protective equipment for the industrial, commercial, healthcare, tertiary, and service sectors.

1.2.Objectives and Scope of the Study

The objective of this document is to provide an indication of the environmental impacts and economic costs generated over the entire life cycle (raw material acquisition, production, distribution in the case of TTR, use, and end-of-life) of disposable and reusable textiles used in operating rooms. The report is intended for internal use by the bilateral body and the relevant trade association.

There are essentially two reasons why Ebli commissioned this study:

- to assess the environmental performance of the different textiles used in operating rooms, particularly regarding the reuse phase through laundering
- to compare the costs associated with the choice of disposable textiles versus reusable alternatives

The results of the study may have several applications, including:

- quantifying the environmental and economic impacts associated with the different textiles, detailed for each life cycle phase
- identifying environmental and economic criticalities within the product life cycle and the resulting potential for optimization
- communicating clear and transparent sector-level environmental information on operating room textiles and on the services provided by industrial laundry
- supporting the development of communication strategies (transparent, credible, objective, and comparable) addressed to various stakeholders (market actors, companies, administrative and legislative bodies, interest groups, etc.)
- providing a quantitative data basis, the results of which may be used for the analysis and comparison of life-cycle studies of similar products or services

1.3.Literature review

The study entitled "*An Environmental Analysis of Reusable and Disposable Surgical Gowns*" (Eric Vozzola, et al., 2020) provides a comprehensive assessment of the environmental impacts of reusable and disposable surgical gowns. Given the importance of surgical gowns both for patient protection and as part of personal protective equipment (PPE) for healthcare workers, this analysis is particularly relevant for healthcare facility administrators seeking to adopt environmentally sustainable practices.

The study employed a Life Cycle Assessment (LCA) approach, tracing environmental impacts from fossil fuel extraction through to end-of-life disposal of the gowns. The analysis included critical factors such as laundry operations, wastewater treatment, and overall energy consumption. The comparison between reusable and disposable gowns highlighted significant environmental advantages of reusable products. Specifically, the study found that reusable gowns reduce natural energy resource consumption by 64%, greenhouse gas emissions by 66%, blue water consumption by 83%, and solid waste generation by 84%.

The LCA was conducted in accordance with International Organization for Standardization (ISO) standards, covering the process from cradle to end of life, including raw material extraction, production, use, laundering, sterilization, disposal, and transportation. The study analyzed 11 reusable gowns and 7 disposable gowns, focusing on gown composition, packaging, and waste disposal practices. The functional unit selected was 1,000 uses of reusable textiles, compared with 1,000 disposable gowns.

Table 1: Comparison of environmental indicators for reusable and disposable surgical gowns assessed in the cradle-to-grave analysis (Eric Vozzola, et al., 2020)

Stage of Life Cycle	NRE, MJ		GWP, kg of CO_2 eq		Blue Water, kg		Solid Waste, kg	
	Reusable 1,000 Uses	Disposable 1,000 Gowns	Reusable 1,000 Uses	Disposable 1,000 Gowns	Reusable 1,000 Uses	Disposable 1,000 Gowns	Reusable 1,000 Uses	Disposable 1,000 Gowns
Gown manufacturing and supply chain	2,366	23,958	143	1,495	69.7	1,058	0-7.90	224
Packaging manufacturing and supply chain	1,246	2,040	76.7	121	56.7	36.6	35.5	40.3
Laundry	4,821	–	278	–	57	–	0	–
Sterilization	343	89.0	19.8	6.26	1.39	2.38	0	0
Use phase transport	596	53.5	38.7	3.47	0	0	0	0
End-of-life	23.9	149	1.40	10.9	0	0	0-0.00842	0.505
Total	9,396	26,289	557	1,636	185	1,097	35.5-43.4	265
Reduction from selecting reusable system, % of disposable system	64		66		83		84-87	

NRE = natural resource energy; MJ = megajoule; GWP = global warming potential; kg of CO_2 eq = kilogram of carbon dioxide equivalents.

Processing the data in the table above for the resource use and climate change indicators highlights the percentage difference in impact between the different stages of the life cycle. The increase in impact for reusable products concerns the stages managed by the rental, washing, and sterilization service, while the reduction in impact concerns fabric production (supply), the packaging used in supply, and the end-of-life stage.

Table 2: Environmental impact of life cycle stages: comparison between reusable and single use (Eric Vozzola, et al., 2020)

Life Cycle Phase	**% difference in impact between reusable and single-use (disposable) items**	
	Resource Use (Energy) (MJ)	Climate Change (GWP)
Material supply	-90.1%	-90%
Packaging	-38.9%	-37%
Laundry	100%	100%
Sterilization	285.4%	216%
Transport during use phase	1014.0%	1015%
End-of-life	-84.0%	-87%
Total	-64.3%	-66%

As can be observed, material supply generates 143 kg CO_2 eq for reusable gowns, whereas the disposable solution generates 1,495 kg CO_2 eq. Packaging also contributes to environmental impacts, with reusable gowns requiring 36.1 g of packaging and disposable gowns requiring 57.8 g. Packaging accounts for 13% of energy consumption and emissions for reusable gowns and 8% for disposable gowns. Laundry operations for reusable gowns contribute 51% of total energy consumption and 50% of greenhouse gas emissions, although they use a minimal amount of net water (57 kg per 1,000 uses). Sterilization has a relatively small impact on both types of gowns, accounting for 4% of energy consumption for reusable gowns and 0.3% for disposable gowns. Overall, the study concludes that reusable gowns are environmentally more sustainable, offering significant reductions in resource use, emissions, and waste generation compared to disposable gowns.

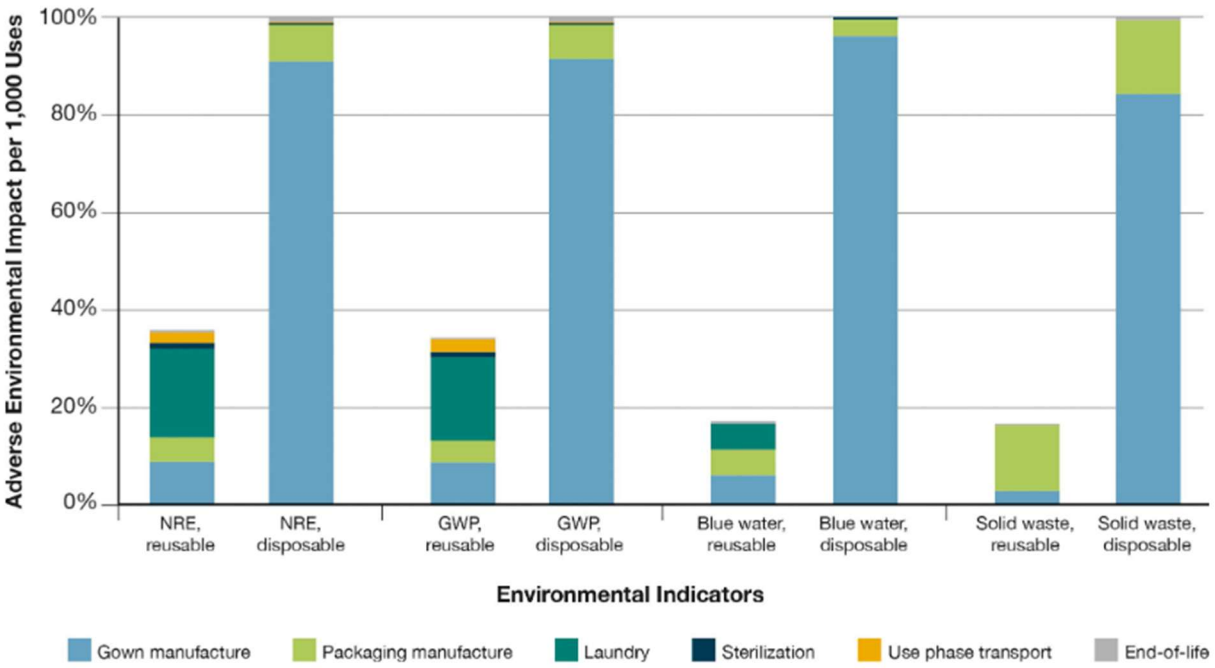


Figure 1. Comparison of the environmental impact of reusable and disposable surgical gowns (Eric Vozzola, et al., 2020)

Several case studies highlighted in materials presented by Gurtler Industries during the 2022 Healthcare Conference (Steven J. Tinker, 2022) provide valuable insights into the economic, environmental, and operational impacts associated with the transition to reusable textiles, particularly surgical gowns and drapes:

NovoHealth

NovoHealth's decision to adopt reusable isolation gowns during the 2020 pandemic demonstrates the effectiveness of reusable textiles in addressing both supply chain challenges and cost efficiency. Due to shortages of disposable PPE, NovoHealth transitioned to 100% reusable gowns, resulting in a 9% reduction in waste volume and a comparable decrease in expenditures for environmental services related to waste disposal.

Financial analysis showed that the cost per gown, including laundering, was USD 0.58, compared to USD 0.60 for disposable gowns. When accounting for savings related to reduced waste and labor costs, the total cost per gown was further reduced to USD 0.28, representing 53% cost savings compared to disposable gowns. This case illustrates how reusable textiles can offer a more cost-effective and environmentally sustainable solution, particularly in crisis situations, while also contributing to long-term operational sustainability.

UCLA Health

UCLA Health's transition to reusable gowns across four hospitals, including the Ronald Reagan and Santa Monica campuses, initiated in 2012, resulted in significant financial and environmental benefits. The shift to reusable gowns enabled the healthcare system to save approximately USD 450,000 per year, with cumulative savings of USD 3.9 million over nine years. Additionally, the transition contributed to the diversion of approximately 2,500 tonnes of waste from landfill, representing a substantial environmental achievement. The change also led to immediate operational efficiency gains, with a 20% reduction in gown usage due to improved management practices. This reduction was largely attributable to the elimination of waste associated with unused disposable gowns that were previously discarded upon patient discharge.

Staff education played a key role in the success of the transition, alongside the fact that the new reusable gowns provided equal or superior protection compared to disposable alternatives. The gowns achieved 75–100 uses per

item, underscoring their long-term cost-effectiveness. This case highlights both the economic and environmental advantages of reusable textiles and the importance of staff training in ensuring successful adoption.

Carilion Clinic, Roanoke, VA

Carilion Clinic's transition from disposable gowns to reusable gowns in 2011, following the swine flu pandemic, resulted in significant cost savings and waste reduction. Over the first three years, the clinic saved more than USD 850,000 and reduced waste by approximately 515,000 pounds. In addition to the economic and environmental benefits, staff reported improved comfort and protection offered by reusable gowns, leading to higher overall satisfaction. Notably, Carilion Clinic did not experience supply disruptions during the COVID-19 pandemic, when many healthcare facilities faced severe shortages of disposable PPE. The reusable gowns were packaged similarly to disposable gowns, ensuring ease of use for clinical staff while also requiring less storage space. This case study demonstrates the long-term financial and operational resilience that can be achieved through the adoption of reusable textiles, particularly in the face of global supply chain disruptions.

The study entitled "*The Environmental Impacts of Disposable Nonwoven Fabrics during the COVID-19 Pandemic: Case Study on the Francesc de Borja Hospital*" (Alberto Quintana-Gallardo, 2023) examines the environmental impacts of disposable nonwoven fabrics used in medical settings during the pandemic.

Conducted at the Francesc de Borja Hospital in Spain, the study aimed to analyze the carbon footprint and plastic waste associated with different types of nonwoven gowns. The study examined five types of gowns: non-sterile gowns made of *spunbond* polypropylene for non-surgical use; sleeveless gowns similar to non-sterile gowns but without sleeves; sterile surgical gowns composed of five layers (SMMMS) for high fluid protection; high-risk sterile surgical gowns with denser layers for enhanced protection; and reinforced sterile surgical gowns made from a blend of *spunbond* polyester and polyethylene to increase strength and impermeability.

A comprehensive Life Cycle Assessment (LCA) was conducted in accordance with ISO 14040 and ISO 14025 standards, using SimaPro version 9 and the Ecoinvent version 3.8 database. The assessment covered the entire life cycle of the gowns, including raw material extraction, production, and transportation. The results revealed that non-sterile gowns had the highest carbon footprint, primarily due to their high annual consumption, exceeding that of other gown types used in the hospital by more than 600%. Their polypropylene content also positions them as suitable candidates for circular economy models aimed at reducing carbon emissions. In contrast, sterile surgical gowns, particularly XL sizes, exhibited significant acidification impacts due to their complex composition and manufacturing processes.

The study highlighted the challenges of managing nonwoven textile waste while maintaining hygiene standards, especially during a pandemic. It proposed that developing a local circular economy strategy could mitigate the waste generation and carbon footprint associated with disposable nonwoven textiles. This strategy would involve converting used gowns into raw materials for other production cycles, potentially leading to significant environmental benefits. The study concluded that more sophisticated gowns, such as high-risk sterile surgical gowns, generally have higher overall environmental impacts. However, non-sterile gowns, despite their lower per-unit environmental impact, contribute significantly to the hospital's overall environmental footprint due to their high annual consumption. Designing a circular economy model for non-sterile gowns could potentially reduce carbon emissions by up to 75% compared to conventional production processes, contributing to a more sustainable approach to medical gown waste management.

Table 3: Characterization of the environmental footprint of disposable nonwoven fabric (Quintana-Gallardo, 2023)

Impact Category	Unit	Non-Sterile Gown	Patient Sleeveless Gown	Sterile Surgical Gown S	Sterile Surgical Gown M	Sterile Surgical Gown L	Sterile Surgical Gown XL
Climate change	kg CO_2 eq	0.1426 $\pm 9.26 \times 10^{-5}$	0.1434 $\pm 4.44 \times 10^{-4}$	0.2003 $\pm 4.58 \times 10^{-5}$	0.2221 $\pm 6.57 \times 10^{-5}$	0.2804 $\pm 1.37 \times 10^{-4}$	0.3208 $\pm 6.11 \times 10^{-4}$
Ozone depletion	kg CFC11 eq	5.96×10^{-9} $\pm 1.62 \times 10^{-19}$	5.99×10^{-9} $\pm 7.75 \times 10^{-19}$	1.16×10^{-8} $\pm 1.54 \times 10^{-19}$	1.25×10^{-8} $\pm 2.08 \times 10^{-19}$	1.49×10^{-8} $\pm 3.87 \times 10^{-19}$	1.66×10^{-8} $\pm 1.64 \times 10^{-18}$

Impact Category	Unit	Non-Sterile Gown	Patient Sleeveless Gown	Sterile Surgical Gown S	Sterile Surgical Gown M	Sterile Surgical Gown L	Sterile Surgical Gown XL
Ionizing radiation	kBq U-235 eq	2.42×10^{-3} $\pm 2.67 \times 10^{-8}$	2.44×10^{-3} $\pm 1.29 \times 10^{-7}$	4.14×10^{-3} $\pm 1.96 \times 10^{-8}$	4.51×10^{-3} $\pm 2.71 \times 10^{-8}$	5.50×10^{-3} $\pm 5.27 \times 10^{-8}$	6.18×10^{-3} $\pm 2.27 \times 10^{-7}$
Photochemical ozone formation	kg NMVOC eq	5.73×10^{-4} $\pm 1.49 \times 10^{-9}$	5.77×10^{-4} $\pm 7.19 \times 10^{-9}$	8.47×10^{-4} $\pm 8.20 \times 10^{-10}$	9.36×10^{-4} $\pm 1.17 \times 10^{-9}$	1.17×10^{-3} $\pm 2.39 \times 10^{-9}$	1.33×10^{-3} $\pm 1.05 \times 10^{-8}$
Particulate matter	disease inc.	5.89×10^{-9} $\pm 1.58 \times 10^{-19}$	5.93×10^{-9} $\pm 7.59 \times 10^{-19}$	8.62×10^{-9} $\pm 8.49 \times 10^{-20}$	9.52×10^{-9} $\pm 1.21 \times 10^{-19}$	1.19×10^{-8} $\pm 2.47 \times 10^{-19}$	1.36×10^{-8} $\pm 1.10 \times 10^{-18}$
Human toxicity, non-cancer	CTUh	1.33×10^{-9} $\pm 8.05 \times 10^{-21}$	1.34×10^{-9} $\pm 3.88 \times 10^{-20}$	1.87×10^{-9} $\pm 4.00 \times 10^{-21}$	2.07×10^{-9} $\pm 5.71 \times 10^{-21}$	2.62×10^{-9} $\pm 1.20 \times 10^{-20}$	2.99×10^{-9} $\pm 5.31 \times 10^{-20}$
Human toxicity, cancer	CTUh	5.30×10^{-11} $\pm 1.28 \times 10^{-23}$	5.33×10^{-11} $\pm 6.13 \times 10^{-23}$	7.66×10^{-11} $\pm 6.70 \times 10^{-24}$	8.47×10^{-11} $\pm 9.56 \times 10^{-24}$	1.06×10^{-10} $\pm 1.96 \times 10^{-23}$	1.21×10^{-10} $\pm 8.69 \times 10^{-23}$
Acidification	mol H+ eq	6.82×10^{-4} $\pm 2.12 \times 10^{-9}$	6.86×10^{-4} $\pm 1.02 \times 10^{-8}$	1.02×10^{-3} $\pm 1.19 \times 10^{-9}$	1.12×10^{-3} $\pm 1.67 \times 10^{-9}$	1.40×10^{-3} $\pm 3.42 \times 10^{-9}$	1.59×10^{-3} $\pm 1.50 \times 10^{-8}$
Eutrophication, freshwater	kg P eq	2.69×10^{-6} $\pm 3.29 \times 10^{-14}$	2.71×10^{-6} $\pm 1.59 \times 10^{-13}$	3.84×10^{-6} $\pm 1.68 \times 10^{-14}$	4.24×10^{-6} $\pm 2.39 \times 10^{-14}$	5.35×10^{-6} $\pm 4.99 \times 10^{-14}$	6.11×10^{-6} $\pm 2.22 \times 10^{-13}$
Eutrophication, marine	kg N eq	1.45×10^{-4} $\pm 9.57 \times 10^{-11}$	1.46×10^{-4} $\pm 4.60 \times 10^{-10}$	2.16×10^{-4} $\pm 5.33 \times 10^{-11}$	2.39×10^{-4} $\pm 7.61 \times 10^{-11}$	2.98×10^{-4} $\pm 1.55 \times 10^{-10}$	3.39×10^{-4} $\pm 6.82 \times 10^{-10}$
Eutrophication, terrestrial	mol N eq	1.65×10^{-3} $\pm 1.24 \times 10^{-8}$	1.66×10^{-3} $\pm 5.95 \times 10^{-8}$	2.45×10^{-3} $\pm 6.86 \times 10^{-9}$	2.71×10^{-3} $\pm 9.78 \times 10^{-9}$	3.38×10^{-3} $\pm 1.99 \times 10^{-8}$	3.85×10^{-3} $\pm 8.80 \times 10^{-8}$
Ecotoxicity, freshwater	CTUe	1.51 $\pm 1.04 \times 10^{-2}$	1.52 $\pm 4.99 \times 10^{-2}$	2.18 $\pm 5.43 \times 10^{-3}$	2.42 $\pm 7.80 \times 10^{-3}$	3.03 $\pm 1.60 \times 10^{-2}$	3.46 $\pm 7.11 \times 10^{-2}$
Land use	Pt	0.51 $\pm 1.18 \times 10^{-3}$	0.52 $\pm 5.84 \times 10^{-3}$	0.76 $\pm 6.60 \times 10^{-4}$	0.84 $\pm 9.40 \times 10^{-4}$	1.05 $\pm 1.92 \times 10^{-3}$	1.19 $\pm 8.41 \times 10^{-3}$
Water use	m^3 depriv.	0.0543 $\pm 1.34 \times 10^{-5}$	0.0546 $\pm 6.44 \times 10^{-5}$	0.0781 $\pm 6.97 \times 10^{-5}$	0.0863 $\pm 9.92 \times 10^{-6}$	0.1085 $\pm 2.05 \times 10^{-5}$	0.1239 $\pm 9.12 \times 10^{-5}$
Resource use, fossils	MJ	4.26 $\pm 8.26 \times 10^{-2}$	4.28 $\pm 3.96 \times 10^{-1}$	5.77 $\pm 3.80 \times 10^{-2}$	6.42 $\pm 5.49 \times 10^{-2}$	8.16 $\pm 1.16 \times 10^{-1}$	9.37 $\pm 5.21 \times 10^{-1}$

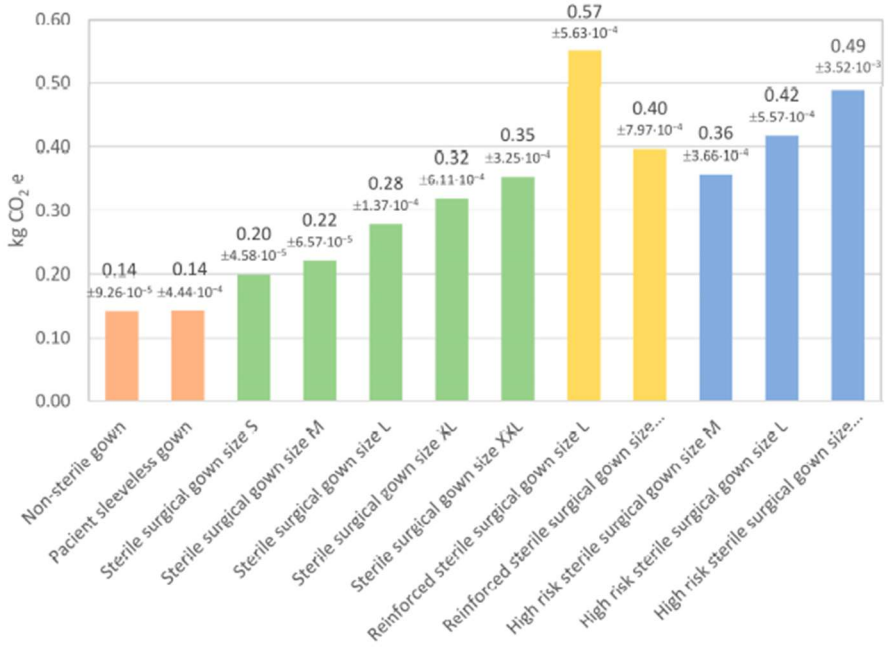


Figure 2. Carbon footprint of a gown unit (Quintana-Gallardo, 2023)

The study "Life Cycle Assessment of Surgical Drapes and Tapes: Reusable and Disposable" (E. Vozzola, 2018) presents a detailed comparative Life Cycle Assessment (LCA) of reusable and disposable surgical drape and tape systems. Commissioned by the European CHAINGE Consortium, the study aimed to evaluate various environmental impacts associated with the two systems, considering factors such as energy and water consumption, solid waste generation, and specific environmental indicators across the product life cycle.

The analysis focused on two surgical gown systems: reusable gowns, which are laundered and reused up to 60 times, and disposable gowns, which are used once and then discarded. The functional unit for the comparison was defined as 1,000 surgical gowns. For disposable gowns, this included the production, use, and disposal of 1,000 individual gowns and the associated surgical tape. For reusable gowns, 1,000 uses required the production and disposal of 16.7 gowns, with each gown undergoing laundering and sterilization prior to reuse.

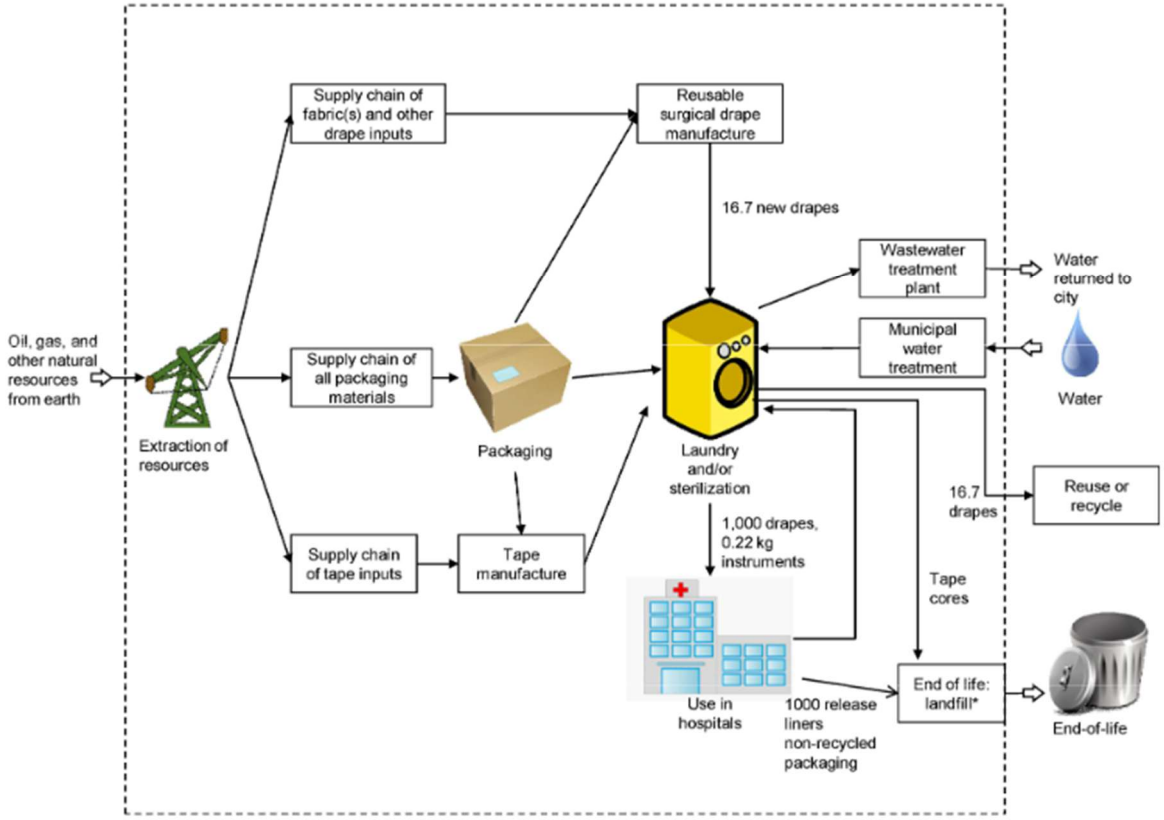


Figure 3. Definition of the life cycle of reusable surgical drapes, 1,000 uses (E. Vozzola, 2018)

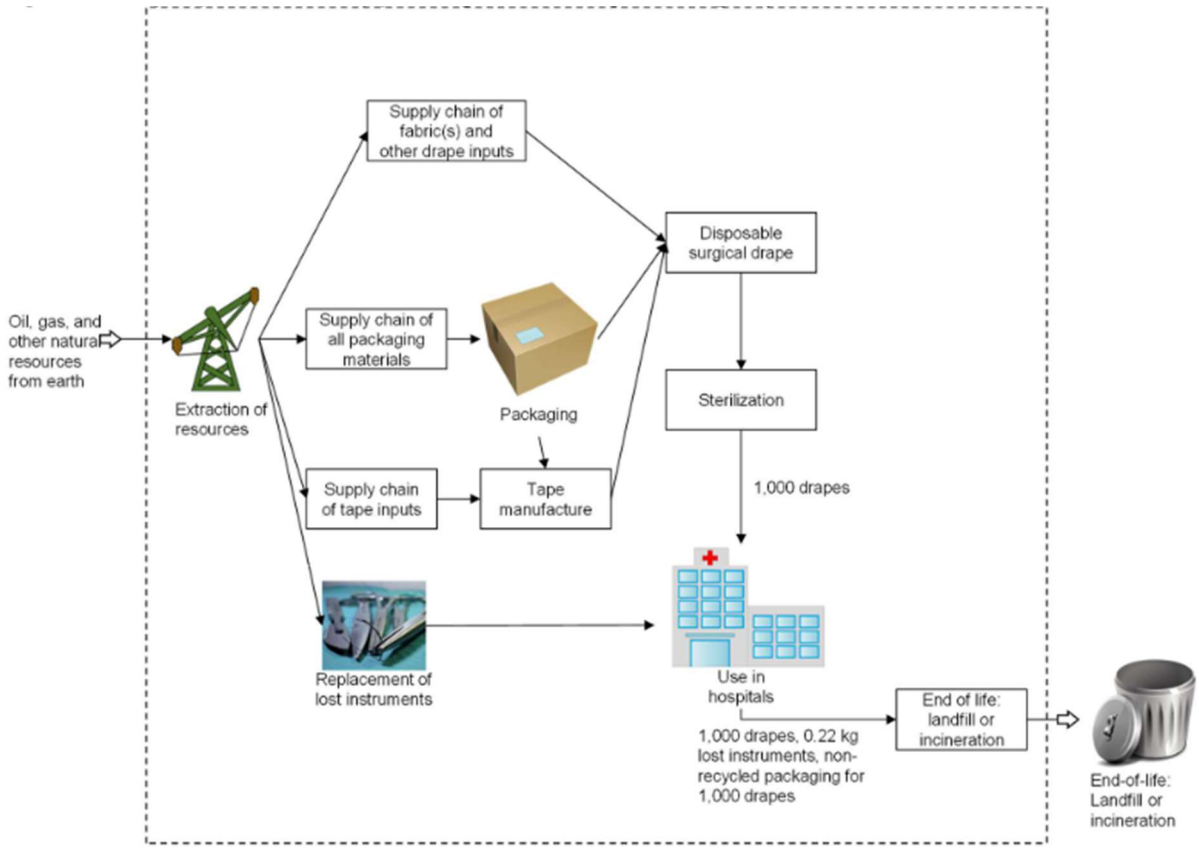


Figure 4. Definition of the life cycle of the disposable surgical drape system, 1,000 uses (E. Vozzola, 2018)

The main assumptions included average weights of 576 g for reusable gowns and 245 g for disposable gowns. The study incorporated factors such as transport impacts, with disposable gowns produced and manufactured in Asia, while reusable gowns involved both Asian and European production. Textile waste generated during cutting was also considered and estimated at 3%, along with end-of-life disposal methods, whereby disposable gowns were assumed to be landfilled or incinerated, and reusable gowns were assumed to be recycled.

The LCA revealed that the reusable surgical gown system has a significantly lower environmental impact than the disposable system. In particular, the reusable system consumes 38% less energy and generates 80% less solid waste. It also uses approximately 62% less "blue water", although this result varies depending on whether water associated with soiled gowns is included. The study found that the reusable system outperformed the disposable system in 10 of the 11 environmental impact categories, including energy consumption and solid waste generation. However, the disposable system showed a lower impact on ozone depletion, attributed to emissions from the production of ePTFE and surgical tapes. The three environmental indicators selected for comparing reusable and disposable surgical drape systems in this study were energy consumption from natural resources, blue water consumption, and solid waste generation.

Table 4: Assessments from cradle to end of life for reusable (60 cycles) and single-use (disposable) surgical drapes, environmental indicators (E. Vozzola, 2018)

Environmental indicator	Units, per 1000 uses	Reusable	Single-use	Reduction (improvement) due to the selection of the reusable system, as a % of single-use	Increase due to the selection of the single-use system, as a % of reusable
Natural resource energy	MJ	11.615	18.774	38%	62%
Blue water consumption	Kg	117**	304	62%	160%
Health care facility solid waste generation for disposal	kg	61,1	308	80%	404%

*Solid waste includes sheets, tapes, biological waste, and plastic and paper packaging. Please note that corrugated cardboard is not included, as it is considered 100% recyclable.
**Blue water recovery from dirty sheets is excluded; consumption for reusable sheets is 405 kg/1000 uses. This represents a net increase of 33% compared to the blue water consumption of disposable sheets.

Table 5: Comparison between reusable and disposable systems for surgical drapes (E. Vozzola, 2018)

LCI Component	Reusable System	Single-Use System
Drape production	9.60 kg produced / 1,000 uses: 16.7 drapes at 0.576 kg per drape (60 cycles for 1,000 uses)	245 kg produced / 1,000 drapes: 0.245 kg per drape
Primary, secondary, and tertiary packaging for drapes	59.0 kg produced / 1,000 uses; 420 kg transported	88.3 kg produced / 1,000 drapes; 101 kg transported
Tape production	6.05 kg produced / 1,000 uses	5.23 kg produced / 1,000 drapes
Tape packaging	0.608 kg produced / 1,000 uses; 1.23 kg transported	0.353 kg produced / 1,000 drapes; 0.743 kg transported
Laundry	1,000 drapes; 576 kg of linen used, 288 kg of water, 23 kg of inorganic waste, and 1.73 kg of organic waste	N/A
Water for laundry (11 kg of measured water per kg washed)	6,342 kg measured / 1,000 uses; 253 kg consumed (blue water) / 1,000 uses; 288 kg recovered from soiled drapes / 1,000 uses	N/A
Wastewater treatment for water recovery	3.30 kg COD / 1,000 uses	N/A
Sterilization	1,000 drapes and tape: 576 kg of linen and 6.05 kg of tape, steam sterilization	1,000 drapes and tape: 245 kg of linen and 5.23 kg of tape, ethylene oxide sterilization
Landfilling of biological waste	0.0107 kg / 1,000 drape uses	0.643 kg / 1,000 drapes
Landfilling of surgical drapes, tape, and packaging	68.0 kg / 1,000 uses	307 kg / 1,000 drapes
Replacement of lost instruments	N/A	0.220 kg / 1,000 drapes, stainless steel surgical bowl

Overall, the study highlights the significant environmental benefits of reusable surgical gown systems compared to disposable ones. It suggests that the integration of reusable systems could significantly reduce carbon emissions and waste in healthcare settings. Future research could further strengthen these findings by including other textile and non-textile items in healthcare facilities, such as surgical gowns, to provide a more comprehensive view of the environmental impacts and benefits associated with reusable systems.

Table 6: Cradle-to-end-of-life assessment of reusable (60 cycles) and single-use surgical drops, environmental impacts, CML v3.01 (E. Vozzola, 2018)

Environmental impact	Units, per 1,000 drape uses	Reusable	Disposable	Reduction (improvement) when selecting reusable system, % of disposable system	Increase when selecting disposable system, % of reusable system
Global warming (GWP100a)	kg CO2 eq	670	1072	38%	60%
Acidification	kg SO2 eq	1.69	3.60	53%	113%
Eutrophication	kg PO4--- eq	0.708	1.37	48%	93%
Ozone layer depletion (ODP)	kg CFC-11 eq	1.34E-04	9.88E-05	-36%	-26%
Photochemical oxidation	kg C2H4 eq	1.59	11.7	86%	637%
Fresh water aquatic ecotox.	kg 1,4-DB eq	123	402	69%	227%
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.09E+05	7.78E+05	47%	90%
Terrestrial ecotoxicity	kg 1,4-DB eq	0.866	1.09	20%	26%
Human toxicity	kg 1,4-DB eq	981	2.84E+04	97%	2797%
Abiotic depletion (fossil fuels)	MJ	9,965	1.55E+04	36%	56%
Abiotic depletion	kg Sb eq	3.44E-04	7.97E-04	57%	131%

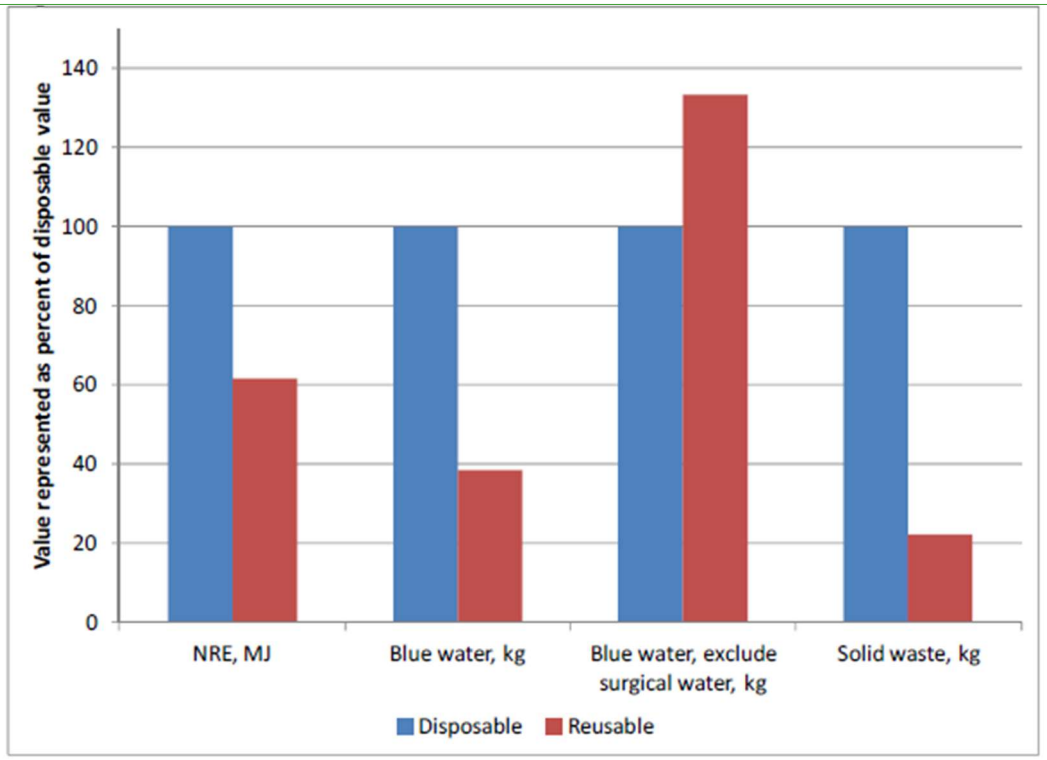


Figure 5. Environmental indicator for surgical drape system, expressed as a percentage of single-use value (E. Vozzola, 2018)

The study *"The Carbon Footprint of Products Used in Five Common Surgical Operations: Identifying Contributing Products and Processes"* (Chantelle Rizan, 2023) evaluates the environmental impact of products used in resource-intensive healthcare settings, such as operating rooms. As the healthcare sector aims to achieve net-zero carbon emissions, the research identifies the main contributors to the carbon footprint of five high-volume surgical procedures and suggests potential strategies to reduce their impact. Using a process-based carbon footprint analysis, the study assessed the environmental burden of products used in five surgical procedures commonly performed within the National Health System (NHS) in England. These procedures included carpal tunnel decompression, inguinal hernia repair, knee arthroplasty, laparoscopic cholecystectomy, and tonsillectomy.

Data were collected through the observation of 6–10 operations for each procedure type, conducted at three NHS sites. The carbon footprint was calculated for each operation, revealing substantial variation among procedures. For example, carpal tunnel decompression had a carbon footprint of 12.0 kg CO_2 eq, inguinal hernia repair 11.7 kg CO_2 eq, knee arthroplasty 85.5 kg CO_2 eq, laparoscopic cholecystectomy 20.3 kg CO_2 eq, and tonsillectomy 7.5 kg CO_2 eq.

Across these operations, 23% of product types accounted for 80% of the total carbon footprint. Disposable items contributed significantly to this impact, with the highest carbon-emitting products varying by procedure. For instance, the disposable hand drape made the largest contribution in carpal tunnel decompression procedures, while the disposable surgical gown had a similar impact in inguinal hernia repair. Likewise, bone cement used in knee arthroplasty, the disposable clip applier in laparoscopic cholecystectomy, and the disposable operating table drape in tonsillectomy were identified as the most carbon-intensive products in their respective procedures.

The production of disposable items accounted for the largest share of carbon emissions, representing 54% of the total carbon footprint. Decontamination processes for reusable items contributed 20%, while waste disposal of disposable items added 8%. The production of packaging for disposable items accounted for 6%, with linen laundering contributing an additional 6%.

The study's findings highlight the importance of addressing the carbon impact of healthcare practices. It suggests that targeted changes in policy and clinical practice could substantially reduce the environmental footprint of surgical operations, with potential emission reductions ranging from 23% to 42%. Key proposed strategies include minimizing the use of disposable items and switching to reusable products where feasible. In addition, optimizing processes such as decontamination and waste disposal could further contribute to reducing carbon emissions.

In conclusion, the research emphasizes the critical role of healthcare systems in adopting more sustainable practices, particularly in high-impact areas such as surgical operations. By prioritizing the reduction of disposable items and improving waste management and sterilization processes, significant progress can be made toward lowering the overall carbon footprint of the healthcare sector, thereby contributing to net-zero carbon goals.

1.4.Methodology

As mentioned above, the study will cover both the environmental performance (LCA) and costs (LCC) of the life cycle of disposable and reusable fabrics used in the healthcare sector. Life cycle assessment is a method of evaluation that allows the environmental impacts (LCA) and overall costs (LCC) of a product to be determined, taking into account all the stages that gave rise to these impacts and costs, from the extraction of the raw materials needed to produce the goods to the end of their life (when the product becomes waste and is therefore destined for disposal).

The product life cycle analysis (defined as "cradle-to-grave") comprises three phases:

- upstream from production, from the extraction of all necessary raw materials to the manufacturer's gate;
- production, with all its internal manufacturing processes (core);
- downstream of production, from the company's exit gate to the end of life, which includes distribution, use, and final disposal.

The study represents an application of the Life Cycle Assessment (LCA) methodology as defined by ISO 14040, according to which: "LCA is a methodology that examines the environmental aspects and potential impacts throughout the entire life of a product, from raw material acquisition, through manufacturing and use, to final disposal".

The main phases that characterize an LCA study are as follows:

1) Goal and scope definition, including the scope of application, system boundaries, functional unit, and reference flow;
2) Life Cycle Inventory (LCI) analysis of resource use and emissions, namely the quantification of material and energy flows throughout the entire life cycle of the product under study, both inputs and outputs;
3) Life Cycle Impact Assessment (LCIA), in which the substance and energy flows identified during the inventory phase are organized, classified, and aggregated using appropriate weighting factors into different environmental impact categories, also referred to as aggregated impact indicators;
4) Interpretation of results, carried out based on the methodological assumptions adopted; in this phase, results are evaluated, also through additional considerations and supporting analyses.

Life Cycle Costing Analysis (LCCA) is a method that enables the evaluation of all costs associated with a product or service over its entire life cycle, from production and use through to end-of-life disposal. LCC analysis has a long tradition of application in industry, particularly for products with long lifespans and/or high maintenance, use, or disposal costs. The analysis provides useful information for both producers and end users. For producers, life cycle costs offer a way to demonstrate how certain acquisition or production costs can be offset by measures that extend product lifetime, resulting in lower maintenance, use, or end-of-life costs. For end users, life cycle cost evaluation shows that purchase cost represents only part of a product's total cost, while other costs—such as those related to use, maintenance, or disposal—may be more significant than the initial purchase cost.

When combined with environmental life cycle assessment, which analyzes the environmental impacts of a product or service, LCCA helps address the economic dimension of sustainability.

Two reference methodologies are applied in this project: “conventional LCC” and “environmental LCC.” The so-called conventional Life Cycle Costing (LCC) techniques are well established in academic literature, in the public sector, and in corporate accounting. As early as the 1930s, the United States General Accounting Office began including operating and maintenance costs in public procurement. Later, in the 1970s, mandatory LCC was introduced in U.S. public procurement for weapons systems and buildings, and during the same period several European countries also began to adopt it. Conventional LCC typically focuses on actual, internal costs borne by the producer or the main user. For these reasons, conventional LCC was used in this study to show the purchase cost of raw materials and, in the case of TTR, the cost of rental, laundering, and sterilization services for the sets used in operating rooms.

The second reference methodology is the SETAC approach, developed between 2002 and 2006, which applies when an LCC study is conducted in parallel with an LCA and is referred to as environmental LCC (E-LCC). Essentially, an E-LCC analysis has a structure similar to the life cycle assessment conducted in parallel and must share the same functional unit. Life cycle and system boundaries must be equivalent, though not necessarily identical, since different processes may have differing relevance from an environmental or cost perspective. In addition, E-LCC takes into account the different “life cycle actors” (e.g., producers, product purchasers, or end-of-life actors). The E-LCC approach was used in this study to analyze end-of-life costs, which affect both final users (healthcare facilities) and operators involved in product treatment and disposal once their use has been completed.

The LCC approach includes the following cost categories:

- Direct costs: purchase of the materials considered in the study, including raw materials (textiles) or the purchase of operating room sets; the cost of rental, laundering, and sterilization services for TTR; this category includes investment costs, financing costs, recurring operating and maintenance costs, and capital replacement costs (CAPEX and OPEX);
- Indirect costs/benefits: recycling initiation, regeneration, and reuse costs of materials/products; these costs include raw materials and various inputs such as energy, labor, depreciation, waste management, and other costs and revenues required to achieve treatment outcomes;
- External costs/benefits: costs/benefits of alternative scenarios—within this study, incineration, landfilling, mechanical recycling, and chemical recycling.

Externalities (the monetary value of environmental damages or benefits) are described in the analysis, as they may be subject to measures aimed at internalizing the negative environmental and social impacts of alternative solutions; however, they are not monetized to avoid double counting. Environmental costs, measured through appropriate indicators characterizing environmental impacts, are reported in the LCA analysis.

In conclusion, the LCCA methodology is used in this study to illustrate effects for two relevant categories of stakeholders. From the producers’ perspective (i.e., suppliers of TNT, suppliers of TTR, and companies providing rental, laundering, and sterilization services for TTR), the analysis allows costs to be associated with different life cycle phases—analogous to the LCA for environmental effects—and thus enables evaluation of the processes involved using a cost-effectiveness parameter. From the users’ perspective (healthcare facilities), the objective is to assess whether it is reasonable to replace the purchase of a disposable product (TNT) with the purchase of a service that leverages the multi-use characteristics of TTR. Since users also express a social interest, the analysis highlights the cost–benefit relationship associated with alternative end-of-life solutions for reusable textiles (whereas for disposable products only incineration with energy recovery is assumed) and the effects resulting from resource savings achieved by substituting disposable materials with multi-use materials.

To obtain the results presented, one of the most widely used life cycle assessment software tools, SimaPro 9.6.0.1, was employed. In addition, the most recent databases related to material production, metallurgical and chemical production processes, transport, and energy systems were used, in particular Ecoinvent 3.10. The outcomes of the analysis are therefore articulated in terms of environmental impacts and costs associated with the product life cycle in relation to the selected functional unit.

2. SCOPE OF THE STUDY

The following paragraphs describe the scope of the study, which identifies the system analyzed in detail and defines the functional unit of reference, the field of application, the boundaries of the system, and the evaluation methods used.

2.1. Product description and functional unit

The functional unit provides the reference to which the input and output data of the system under consideration are related. In order to compare the life cycle impacts of different items performing the same function, it is necessary to refer to a unit that reflects both the differences between disposable and reusable products and the differences among the products themselves within the two categories. In the first case, it would be sufficient to compare 1 kg of textiles, since the life cycle is substantially different. In the second case, however, when considering different items that are all either reusable or disposable, a functional unit equal to 1 kg—although consistent with the available PCR and RCP[1]—is not sufficient to capture all the differences or similarities among the products. The most appropriate functional unit is therefore defined as **1 item made of specific textiles that make it suitable for use in an operating room, included or not in a dedicated or standard kit, and reused 60 times**.

Conversely, the functional unit described in the PCR for garments[2]—partially applicable to disposable products—defined as one use of the functional unit, was not considered appropriate for this study. The end-of-life of the products coincides with the point at which they lose the qualities that made them suitable for their intended function: in the case of disposable products, this occurs after a single use, whereas for reusable textiles, products undergo a defined number of laundering cycles before being discarded. In the healthcare sector, numerous types of textiles are used, such as surgical drapes, gowns (surgical and non-surgical), and bed linen (sheets, pillowcases, etc.); however, this study focuses on the analysis of medical products used in operating rooms. Accordingly, the product type selected for analysis is the one that best represents the activity. The specific function of the different items is related to their use during the performance of tasks, but all the analyzed items fulfill the general function of use in the operating room. The comparison is therefore carried out between items with the same characteristics. The items selected for the analysis are reported below:

Table 7: Description of the types of products analyzed

TERM	ARTICLE	AVERAGE ITEM WEIGHT (kg)		ITEM AREA (m^2)
		TNT	TTR	BOTH
Characteristics	Reinforced sterile gown, size L	0.134	0.350	-
	Reinforced sterile gown, size XL	0.142	0.375	-
	Standard sterile gown, size L	0.100	0.300	-
	Standard sterile gown, size XL	0.115	0.325	-
	Main table drape	0.243	0.578	3.96
	Lateral drape	0.050	0.185	0.81
	Pillowcase	0.137	0.323	2.24
	Head drape	0.272	0.663	4.44
	Foot drape	0.221	0.532	3.60

NOTE 1: The area was calculated based on technical data sheets shared by manufacturers and laundries.
NOTE 2: Values shown in bold are averages.

[1] PCR Professional laundry and cleaning services of items, version 1.0; RCP Servizi delle attività di lavanderia industriale versione 0.3 (Industrial laundry services RCP), *in Italian*.

[2] PCR Apparel, except fur and leather apparel, version 1.0

2.2.System boundaries

The system boundaries determine the process units to be included in the LCA and LCC study and the type of data "input" and/or "output" to the system that can be omitted. In the system analyzed, those related to washing activities and the manufacture of TTR products can be classified as foreground processes (defined by the PEF guide as processes for which information can be accessed directly). All other product stages for which it was not possible to find specific data can be classified as background processes, including the production of fabrics and their packaging, transport processes, and the end of life of products. The following figures show all the phases included within the system boundaries; for the life cycle of reusable products—illustrated in the diagram on the left—the washing phase is also included.

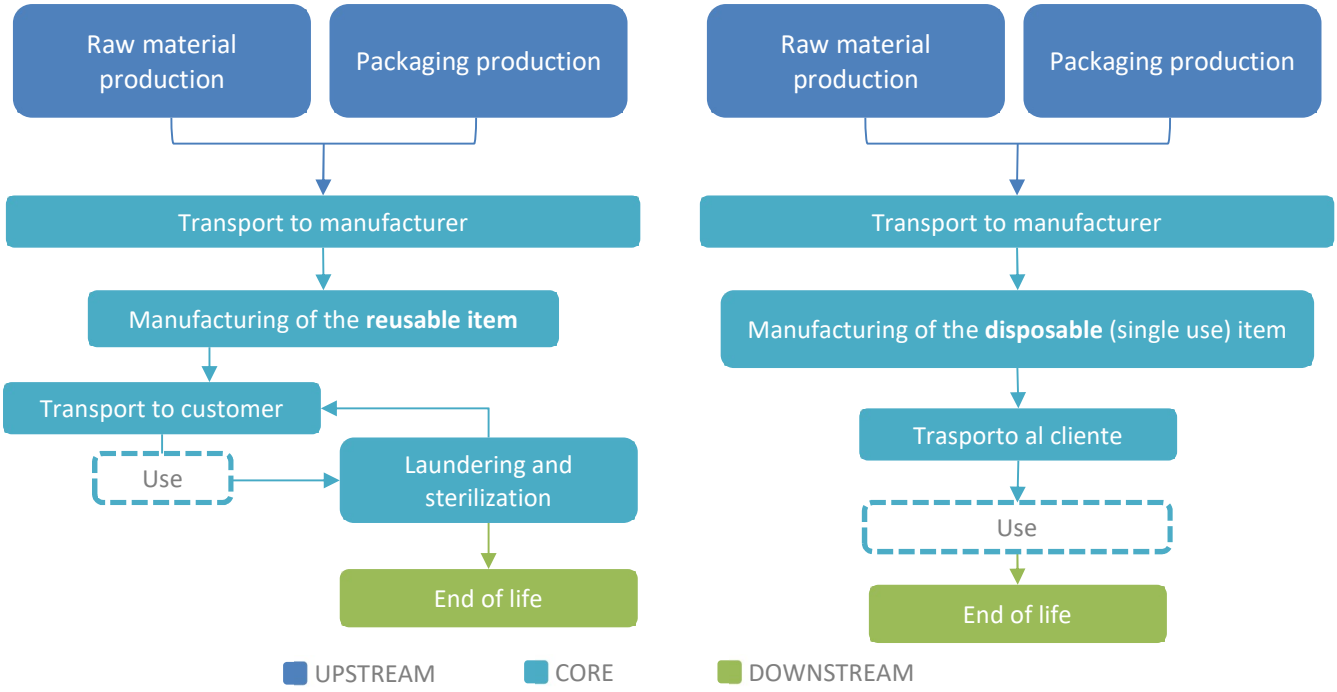


Figure 6. System boundaries of the analyzed reusable products (left) and single-use products (right).

The life cycle of textile products used in operating rooms therefore includes all phases ranging from resource extraction and raw material production to the point at which the product becomes waste, considering within these boundaries both product manufacturing and, in the case of reusable products, laundering. All transport processes required by the production cycle are included, as well as the production of auxiliaries and packaging, and waste flows generated over the entire life cycle have been accounted for. For each phase (process unit), the following input and output flows to and from the system were evaluated:

- energy consumption (electricity, fuels, etc.);
- water consumption;
- consumption of chemicals and auxiliary raw materials (auxiliaries in general);
- packaging consumption;
- waste generation;
- emissions to air, water, and soil;
- land use (where relevant).

2.3.General assumptions

The assumptions concerned several general aspects summarized below; additional specific assumptions are described in detail in Chapter **Errore. L'origine riferimento non è stata trovata.**.

- The definition of a functional unit representative of **all analyzed products**;
- The raw material modeling for all products was carried out based on information contained in technical data sheets collected from suppliers, laundries, or contracting authorities;
- Packaging for drapes was assumed to be identical for all analyzed products, regardless of whether they were disposable or reusable: a carton containing 25 items was considered;
- With regard to the shipment of products from the manufacturing company to the end user, carton and pallet labels, shrink wrap around the pallet (tertiary packaging), and box adhesive tape were excluded from the study;
- In the modeling of reusable textiles, no allowance was made for a percentage of products to be replaced due to breakage or loss during multiple use cycles;
- Product costs include the cost of packaging and transportation;
- All processes were sourced from the Ecoinvent 3.10 database (2023).

2.4.Exclusion criteria

Cut-off criteria allow the exclusion, from the calculation of impact categories, of certain material and energy flows entering or leaving the system under consideration.

For this study, components contributing less than 1% of the total impact were excluded. In particular, the following processes were excluded from the analysis:

- ✓ the construction of production facilities;
- ✓ the construction of machinery and equipment;
- ✓ products used for ordinary and extraordinary maintenance of facilities; only products required for water softening and purification in laundries were included;
- ✓ lost medical instruments and other objects that are often recovered and returned by laundry operators during the processing of reusable surgical textiles. It is considered reasonable to assume that similar items would also be sent to landfill when associated with disposable textiles (Vozzola et al., 2018); these items were therefore excluded from the comparative analysis;
- ✓ the production of packaging for auxiliary materials.

2.5.Data Description

The types of data used in the LCA and LCC for the calculation of indicators include:

- ✓ Specific (primary) data, directly measured or collected at company sites and representative of the activities performed;
- ✓ Generic (secondary) data, meaning data not directly collected, measured, or assessed, but obtained from life cycle inventory databases (both commercial and non-commercial) or from the scientific literature (both specific and general), related to the product category under analysis or to other systems that are technologically, geographically, and temporally equivalent. For this type of data, Ambiente Italia ensured access to highly up-to-date databases, such as Ecoinvent 3.10, in order to guarantee compliance with data quality requirements

In addition, data related to certain transport distances were calculated using Google Maps online tools to estimate road transport distances. In this study, the use of specific data was prioritized; for this reason, a detailed data

collection process was carried out, allowing for a more in-depth analysis of certain life cycle phases. With regard to the LCC analysis, direct costs were based on information provided by companies carrying out rental, laundering, and sterilization services, as well as by healthcare organizations. The construction of machinery, facilities, and other capital goods, as well as business travel and commuting by workers to and from the workplace, were not included.

2.6.Data Representativeness, Adequacy, and Validation

The validation of specific data provided by member companies and other organizations involved in the study was carried out through comparison with other LCA studies and published research, international databases (in particular Ecoinvent 3.10), and literature data (reported in the bibliography).

The table below summarizes all life cycle phases, the related processes, the type of data used (specific or generic), the data sources, and the temporal and geographical coverage. For the different phases, foreground and background processes were distinguished.

Table 8: Data sources by life cycle stage

Phases	Specific process	Data category	Source	Time coverage	Geographic coverage
BACKGROUND					
Raw material extraction and production of synthetic fibers	Extraction of fossil sources and spinning	Selected generic data	Ecoinvent 3.10	2023**	Global
Nonwoven fabric production	Opening, blending, layering, humidification, carding, needle punching	Selected generic data and specific data	Ecoinvent 3.10 companies involved	2023**	India, rest of the world
Transport of auxiliaries and packaging to the laundry	Fuel production and use; transport parameters by vehicle type	Selected generic data	Ecoinvent 3.10	2023**	Rest of the world
Imballaggi e ausiliariPackaging and auxiliaries	Production	Selected generic data	Ecoinvent 3.10	2023**	Europe and rest of the world
End of life	Recycling and disposal processes	Selected generic data	Ecoinvent 3.10	2023**	Italy
FOREGROUND					
Laundry and rental service	Industrial laundering	Specific data	Involved facilities	2023	Italy
	Collection and delivery	Specific data	Involved facilities	2023	Italy

** Refers to the publication year of the database.

2.7.Allocation rules

Allocation is a calculation methodology that allows the distribution within the product system under study of the input and output flows of a process unit. This methodology is required when the process under analysis involves the production of co-products, in order to assign the appropriate environmental burden to the product under assessment.

With regard to specific data and some generic data (not derived from databases), the allocation rule used to calculate inputs and outputs was based on mass (on an annual basis). For the remaining generic data (derived from databases), the existing allocation procedures provided in the databases were maintained.

2.8.Categories of environmental footprint impact

An *impact category* is defined as the class representing the environmental issues of interest to which the results of the life cycle inventory (LCI) analysis can be assigned. An impact category indicator is instead defined as the quantifiable representation of those categories.

In this study, it was decided to consider the environmental impacts of the product with respect to all impact categories indicated in Commission Recommendation (EU) 2021/2279 on the Product Environmental Footprint (PEF), which are reported in the table below together with a brief description.

Table 9: Brief description of the impact categories considered in the study.

Impact category	Indicator	Model	Description
Climate change (greenhouse effect)	kg CO_2 eq	IPCC 2013: GWP 100, global warming potentials over 100 years	Ability of a greenhouse gas to influence changes in the global mean near-surface air temperature and subsequent variations in climatic parameters and their effects (expressed in CO_2 equivalents over a specific time horizon: 100 years).
Ozone layer depletion	kg CFC-11 eq	EDIP model (ozone depletion potentials of the World Meteorological Organization)	Degradation of stratospheric ozone due to emissions of ozone-depleting substances, such as chlorine- and bromine-containing gases with long atmospheric lifetimes (e.g., CFCs, HCFCs, halons).
Ionizing radiation – human health effects	kg U^{235} eq	Human health effects model	Negative effects on human health caused by radioactive emissions.
Photochemical ozone formation	kg NMVOC eq	LOTOS-EUROS model	Formation of ground-level tropospheric ozone caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High ground-level ozone concentrations are harmful to vegetation, the human respiratory system, and artificial materials through reactions with organic substances.
Particulate matter / smog caused by inorganic emissions	Disease incidence	Recommended by the United Nations Environment Programme (UNEP, 2016)	Adverse effects on human health caused by emissions of particulate matter (PM) and its precursors (NOx, SOx, NH_3).
Human toxicity – carcinogenic effects	CTUh	USEtox model	Negative effects on human health caused by the intake of toxic substances through inhalation of air, ingestion of food/water, skin penetration, insofar as these substances are carcinogenic.
Human toxicity – non-carcinogenic effects	CTUh	USEtox model	Negative effects on human health caused by exposure to toxic substances through inhalation of air, ingestion of food and water, and skin contact. This category includes non-carcinogenic substances not caused by particulate matter/smog from inorganic emissions or ionizing radiation.

Impact category	Indicator	Model	Description
Acidification	mol H+ eq	Accumulated exceedance model	Adverse effects on ecosystems caused by emissions of NOx, SOx, and NH_3, which result in the release of hydrogen ions when gases are mineralized. Protons promote acidification of soils and surface waters where buffering capacity is low, leading to forest degradation and lake acidification.
Eutrophication – freshwater	kg P eq	EUTREND model	Nutrients (mainly nitrogen and phosphorus) from wastewater discharges and agricultural land accelerate the growth of algae and other aquatic vegetation. The degradation of organic matter consumes oxygen, causing oxygen depletion and, in some cases, fish mortality in freshwater bodies.
Eutrophication – marine	kg N eq	EUTREND model	Nutrients (mainly nitrogen and phosphorus) from wastewater discharges and fertilized agricultural land accelerate the growth of algae and other vegetation in marine waters. The degradation of organic matter consumes oxygen, causing oxygen depletion and, in some cases, fish mortality in marine waters.
Eutrophication – terrestrial	mol N eq	Accumulated exceedance model	Nutrients (mainly nitrogen and phosphorus) from wastewater discharges and agricultural land accelerate vegetation growth. The degradation of organic matter consumes oxygen, causing oxygen depletion.
Ecotoxicity – freshwater	CTUe (comparative toxic unit for ecosystems)	USEtox model	Toxic impacts on ecosystems that damage individual species and alter ecosystem structure and function.
Land use	pt	Soil Quality Index	Use and transformation of land for activities such as agriculture, construction of roads, buildings, mines, etc. The SQI index is based on the LANCA model (Bos et al., 2016). It represents the aggregation of four indicators: biotic production, erosion resistance, mechanical filtration, and groundwater recharge.
Resource depletion – water	m^3 water eq	AWARE method (Available WAter REmaining), recommended by UNEP (2016)	Indicator of water use that assesses the potential deprivation of water for humans and ecosystems. The water remaining per area refers to the amount of water left after human consumption and environmental water demand has been subtracted from available renewable resources in the river basin.
Resource depletion – minerals and metals	kg Sb eq	CML 2002 model	Depletion of abiotic resources (minerals, metals) expressed as kg of antimony equivalents, one of the most common reference elements for these resources. The indicator characterizes the depletion of abiotic resources based on extraction rates and reserve estimates.
Resource depletion – energy carriers	MJ	CML 2002 model	Depletion of abiotic energy resources (fossil fuels) expressed in MJ, referring to their characteristics as energy carriers.

3. LIFE CYCLE INVENTORY ANALYSIS

The life cycle inventory (LCI) of the product consists of quantifying the material and energy flows entering and leaving the system under analysis. In most cases, the data used for the LCA calculations represent average values derived from all data collected across the different available sources and years; in specific cases where this was not possible, an explanation and description of the assumed value are provided.

3.1.Procedure for the Collection of Specific Data

The collection of sector-specific data began with the definition by Assosistema of a representative sample of member companies that could participate in the data collection process. This included a list of companies from the textile production supply chain (hereinafter referred to as manufacturers) and from the integrated healthcare services sector (hereinafter referred to as industrial laundries). Data collection was then carried out by Ambiente Italia through a structured work program that included:

- the preparation of dedicated questionnaires (data collection checklists);
- the distribution of questionnaires to the companies identified by Assosistema;
- on-site visits to production facilities (in a limited number of cases, direct contact was carried out through telephone interviews with responsible personnel);
- analysis of the information received (completed checklists) and, where necessary, integration of missing data through further investigations conducted during dedicated meetings.

In particular, for the collection of data from textile manufacturers, data obtained from two of the main producers supplying the sampled laundries were used, together with information derived from a review of the available literature.

3.2.The manufacture of products

In this life cycle phase, all the most significant processes contributing to the manufacturing of finished products, ready to be shipped to end users and packaged in different packaging configurations, were included. The general assumptions for this phase were as follows:

> The **quantity of raw material** considered for this phase corresponds to the weight of each product, increased by the production scrap rate communicated by the interviewed manufacturers.

> For reusable products, the impacts associated with raw material production were allocated according to the **reuse rate defined by the PEF methodology**, i.e., the number of cycles the products undergo before reaching end of life. For disposable products, these processes were considered as many times as the number of uses, since production is repeated for each disposable product for an equivalent number of uses.

> **Gown sizes** were selected based on the most used sizes by customers (size L and XL); for drapes, dimensions were derived from the collected technical data sheets.

> In all cases, Ecoinvent market[3] **processes** were used, including average transport distances, since the specific raw material producers were not known.

> **Sterilization of disposable textiles** was considered part of this life cycle phase; for this activity, sterilization with ethylene oxide was assumed, with the following energy consumption values: electric energy: 0.0399 MJ per item; thermal energy: 0.0228 MJ per item.

3.2.1. Production of reinforced reusable gowns, packaging in cardboard and plastic film

Reusable reinforced gowns are made of polyester fabrics reinforced with a polyurethane (PU) or polytetrafluoroethylene (PTFE) membrane—also known as Teflon—and antistatic carbon fiber. Polyester, the base

[3] When modeling with SimaPro, it is recommended to use “Market” processes for the country/area of reference when the supplier is unknown; these processes contain generic transformation processes with all inputs and outputs to and from nature and other processes with average distances.

component of the fabric, is a synthetic fiber obtained from macromolecules composed of polyethylene terephthalate which, when combined with a PU or PTFE membrane, forms the so-called trilaminate; this reinforced polyester fabric ensures insulation by creating an effective barrier effect. Carbon fiber, on the other hand, is used to impart antistatic properties to the microfiber. Synthetic fibers (such as polyester), due to their hydrophobic nature, exhibit electrical conductivity (albeit limited), allowing them to retain electric charges for long periods after friction with other materials or in the presence of magnetic fields. Carbon is therefore used because it can dissipate accumulated electricity thanks to its conductive properties.

For PES, membranes, and carbon fiber, datasets defined in the Ecoinvent 3.10 database were used. To produce the PES fabric, a process related to the manufacture of a polyester fabric was considered, accounting for two membranes and a production scrap rate of 0.005%; the polyester fabric represents approximately 85% by weight of the trilaminate. The membrane accounts for approximately 7% of the total garment weight, considering a scrap rate of 0.007%. To produce the polyurethane (PU) membrane, raw material production processes were considered, followed by a film extrusion phase. Specifically, for the polytetrafluoroethylene (PTFE) membrane, production processes were sourced from Vozzola et al. (2018). The membrane and the polyester fabric are bonded together using polyurethane adhesive, accounting for approximately 7% by weight. The compound 1,4-butanediol was therefore considered and assimilated to carbon fiber, representing approximately 1% of the fabric mass, as an auxiliary material. Manufacturing energy consumption amounts to 0.007 MJ/kg of electricity and 0.112 MJ/kg of steam heat.

In addition, a quantity of water-repellent yarn equal to 3.25 g/kg of fabric was considered (modeled as polyester fiber and associated with spinning energy consumption), as well as secondary packaging consisting of cardboard and plastic film, derived from the quantities used by one manufacturer for packaging these products in 2023. The same manufacturer reported an energy consumption of 0.98 kWh per item for logistics management of production carried out in Italy. Energy consumption related to the actual garment manufacturing was derived from data collected from a second manufacturer whose facilities are in Eastern Europe; these values are confidential and are therefore not reported in this document. The assembly phase consists of cutting, hemming, and sewing of microfiber and trilaminate fabrics.

3.2.2. Production of reinforced disposable gowns and packaging

Disposable reinforced gowns are made of bilaminated nonwoven fabric (TNT) composed of two layers: a hydrophilic spunbond polypropylene (PP) nonwoven coupled with an impermeable LDPE layer. The polyethylene layer was assumed to account for approximately 9% of the gown mass. In addition, based on literature, the polypropylene used in these products was assumed to contain 1% dye; a 2.7% production scrap was added to the total quantity (E. Vozzola, 2018) Ecoinvent 3.10 datasets were used for the modeling of raw materials.

A quantity of water-repellent yarn equal to 3.25 g/kg of fabric was also considered (modeled as polyester fiber and associated with spinning energy consumption), as well as secondary packaging consisting of a cardboard box of approximately 500 g containing 50 items. The disposable surgical upper drape is manufactured in a cutting, sewing, and finishing facility by thermally bonding the PP barrier film to the PP nonwoven fabric. In general, disposable drapes are made of SMS PP nonwoven fabric with PP or PU barrier films added in critical areas to provide enhanced protection; an energy consumption of 0.5633 MJ/kg was assumed for packaging operations (E. Vozzola, 2018).

3.2.3. Production of reusable sheets and packaging

The surgical drapes used in operating rooms consist of a critical area made of PES–PU trilaminate (see Section 3.2.1 for details), with an areal density of approximately 185 g/m², and a less critical area composed of 99% microfiber and 1% carbon fiber, with an areal density of approximately 125 g/m² (source: technical data sheets). The microfiber was

modeled by considering the production of polyester fiber, carbon fiber, and energy consumption for weaving. An energy consumption of 0.5633 MJ/kg was assumed for assembly operations (E. Vozzola, 2018).

For secondary packaging, a 1 kg cardboard box containing 25 items was considered, as indicated by one of the interviewed manufacturers. It was assumed that reusable drapes include an adhesive tape that is removed prior to laundering; therefore, a new tape is applied at each subsequent use, for which datasets related to the production of cotton fabric (from technical data sheets) were used. The size of the critical and less critical areas, and thus the allocation of the two different fabrics, was calculated based on the available technical specifications, referring to products purchased and rented in the reference year.

Table 10. Mass and weight distribution between critical and less critical areas in the analyzed drapes

Item	Critical area (m^2)	Less critical area (m^2)
MAIN OPERATING TABLE DRAPE	**1.38**	**2.58**
LATERAL DRAPE	**0.40**	**0.405**
PILLOWCASE	**0.72**	**1.52**
HEAD DRAPE	**0.35**	**4.09**
FOOT DRAPE	**0.77**	**2.83**

3.2.4. Production of Disposable Drapes and Related Packaging

The disposable sheets are made in the critical area with extruded polypropylene (PP), with a mass per unit area of 48 g/m2, according to the literature, and in the less critical area with spunbound PP, with a mass per unit area of 30 g/m2, according to technical data sheets (source of compositions: Vozzola et al, 2018). The dimensions of the two areas for each drape type were taken from Table 10. The first component was modeled starting from PP granulate and an extrusion process, whereas the second component was modeled as a polypropylene nonwoven fabric. An energy consumption of 0.5633 MJ/kg was assumed for assembly operations. (E. Vozzola, 2018). For secondary packaging, a 1 kg cardboard box containing 25 items was considered, as indicated by a supplier. Disposable drapes include an adhesive tape strip (75% polyurethane and 25% polyester) that is disposed of after each use (E. Vozzola, 2018).

3.2.5. Transport from the manufacturer

Regarding product distribution, the average distance between the manufacturing companies supplying the kits and the industrial laundries considered (Laundries A, B, C, and D) was used as a reference. The use of a European truck with a capacity of 7.5–16 t and Euro 4 emission standard was assumed. For disposable products, a conservative transport radius of 500 km was assumed, including transport from the manufacturer to the contracting authority and from the contracting authority to the various hospital.

3.3. Use Phase

The use phase includes the actual use of textile products in healthcare settings, the subsequent transport to the industrial laundry (collection and delivery service), and industrial laundering and sterilization. Within the laundry, activities include sorting and handling of soiled textiles, washing, drying and folding, followed by packaging of the kit to be sent to the customer and its sterilization in an autoclave using steam only. In general, integrated healthcare service providers offer a laundering and rental service consisting of supplying ready-to-use items in the correct quantities, ensuring constant availability of sufficient items, even in cases of increased patient flow.

In this life cycle phase, the reference flow is equal to 1 kg of textiles composing the washed and sterilized kit. Specific data provided by the identified laundries (Laundries A, B, C, and D) for the years 2022 and 2023 were used; an average value over the period was calculated and applied. Each individual laundry was modeled separately. Where specific data from participating companies were unavailable, an average value from the other three industrial laundries was used to reconstruct the missing data (e.g., estimates of pollutant emissions to water or air when analysis data were not provided).

For collection and delivery transport, the average distance between the laundries and their customers was identified (calculated in relation to the transported quantity); where this information was not available, an assumed distance of 50 km was used. Transport typically occurs via trucks with a capacity of 3.5–7.5 t (assumed Euro 5) for a single route without intermediate deliveries; the average customer distance was multiplied by two to account for both collection and delivery. Products are transported using steel cages owned by the industrial laundries. Packaging consists of a plastic film wrapping the kit to be delivered to the customer.

With regard to the washing phase, process additives were classified according to their function into the following categories: detergent, bleaching agent, disinfectant, descaling agent, starch, formic acid, softener, sequestrant, sodium bisulfite, processing aids, caustic soda, and salt. For these auxiliaries, transport was considered using average distance data from the various suppliers, assuming the use of 7.5–16 t Euro 5 trucks.

The laundries participating in the project were asked to indicate the number of washing cycles that drapes and gowns can typically withstand without losing their functional characteristics. Based on this feedback, the use phase of a single textile product was assumed to be 60 washing cycles before disposal, as an estimate derived from the provided data. A sensitivity analysis was also carried out on the variation of results as a function of the number of washing cycles, within a range of 20 to 100 cycles (see Section 5.1), confirming the robustness of this assumption and the representativeness of the study even for scenarios significantly different from the 60-cycle case analyzed. The quantity of evaporated water was calculated as the difference between pre-wash water and the water discharged from the laundry.

Regarding packaging, corresponding to kit preparation for sterilization and shipment, transparent polyethylene film bags and crepe paper sheets were considered. Kit identification is performed by applying a self-adhesive label to each package, containing usage warnings and additional information such as the expiration date and kit components. Quantitative packaging data were taken directly from each individual laundry.

With respect to waste generated during this phase, the laundries were asked to indicate the quantities produced and their final destination. These mainly consist of mixed packaging waste from products used in washing (not considered here, as specific packaging scenarios were modeled for each product) and sludge from wastewater treatment processes, which is sent for treatment.

To model the washing phase, data from four laundries were taken into consideration, modeled individually, considering all inventory data relating to the ton of fabric treated. The following table shows the specific data used.

Table 11: Washing phase – input and output data per 1 t of treated textile (weighted average value)

	Item	Unit of measure	WEIGHTED AVERAGE
INPUT	Transport of TTR from producers	km (weighted average)	394.09
	Chemical products	kg	0.0354
	Packaging production	kg	0.0686
	Polyethylene film	kg	0.0057
	Plastic bags	kg	0.0449
	Cardboard	kg	0.0010

	Crepe paper sheets	kg	0.0169
	Transport of auxiliaries and packaging	km (weighted average)	138.22
	Total Water	m^3	0.0154
	from well	m^3	0.0132
	surface water	m^3	0.0020
	from aqueduct	m^3	0.0002
	ELECTRICITY	kWh	0.3007
	from national grid	kWh	0.1825
	from cogeneration	kWh	0.0967
	from renewables (certified)	kWh	0.0215
	of which photovoltaic	kWh	0.0006
	of which energy recovers from waste	kWh	0.0093
	of which hydroelectric sources	kWh	0.0118
OUTPUT	METHANE	MWh	0.0012
	Emissions to water	kg	0.0030
	Evaporated water	m^3	0.0033
	Particulate matter	kg	0.000001
	Waste (excluding packaging waste)	kg	0.0040
	TTR collection and delivery	km (weighted average)	184.07
	Scrap	kg per total treated	0.0068

To obtain the weighted average of the values, the total kilograms of TTR treated in each sample laundries were used as weighting factors:

- Laundry A: 15.1%
- Laundry B: 27.2%
- Laundry C: 21.9%
- Laundry D: 35.8%

3.4.End of product life

This phase covers the end of life of old textile products, both disposable and reusable. For single-use products, the scenario considered is 100% incineration; for the sake of completeness, the methodological choice was to analyze four different scenarios for reusable products: two recycling scenarios (chemical and mechanical, with data from the literature: Bassi et al., 2022), one incineration scenario, and one landfill scenario. The Circular Footprint Formula provided by the PEF methodology was applied to model this phase: the equation is in fact a combination of "material + energy + disposal," as shown below.

Materials

Eq.1 $$(1-R_1)E_v + R_1 \times \left(AE_{recycled} + (1-A)E_v \times \frac{Q_{Sin}}{Q_p}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E *_v \times \frac{Q_{Sout}}{Q_p}\right)$$

Energy

Eq.2 $$(1-B)R_3 \times \left(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}\right)$$

Disposal

Eq. 3 $$(1-R_2-R_3) \times E_D$$

Formula parameters:

A: Allocation factor of burdens and credits between the supplier and the user of recycled materials.
B: Allocation factor for energy recovery processes. It is the share of burdens and credits.
Q_{sin}: quality of secondary material at the input, i.e., the quality of recyclable material at the substitution point.
Q_{out}: quality of secondary material at the output, i.e., the quality of recyclable material at the substitution point.
Q_p: quality of primary material, i.e., the quality of virgin material.
R_1: proportion of input material from production that is recycled starting from a previous system.
R_2: proportion of material in the product that will be recycled (or reused) in a subsequent system. This value must therefore take into account inefficiencies in recycling processes and recycled (or reused) material must be measured at the output of the recycling impact.
R_3: proportion of material in the product that will be used for energy recovery in the end-of-life phase.
$E_{recycled}$ (Er_{ec}): emissions and specific resources consumed (per functional unit) resulting from the recycling process of the recycled material (reutilization), including collection, sorting, and transport.
$E_{recyclingEoL}$ (Er_{ecEoL}): emissions and specific resources consumed (per functional unit) resulting from the recycling process in the end-of-life phase, including collection, sorting, and transport.
E_v: emissions and specific resources consumed (per functional unit) resulting from the acquisition and extraction of virgin material.
E_v*: emissions and specific resources consumed (per functional unit) resulting from the acquisition and extraction of virgin material, assuming substitution with recyclable materials.
E_{ER}: emissions and specific resources consumed (per functional unit) resulting from the energy recovery process (e.g., incineration with energy recovery, landfill with energy recovery, etc.).
$E_{SE,heat}$ and **$E_{SE,elec}$:** emissions and specific resources consumed (per functional unit) that would have been associated with the substituted energy source, respectively thermal and electrical.
E_D: emissions and specific resources consumed (per functional unit) resulting from the disposal of material waste in the end-of-life phase of the analyzed product, without energy recovery.
$X_{ER,heat}$,and **$X_{ER,elec}$**: efficiency of the energy recovery process for heat and electricity.

LHV: lower heating value of the material in the product, used for energy recovery.

It should be noted that, in the absence of accessible data from the PEF database, for parameters E_V*, E_{ER}, E_{SEheat}, E_{SEelec}, E_{ED}, the datasets related to end-of-life operations contained in Ecoinvent 3.10 were used.

3.5.Collection of economic data and assumptions

Regarding the data collected for this study, it should first be noted that, due to the confidential nature of economic information related to products and services, not all interviewees fully completed the economic data requested in the checklists. This resulted in two main effects. On the one hand, some information was provided by only one respondent, making the data weakly representative for comparison purposes; therefore, such data were compared with available information from the literature in order to assess their usability. For other information, given the limited number of respondents who completed the checklists, an uncertainty analysis was carried out to evaluate data representativeness.

On the other hand, complementary information was obtained from literature studies or databases, both to validate certain data collected from the survey of operators and to obtain information necessary to complete the economic analysis. A review of the consulted literature is provided in the bibliographic appendix. The following scheme shows the sources of direct data collection used in the study, with reference to the checklists completed during the survey.

With regard to TTR, average values derived from the interviewed companies were calculated. These data were then compared with information obtained from manufacturers and with literature data.

The values estimated in the study to assess the purchase cost of the products (TTR), the cost of the rental service, washing, and sterilization are shown below. The percentage weight of energy costs and raw material costs (depreciation share) included in the cost of the service is also shown. The information on product characteristics is the same as that collected and examined for the LCA study, to which reference should be made for technical details.

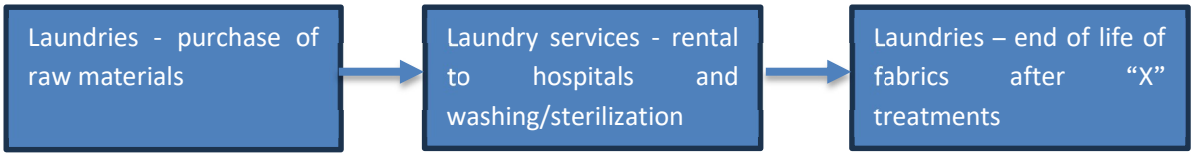


Figure 7. Data collection for LCC assessment of TTR (reusable fabrics)

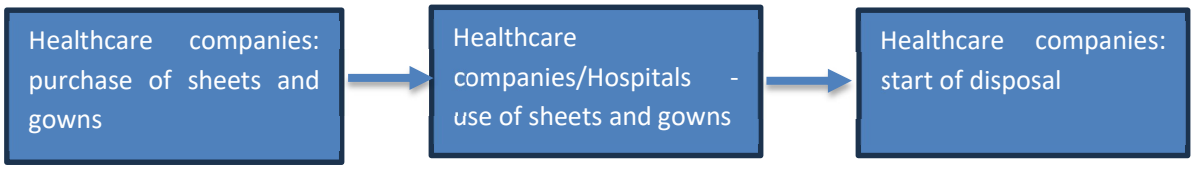


Figure 8. Data collection for LCC assessment of TNT (non-woven fabric, disposable)

Service costs are expressed per kg of fabric, so that they can be used later to estimate the life cycle cost for different sizes of gowns (which have different weights) and for different sizes of drapes and then reported in Euro/piece (see chapter on results), which is the functional unit used in the study.

Table 12: Cost estimate for rental, washing, and sterilization services, including the purchase of gowns and sheets in TTR

Composition of the set in TTR	EUR/kg – average value	Standard deviation on the survey sample
Reinforced gown	6.56	1.71
Standard gown, microfiber	4.38	1.71
Main operating table drape, microfiber	6.11	3.32
Lateral drape, trilaminate	6.04	3.02
Pillowcase, microfiber and trilaminate	6.68	5.55
Head drape, trilaminate	10.85	2.13
Foot drape, trilaminate	10.10	1.05

Table 13: Percentage breakdown of energy costs for the TTR rental and sterilization service

Composition of the set in TTR	% on service costs	Standard deviation on the survey sample
Reinforced gown	9%	0.22
Standard gown, microfiber	9%	0.22
Main operating table drape, microfiber	9%	0.31
Lateral drape, trilaminate	9%	0.30
Pillowcase, microfiber and trilaminate	9%	0.43

Head drape, trilaminate	10%	0.59
Foot drape, trilaminate	10%	0.52

Table 14: Percentage composition of raw material costs (fabrics) for the TTR rental and sterilization service

Composition of the set in TTR	% on service costs	Standard deviation on the survey sample
Reinforced gown	21%	0.97
Standard gown, microfiber	21%	0.65
Main operating table drape, microfiber	22%	0.78
Lateral drape, trilaminate	21%	0.83
Pillowcase, microfiber and trilaminate	22%	0.96
Head drape, trilaminate	28%	2.01
Foot drape, trilaminate	27%	1.76

Table 15 shows the estimated values for the purchase cost of TNT textiles. Also in this case, the technical data are the same as those used for the LCA analysis. The data, derived from a single respondent to the survey, were adjusted by comparing the available information with literature data. The values are expressed in EUR per item, in accordance with the functional unit of the study.

In the model, the total service cost was considered, which includes both the purchase costs of TTR gowns and drapes and the costs related to the rental, laundering, and sterilization services for the same items. Therefore, the service cost also includes the portion related to raw materials already accounted for, namely the amortization of their value, in order to fully represent the actual cost of the materials used.

Table 15: Cost estimate for the purchase of TNT gowns and drapes

Composition of the set in TNT	EUR/piece – estimated value
Reinforced gown – LL size	2.569
Reinforced gown – XL size	2.656
Standard gown – LL size	2.299
Standard gown – XL size	2.394
Main operating table drape	3.355
Lateral drape (surgical drape)	1.281
Pillowcase (surgical drape)	1.281
Head drape	6.222
Foot drape	6.222

With regard to disposal and end-of-life costs, the questionnaires completed by both some operators (two respondents) and healthcare facilities (only one provided this information) were considered partially representative of actual conditions, with the risk of underestimating this value. This aspect is particularly relevant in an LCC analysis, as it highlights a cost associated with the environmental management of a product at end of life. Therefore, a set of assumptions were made, based on selected literature sources and databases representative of both the national and European context. Regarding the information provided by economic operators, the data made it possible to estimate the cost of transporting the material prior to its being sent for treatment. This cost was included in the model, even though in some cases operators declared that they incurred zero cost. Nevertheless, since transport represents a component of the end-of-life management costs borne by the entity responsible for transporting the materials, it was calculated for the purposes of the LCC analysis.

Table 16: Estimated cost of transport for final disposal

Type of cost	EUR/kg of material sent for disposal	Notes
Transportation Cost	0,124	It is estimated that transport costs account for approximately 30% of the average cost declared for the disposal of CER category 040222 by the industrial laundries surveyed.

Regarding disposal and treatment costs, as well as the raw material savings resulting from the use phase of textiles and their subsequent treatment, the data and information sources are reported in Table 17. These values were used to calculate the costs of the different material disposal scenarios, which for TTR include incineration (with energy recovery), landfilling, mechanical recycling, and chemical recycling, whereas for TNT only incineration (with energy recovery) was considered.

Table 17: Literature data and databases for disposal and raw material saving scenarios

Cost type	Unit	Costs	Sources
Incineration cost (CAPEX + OPEX)	EUR/kg	0.619	Andreassi Bassi, S., Tonini, D., Saveyn, H., & Astrup, T. F. (2022). Environmental and Socioeconomic Impacts of Polyethylene terephthalate) (PET) Packaging Management Strategies in the EU.
Landfill cost	EUR/kg	0.0697	Andreassi Bassi, S., Tonini, D., Saveyn, H., & Astrup, T. F. (2022). Environmental and Socioeconomic Impacts of Poly(ethylene terephthalate) (PET) Packaging Management Strategies in the EU.
Mechanical recycling cost – PET regranulate (non-food grade)	EUR/kg	0.25	JRC Technical Report "Environmental and economic assessment of plastic waste recycling", EU 2023
Life cycle costs – mechanical recycling (reference to PET)	EUR/kg	-0.274	JRC Technical Report "Environmental and economic assessment of plastic waste recycling", EU 2023
Chemical recycling cost – MPO flexible pack waste (PET, HDPE, PP, films) – conventional pyrolysis	EUR/kg	0.141	JRC Technical Report "Environmental and economic assessment of plastic waste recycling", EU 2023
Life cycle costs – chemical recycling (as above)	EUR/kg	0.273	JRC Technical Report "Environmental and economic assessment of plastic waste recycling", EU 2023
Electricity price (sale)	EUR/MWh	127.24	GME – average purchase price on the Day-Ahead Market, annual average 2023
Heat price (sale)	EUR /MWh	106	Price (low-end value) of thermal energy for district heating supply, A2A S.p.A. – October 2022
Raw material cost – PP (average value)	EUR/kg	1.166	https://plasticker.de/preise/preise_monat_single_en.php - Raw Materials & Prices - Average price PP 2022-2023

With reference to the costs described in the table above, the values indicated as “life cycle costs” internalize, within the calculation, the resource savings resulting from the different treatment solutions considered in the scenarios.

4. RESULTS OF THE IMPACT ASSESSMENT OF THE ENVIRONMENTAL FOOTPRINT AND COSTS

In this Life Cycle Impact Assessment (LCIA) phase, using the results of the previous inventory analysis, the significance of potential environmental impacts and, in this case, the impact of costs is assessed. The analysis was performed using SimaPro 9.6.0.1 software.

4.1. Analysis of results

The purpose of the life cycle environmental impact assessment of a product or service is to highlight the magnitude of environmental changes resulting from releases to the environment and resource consumption caused by production activities. In this phase, the transition is made from the objective data calculated during the inventory phase to an evaluation of environmental significance, by assigning the resource uses and emissions identified in the inventory phase to specific impact categories. The selected impact categories are described in Section 2.8.

The charts present the results of the individual damage scores obtained from the life cycle assessment (LCA) of various types of medical gowns and surgical drapes.

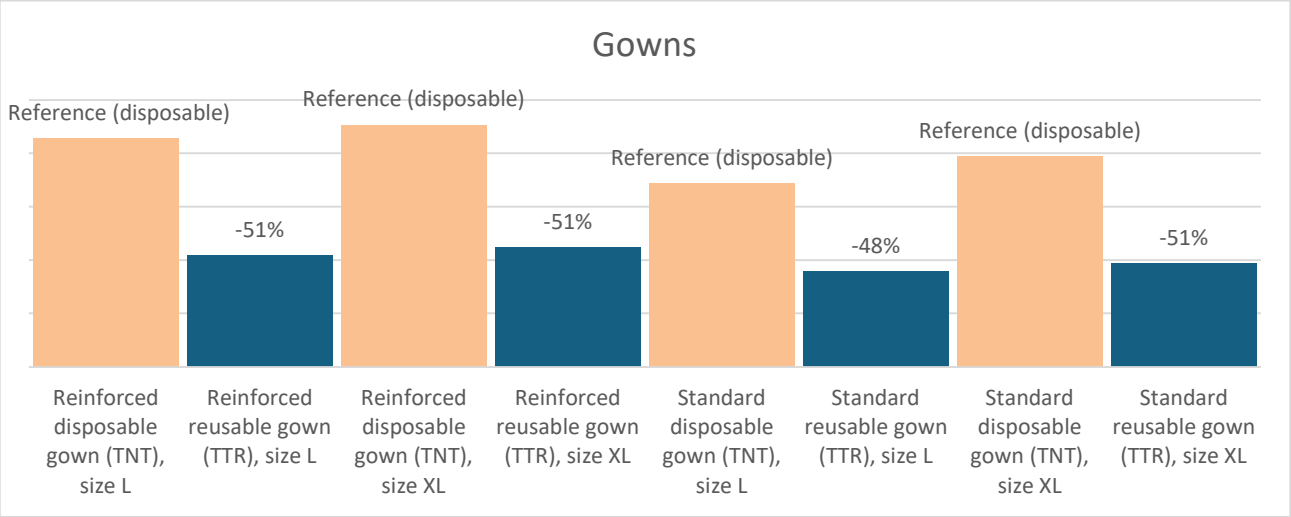


Figure 9. Product comparison - single indicator - Gowns

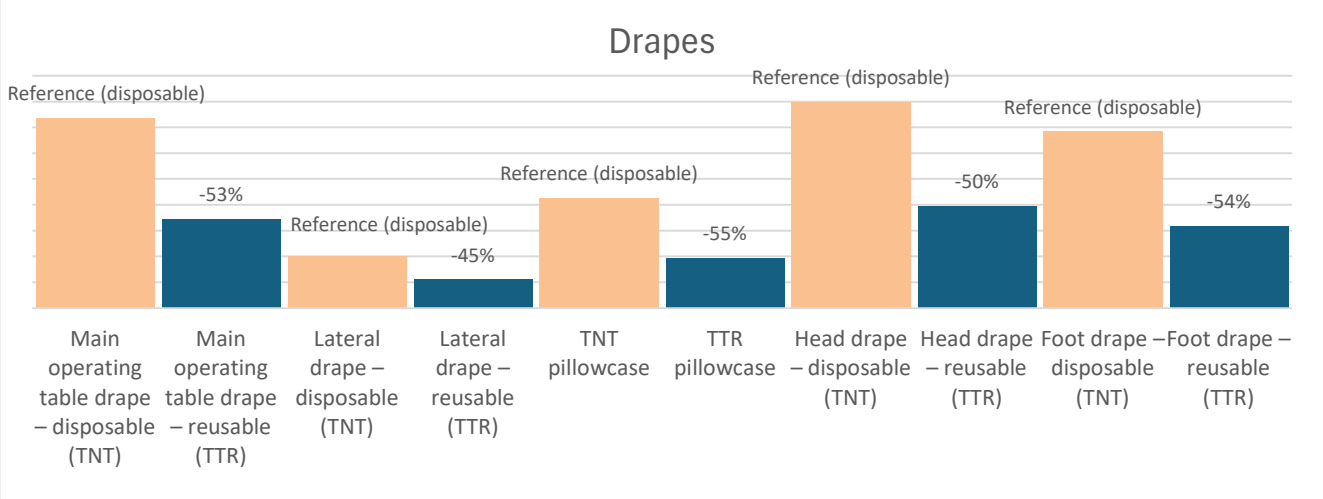


Figure 10. Comparison of articles - single indicator - Drapes

In both categories, TNT shows a significantly higher environmental burden than TTR. Regarding gowns, reinforced TNT options, particularly in larger sizes, exhibit the highest impacts, with the reinforced TNT XL gown reaching the highest score. In contrast, standard TTR gowns, especially in size XL, show the lowest environmental footprint.

Similarly, in the analysis of drapes, TNT materials once again display the highest impact values, with main operating table, head, and foot drapes showing particularly high impacts. TTR alternatives, for all drape types, achieve significantly lower environmental scores. This consistent trend highlights TTR as the more sustainable material and suggests that a transition to TTR for both gowns and drapes could substantially reduce the environmental impact of healthcare operations.

The following charts show the results of the environmental impact assessment for each impact category, based on the functional unit of 1 item and for each of the analyzed products, under the worst-case scenario for TTR, corresponding to landfilling at end of life.

4.1.1. Climate change

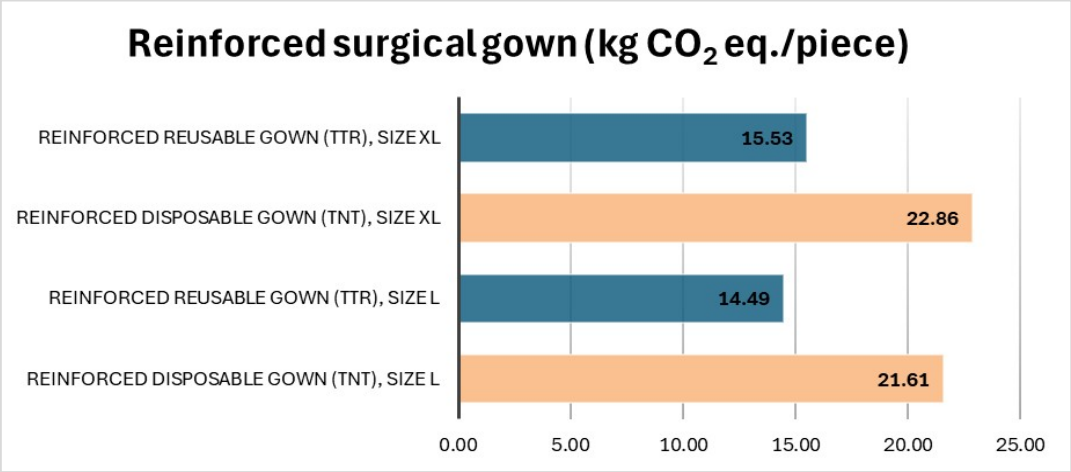


Figure 11. Comparison of Climate Change Impact of Reinforced TNT and TTR Gowns by Size (kg CO_2 eq./piece)

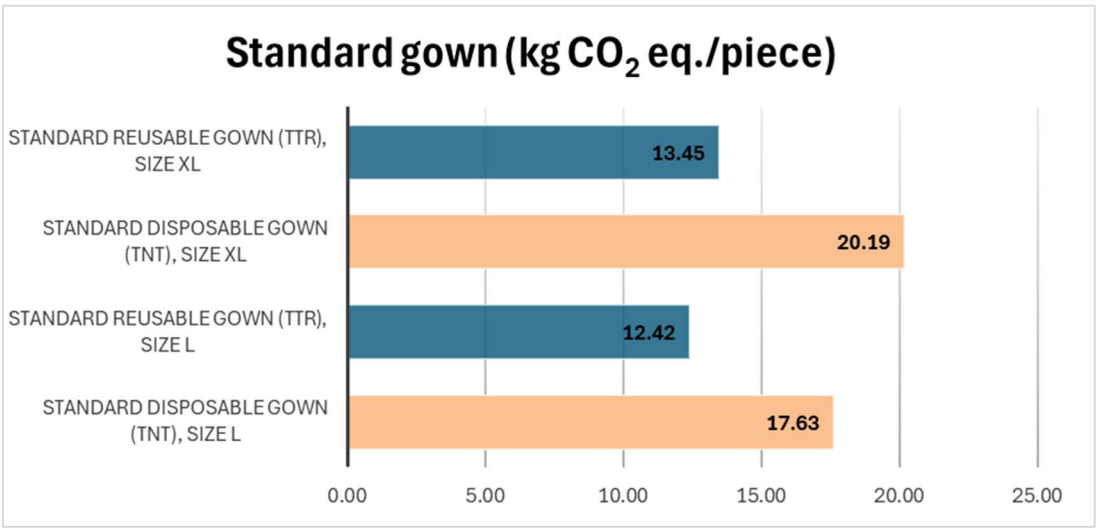


Figure 12. Comparison of Climate Change Impact of Standard TNT and TTR Gowns by Size (kg CO_2 eq./piece)

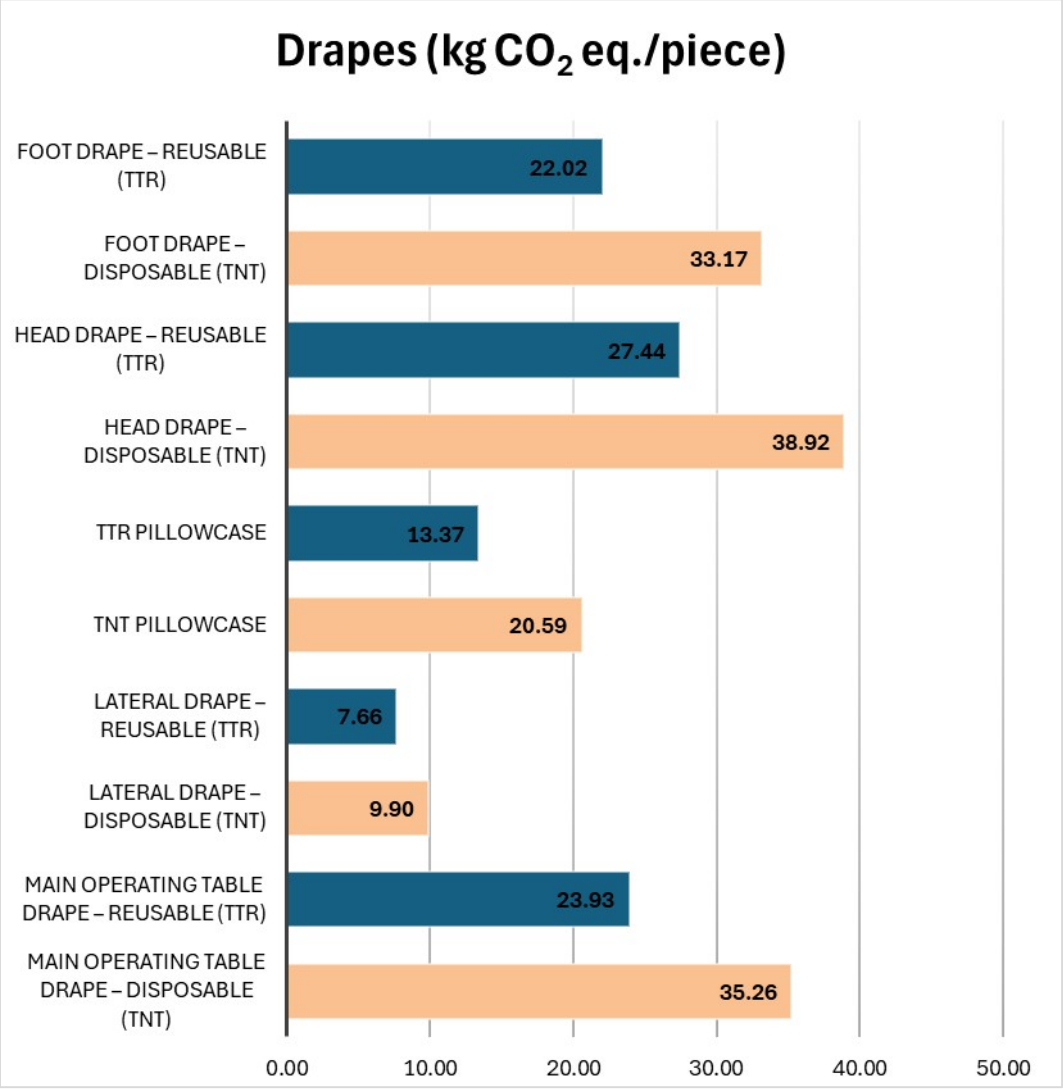


Figure 13. Comparison of Climate Change Impact of Drapes by Type (kg CO_2 eq./piece)

4.1.2. Particulate Matter

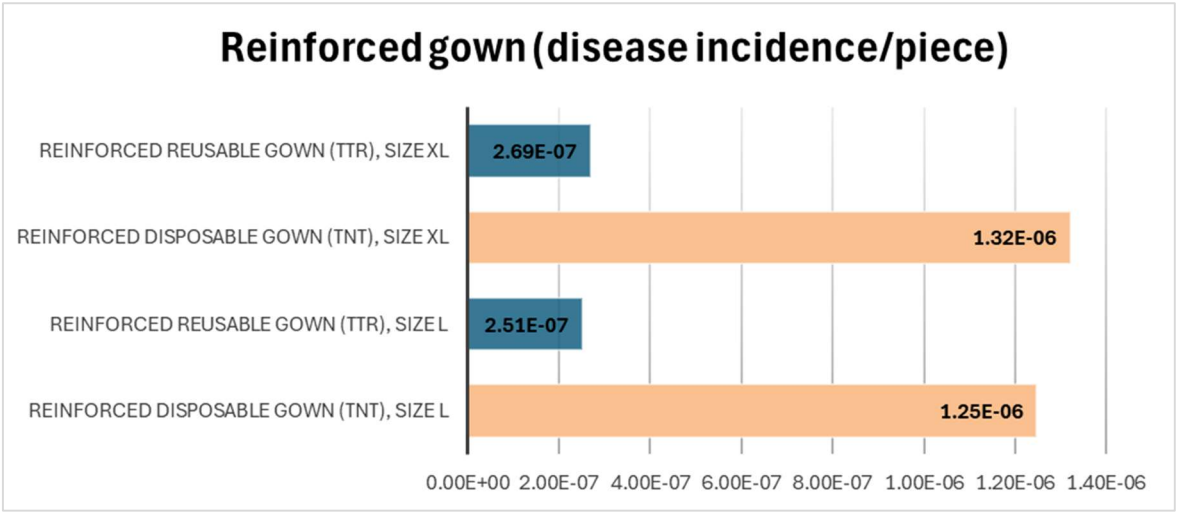


Figure 14. Comparison of Particulate Matter Impact of Reinforced TNT and TTR Gowns by Size (incidence/piece)

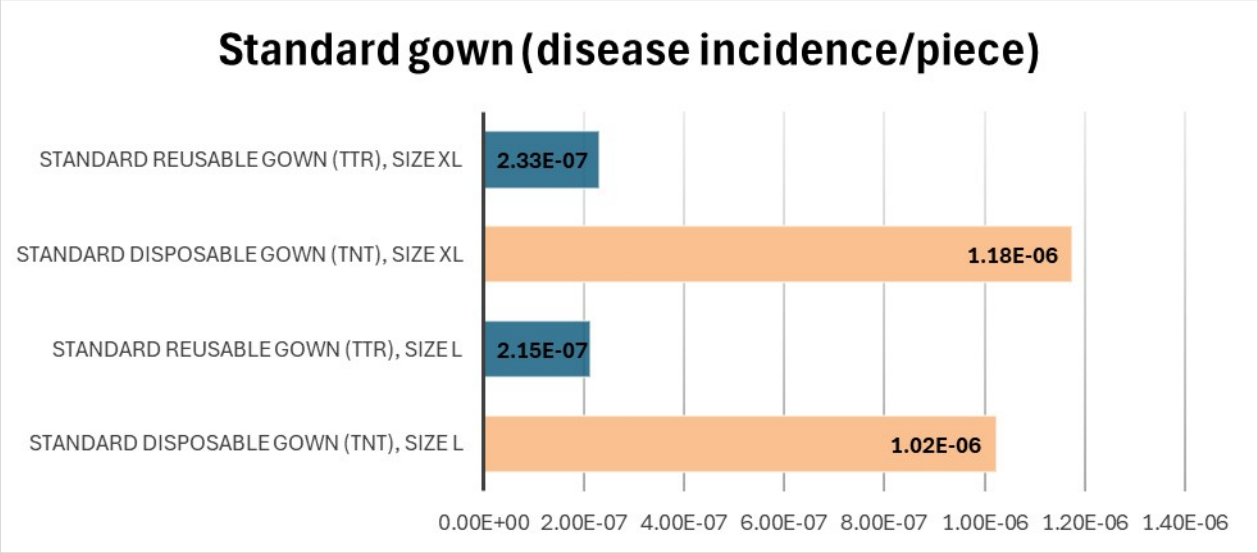


Figure 15. Comparison of Particulate Matter Impact of Standard TNT and TTR Gowns by Size (incidence/piece)

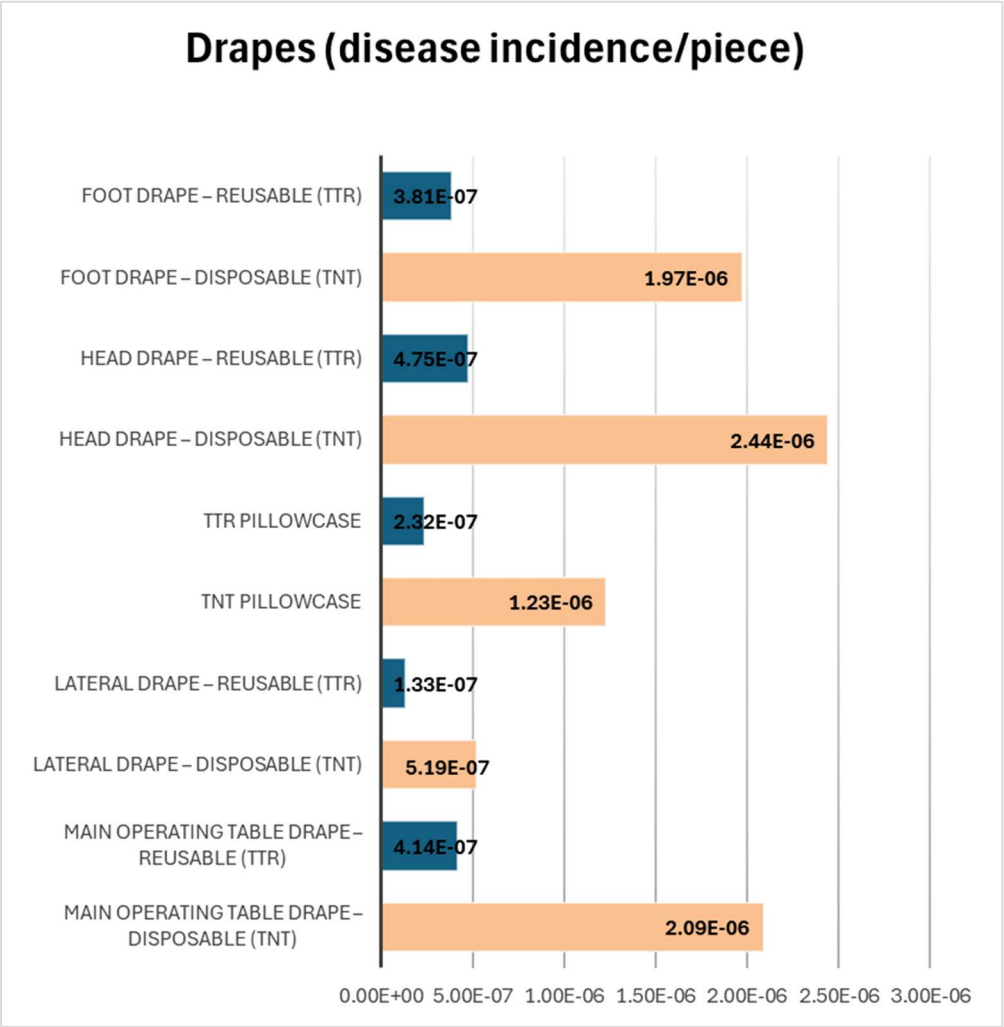


Figure 16. Comparison of Particulate Matter Impact of Drapes by Type (incidence/piece)

4.1.3. Photochemical Ozone Formation

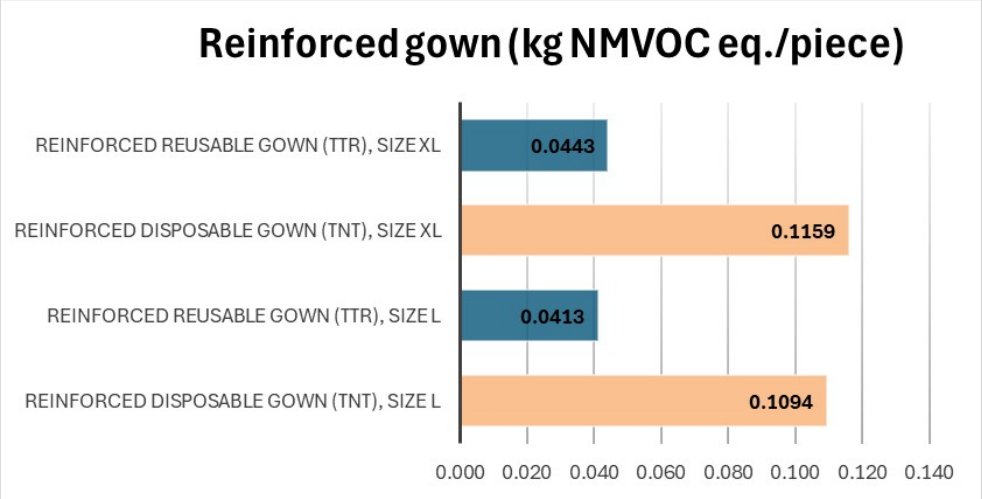


Figure 17. Comparison of Photochemical Ozone Formation Impact of Reinforced TNT and TTR Gowns by Size (kg NMVOC eq./piece

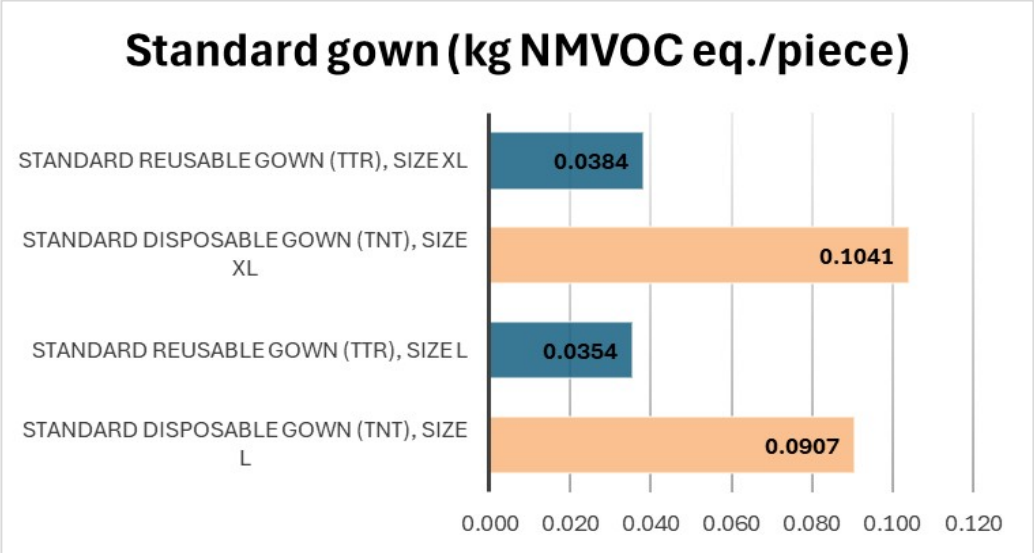


Figure 17. Comparison of Photochemical Ozone Formation Impact of Standard TNT and TTR Gowns by Size (kg NMVOC eq./piece)

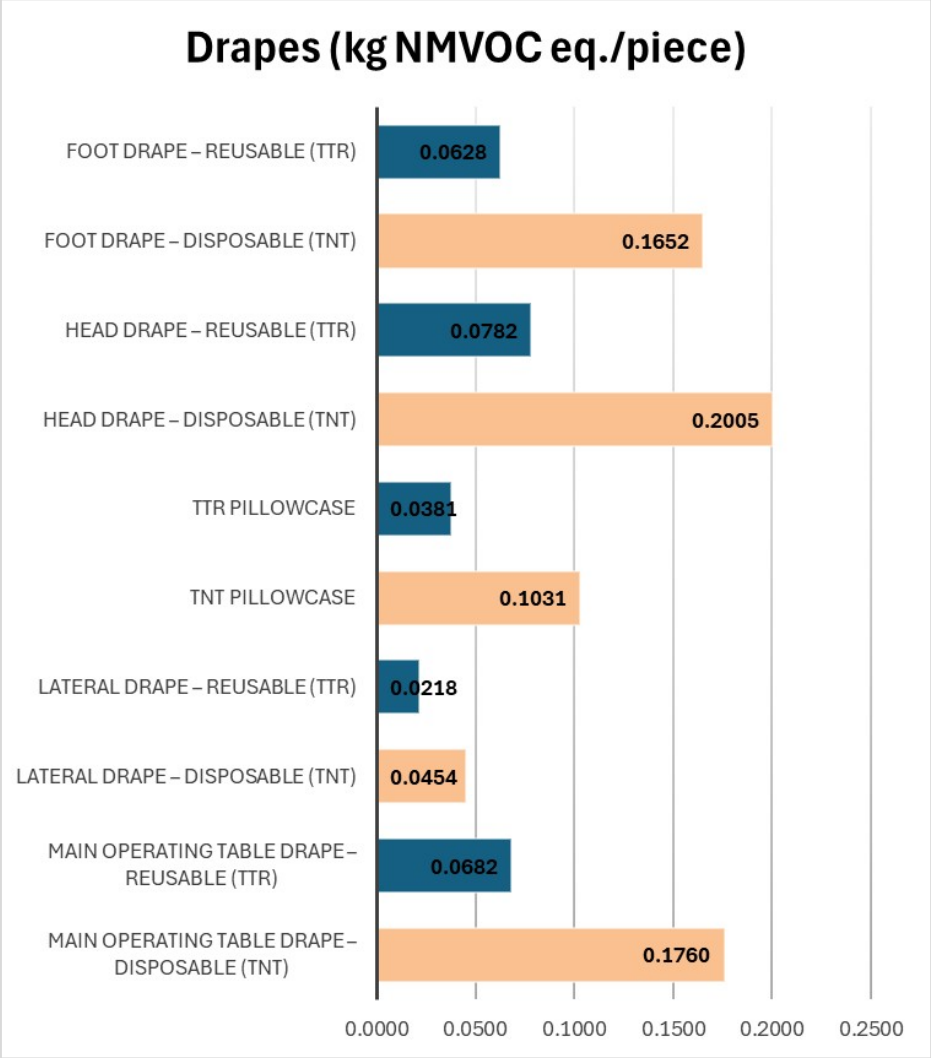


Figure 18. Comparison of Photochemical Ozone Formation Impact of Drapes by Type (kg NMVOC eq./piece)

4.1.4. Fossil Resource Use

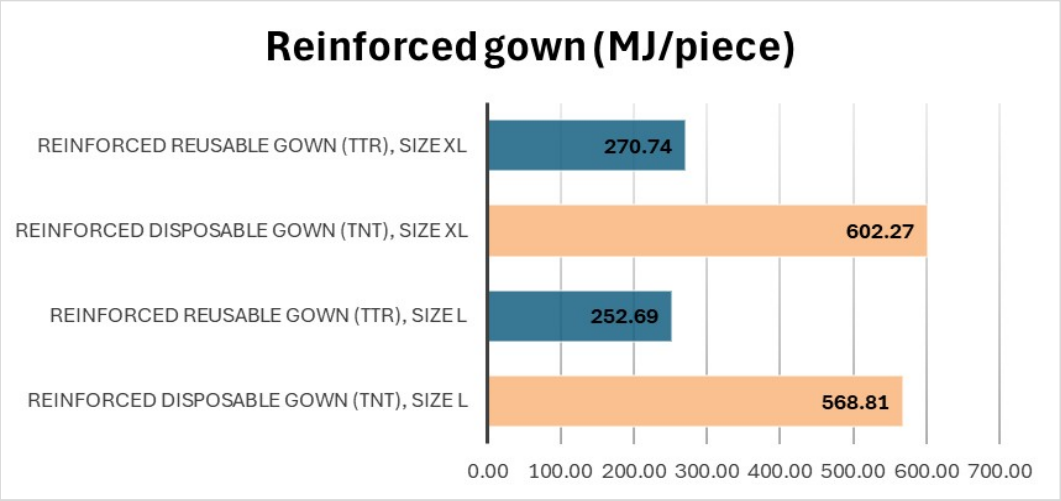


Figure 19. Comparison of Fossil Resource Use Impact of Reinforced TNT and TTR Gowns by Size (MJ/piece)

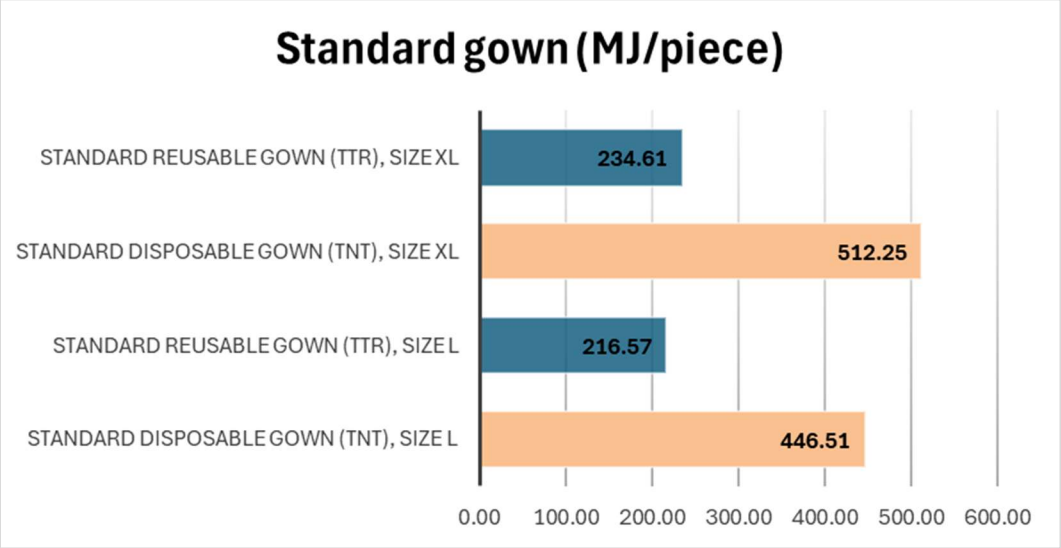


Figure 20. Comparison of Fossil Resource Use Impact of Standard TNT and TTR Gowns by Size (MJ/piece)

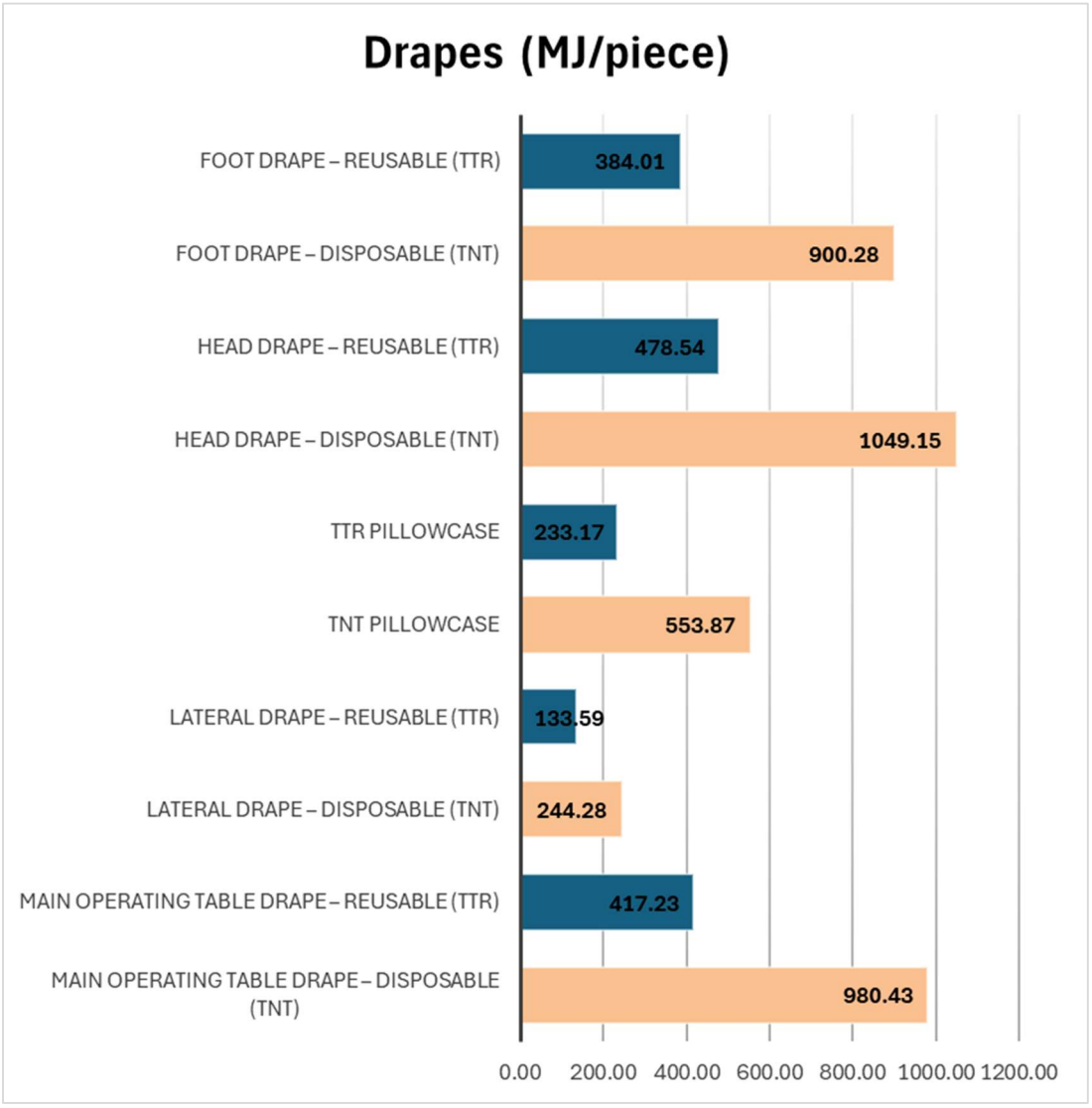


Figure 21. Comparison of Fossil Resource Use Impact of Drapes by Type (MJ/piece)

4.1.5. Results by life cycle stage

To analyze all the contributions of the various processes that determine the impact values reported above, the different life cycle macro-phases were separated. The contributions, shown below (from Table 19 to Table 30), generally indicate that for disposable products, the manufacturing phase is the main contributor, as it is repeated as many times as the reusable item undergoes washing and sterilization. For some impact categories, end of life, considered as incineration, also has a significant contribution, on the order of 30–40%.

In the case of reusable products, the phase with the greatest contribution is laundering, due to the environmental impacts associated with each washing cycle. For several indicators, transport to and from customers also plays a significant role, while end of life (shown here in the worst-case scenario of landfilling) accounts for values as low as around 3% in the case of Climate Change. The end-of-life scenarios analyzed for reusable products show impact reductions that increase when moving from the worst-case scenario (landfilling) to the most advantageous options. The results compared with respect to the Climate Change indicator are reported below: for example, in the case of the reinforced gown, if the reusable item is landfilled, the impact reduction is 3 percentage points lower than in the mechanical recycling scenario. The limited variability among these values is due to the fact that, for TTR products, the end-of-life phase has a very small weight compared with the laundering and delivery phases (see the following tables).

Table 18. Comparison of end-of-life scenarios for TTR for the Climate Change indicator

Item	TNT – disposable	TTR – reusable 1 pc			
	60 pc	TTR E-o-L mechanical recycling	TTR E-o-L chemical recycling	TTR E-o-L incineration	TTR E-o-L landfill
Sterile reinforced gown, size L	21.61	13.78	14.00	14.03	14.49
Sterile reinforced gown, size XL	22.86	14.76	15.00	15.04	15.53
Sterile standard gown, size L	17.63	11.81	12.00	12.03	12.42
Sterile standard gown, size XL	20.19	12.79	13.00	13.03	13.45
Main operating table drape	35.26	22.75	23.12	23.17	23.93
Lateral drape	9.90	7.29	7.40	7.42	7.66
Mayo stand cover	20.59	12.71	12.92	12.95	13.37
Head drape	38.92	26.09	26.51	26.58	27.44
Foot drape	33.17	20.94	21.28	21.33	22.02

E-o-L: *end-of-life*

Table 19. Results by life cycle phase, reinforced gown size L (DISPOSABLE)

Impact category	Unit	Product and packaging production	Sterilization	Transport to customers	End of life
Acidification	mol H+ eq	71.2%	0.9%	0.8%	27.0%
Climate change	kg CO_2 eq	68.8%	1.2%	1.1%	28.9%
Freshwater ecotoxicity	CTUe	99.6%	0.1%	0.2%	0.1%
Particulate matter	disease inc.	87.7%	2.7%	0.5%	9.1%
Marine eutrophication	kg N eq	76.1%	1.7%	0.7%	21.4%
Freshwater eutrophication	kg P eq	80.0%	<0.01%	0.6%	19.3%
Terrestrial eutrophication	mol N eq	74.7%	1.8%	0.8%	22.7%
Human toxicity, carcinogenic effects	CTUh	39.6%	0.2%	1.0%	59.2%
Human toxicity, non-carcinogenic effects	CTUh	83.0%	2.8%	1.0%	13.2%
Ionizing radiation	kBq U-235 eq	59.8%	0.1%	0.4%	39.7%
Land use	Pt	61.5%	<0.01%	0.5%	38.1%
Ozone layer depletion	kg CFC11 eq	26.1%	0.1%	0.1%	73.8%
Photochemical ozone formation	kg NMVOC eq	77.1%	1.4%	0.7%	20.7%
Resource use, fossil	MJ	75.0%	0.8%	0.8%	23.5%
Resource use, minerals and metals	kg Sb eq	24.8%	0.1%	<0.01%	75.1%
Water scarcity	m^3 depriv.	57.2%	<0.01%	0.6%	42.1%

Table 20. Results by life cycle stage, reinforced gown size L (REUSABLE, worst-case scenario: end of life in landfill)

Categoria di impatto	Unità	Produzione dell'articolo e del suo imballaggio	Trasporto alla lavanderia	Lavaggio e sterilizzazione	Ritiro e consegna clienti	Fine vita
Acidification	mol H+ eq	0.7%	0.2%	82.6%	16.4%	0.1%
Climate change	kg CO_2 eq	0.4%	0.1%	84.8%	12.2%	2.4%
Freshwater ecotoxicity	CTUe	0.9%	<0.01%	96.9%	2.2%	<0.01%
Particulate matter	disease inc.	0.6%	0.5%	66.2%	32.4%	0.3%
Marine eutrophication	kg N eq	0.5%	0.2%	79.1%	20.0%	0.2%
Freshwater eutrophication	kg P eq	0.5%	<0.01%	98.8%	0.7%	<0.01%
Terrestrial eutrophication	mol N eq	0.5%	0.3%	76.1%	22.9%	0.2%
Human toxicity, carcinogenic effects	CTUh	0.9%	<0.01%	96.5%	2.6%	<0.01%
Human toxicity, non-carcinogenic effects	CTUh	0.6%	0.3%	75.4%	22.0%	1.7%
Ionizing radiation	kBq U-235 eq	0.9%	<0.01%	96.4%	2.6%	<0.01%
Land use	Pt	<0.01%	<0.01%	99.6%	0.1%	0.2%
Ozone layer depletion	kg CFC11 eq	13.8%	0.1%	79.8%	6.3%	<0.01%
Photochemical ozone formation	kg NMVOC eq	0.6%	0.2%	81.7%	17.1%	0.4%
Resource use, fossil	MJ	0.5%	0.1%	90.3%	9.1%	<0.01%
Resource use, minerals and metals	kg Sb eq	4.0%	0.1%	86.8%	9.1%	0.1%
Water scarcity	m^3 depriv.	0.1%	<0.01%	99.8%	0.1%	<0.01%

Table 21. Results by life cycle phase, standard gown size L (DISPOSABLE)

Impact category	Unit	Product and packaging production	Sterilization	Transport to customers	End of life
Acidification	mol H+ eq	72.2%	0.9%	1.1%	25.8%
Climate change	kg CO_2 eq	69.6%	1.2%	1.4%	27.8%
Freshwater ecotoxicity	CTUe	99.6%	0.1%	0.2%	0.1%
Particulate matter	disease inc.	88.5%	2.5%	0.6%	8.4%
Marine eutrophication	kg N eq	77.4%	1.6%	0.9%	20.1%
Freshwater eutrophication	kg P eq	79.8%	0.0%	0.8%	19.3%
Terrestrial eutrophication	mol N eq	75.8%	1.7%	1.0%	21.5%
Human toxicity. carcinogenic effects	CTUh	41.3%	0.1%	1.3%	57.3%
Human toxicity. non-carcinogenic effects	CTUh	84.3%	2.5%	1.2%	12.0%
Ionizing radiation	kBq U-235 eq	55.1%	0.1%	0.6%	44.3%
Land use	Pt	66.2%	<0.01%	0.5%	33.2%
Ozone layer depletion	kg CFC11 eq	51.5%	<0.01%	0.1%	48.4%
Photochemical ozone formation	kg NMVOC eq	78.3%	1.4%	0.9%	19.5%
Resource use. fossil	MJ	75.4%	0.7%	1.0%	22.9%
Resource use. minerals and metals	kg Sb eq	32.0%	0.1%	<0.01%	67.9%
Water scarcity	m^3 depriv.	56.2%	<0.01%	0.9%	42.9%

Table 22. Results by life cycle phase, standard gown size L (REUSABLE – worst-case scenario: end of life to landfill)

Impact category	Unit	Product and packaging production	Transport to laundry	Laundering and sterilization	Collection and delivery to customers	End of life
Acidification	mol H+ eq	0.7%	0.2%	82.6%	16.4%	0.1%
Climate change	kg CO_2 eq	0.4%	0.1%	84.8%	12.2%	2.4%
Freshwater ecotoxicity	CTUe	0.5%	<0.01%	97.3%	2.2%	<0.01%
Particulate matter	disease inc.	0.6%	0.5%	66.3%	32.4%	0.3%
Marine eutrophication	kg N eq	0.5%	0.2%	79.1%	20.0%	0.2%
Freshwater eutrophication	kg P eq	0.5%	<0.01%	98.8%	0.7%	<0.01%
Terrestrial eutrophication	mol N eq	0.5%	0.3%	76.1%	22.9%	0.2%
Human toxicity, carcinogenic effects	CTUh	0.3%	<0.01%	97.1%	2.6%	<0.01%
Human toxicity, non-carcinogenic effects	CTUh	0.6%	0.3%	75.4%	22.0%	1.7%
Ionizing radiation	kBq U-235 eq	0.9%	<0.01%	96.5%	2.6%	<0.01%
Land use	Pt	<0.01%	<0.01%	99.7%	0.1%	0.2%
Ozone layer depletion	kg CFC11 eq	15.7%	0.1%	78.1%	6.2%	<0.01%
Photochemical ozone formation	kg NMVOC eq	0.6%	0.2%	81.7%	17.1%	0.4%
Resource use, fossil	MJ	0.4%	0.1%	90.3%	9.1%	<0.01%
Resource use, minerals and metals	kg Sb eq	2.9%	0.1%	87.7%	9.2%	0.1%
Water scarcity	m^3 depriv.	<0.01%	<0.01%	100.0%	0.1%	<0.01%

Table 23. Results by life cycle phase, main operating table drape (DISPOSABLE)

Impact category	Unit	Product and packaging production	Sterilization	Transport to customers	End of life
Acidification	mol H+ eq	69.8%	1.0%	0.5%	28.7%
Climate change	kg CO_2 eq	67.9%	1.3%	0.6%	30.2%
Freshwater ecotoxicity	CTUe	99.7%	0.1%	0.1%	0.1%
Particulate matter	disease inc.	87.1%	2.9%	0.3%	9.7%
Marine eutrophication	kg N eq	74.9%	1.8%	0.4%	22.9%
Freshwater eutrophication	kg P eq	79.7%	<0.01%	0.4%	19.9%
Terrestrial eutrophication	mol N eq	73.1%	2.0%	0.5%	24.5%
Human toxicity, carcinogenic effects	CTUh	53.2%	0.1%	0.4%	46.2%
Human toxicity, non-carcinogenic effects	CTUh	83.3%	2.8%	0.5%	13.4%
Ionizing radiation	kBq U-235 eq	60.1%	0.1%	0.2%	39.6%
Land use	Pt	71.2%	<0.01%	0.2%	28.6%
Ozone layer depletion	kg CFC11 eq	10.0%	0.1%	<0.01%	89.8%
Photochemical ozone formation	kg NMVOC eq	75.8%	1.6%	0.4%	22.2%
Resource use, fossil	MJ	74.6%	0.8%	0.4%	24.1%
Resource use, minerals and metals	kg Sb eq	30.4%	0.1%	<0.01%	69.5%
Water scarcity	m^3 depriv.	61.4%	<0.01%	0.3%	38.3%

Table 24. Results by life cycle phase, main operating table drape (REUSABLE – worst-case scenario: end of life to landfill)

Impact category	Unit	Product and packaging production	Transport to laundry	Laundering and sterilization	Collection and delivery to customers	End of life
Acidification	mol H+ eq	0.7%	0.2%	82.6%	16.4%	0.1%
Climate change	kg CO_2 eq	0.4%	0.1%	84.8%	12.2%	2.4%
Freshwater ecotoxicity	CTUe	0.7%	<0.01%	97.1%	2.2%	<0.01%
Particulate matter	disease inc.	0.6%	0.5%	66.3%	32.4%	0.3%
Marine eutrophication	kg N eq	0.6%	0.2%	79.0%	20.0%	0.2%
Freshwater eutrophication	kg P eq	0.5%	<0.01%	98.7%	0.7%	<0.01%
Terrestrial eutrophication	mol N eq	0.6%	0.3%	76.1%	22.9%	0.2%
Human toxicity, carcinogenic effects	CTUh	0.6%	<0.01%	96.8%	2.6%	<0.01%
Human toxicity, non-carcinogenic effects	CTUh	0.6%	0.3%	75.4%	22.0%	1.7%
Ionizing radiation	kBq U-235 eq	0.9%	<0.01%	96.4%	2.6%	<0.01%
Land use	Pt	0.1%	<0.01%	99.6%	0.1%	0.2%
Ozone layer depletion	kg CFC11 eq	14.5%	0.1%	79.2%	6.2%	<0.01%
Photochemical ozone formation	kg NMVOC eq	0.6%	0.2%	81.7%	17.1%	0.4%
Resource use, fossil	MJ	0.4%	0.1%	90.3%	9.1%	<0.01%
Resource use, minerals and metals	kg Sb eq	3.4%	0.1%	87.3%	9.2%	0.1%
Water scarcity	m^3 depriv.	<0.01%	<0.01%	99.9%	0.1%	<0.01%

Table 25. Results by life cycle phase, Pillowcase (DISPOSABLE)

Impact category	Unit	Product and packaging production	Sterilization	Transport to customers	End of life
Acidification	mol H+ eq	69.7%	1.0%	0.9%	28.4%
Climate change	kg CO_2 eq	67.9%	1.3%	1.1%	29.8%
Freshwater ecotoxicity	CTUe	99.7%	0.1%	0.1%	0.1%
Particulate matter	disease inc.	87.3%	2.8%	0.5%	9.4%
Marine eutrophication	kg N eq	75.3%	1.8%	0.8%	22.2%
Freshwater eutrophication	kg P eq	78.5%	<0.01%	0.7%	20.8%
Terrestrial eutrophication	mol N eq	73.5%	1.9%	0.8%	23.8%
Human toxicity, carcinogenic effects	CTUh	60.8%	0.1%	0.6%	38.4%
Human toxicity, non-carcinogenic effects	CTUh	83.9%	2.6%	0.9%	12.6%
Ionizing radiation	kBq U-235 eq	54.0%	0.1%	0.5%	45.4%
Land use	Pt	73.8%	<0.01%	0.3%	25.8%
Ozone layer depletion	kg CFC11 eq	13.5%	0.1%	0.1%	86.3%
Photochemical ozone formation	kg NMVOC eq	76.0%	1.5%	0.7%	21.7%
Resource use, fossil	MJ	74.3%	0.8%	0.8%	24.1%
Resource use, minerals and metals	kg Sb eq	37.7%	0.1%	<0.01%	62.2%
Water scarcity	m^3 depriv.	61.2%	<0.01%	0.6%	38.2%

Table 26. Results by life cycle phase, Pillowcase (REUSABLE – worst-case scenario: end of life to landfill)

Impact category	Unit	Product and packaging production	Transport to laundry	Laundering and sterilization	Collection and delivery to customers	End of life
Acidification	mol H+ eq	0.7%	0.2%	82.6%	16.4%	0.1%
Climate change	kg CO_2 eq	0.4%	0.1%	84.8%	12.2%	2.4%
Freshwater ecotoxicity	CTUe	0.7%	<0.01%	97.0%	2.2%	<0.01%
Particulate matter	disease inc.	0.6%	0.5%	66.2%	32.4%	0.3%
Marine eutrophication	kg N eq	0.6%	0.2%	79.0%	20.0%	0.2%
Freshwater eutrophication	kg P eq	0.5%	<0.01%	98.7%	0.7%	<0.01%
Terrestrial eutrophication	mol N eq	0.6%	0.3%	76.1%	22.9%	0.2%
Human toxicity, carcinogenic effects	CTUh	0.6%	<0.01%	96.8%	2.6%	<0.01%
Human toxicity, non-carcinogenic effects	CTUh	0.6%	0.3%	75.4%	22.0%	1.7%
Ionizing radiation	kBq U-235 eq	0.9%	<0.01%	96.4%	2.6%	<0.01%
Land use	Pt	0.1%	<0.01%	99.6%	0.1%	0.2%
Ozone layer depletion	kg CFC11 eq	14.6%	0.1%	79.1%	6.2%	<0.01%
Photochemical ozone formation	kg NMVOC eq	0.6%	0.2%	81.7%	17.1%	0.4%
Resource use, fossil	MJ	0.4%	0.1%	90.3%	9.1%	<0.01%
Resource use, minerals and metals	kg Sb eq	3.4%	0.1%	87.2%	9.2%	0.1%
Water scarcity	m3 depriv.	0.1%	<0.01%	99.9%	0.1%	<0.01%

Table 27. Results by life cycle phase, lateral drape (DISPOSABLE)

Impact category	Unit	Product and packaging production	Sterilization	Transport to customers	End of life
Acidification	mol H+ eq	72.3%	0.8%	2.0%	24.8%
Climate change	kg CO_2 eq	69.8%	1.1%	2.7%	26.4%
Freshwater ecotoxicity	CTUe	99.6%	0.1%	0.2%	0.1%
Particulate matter	disease inc.	88.0%	2.5%	1.3%	8.3%
Marine eutrophication	kg N eq	78.0%	1.5%	1.8%	18.7%
Freshwater eutrophication	kg P eq	81.9%	<0.01%	1.4%	16.6%
Terrestrial eutrophication	mol N eq	75.8%	1.7%	1.9%	20.6%
Human toxicity, carcinogenic effects	CTUh	75.1%	0.1%	1.1%	23.8%
Human toxicity, non-carcinogenic effects	CTUh	86.9%	1.9%	1.8%	9.3%
Ionizing radiation	kBq U-235 eq	63.3%	0.1%	1.0%	35.7%
Land use	Pt	83.3%	<0.01%	0.5%	16.2%
Ozone layer depletion	kg CFC11 eq	24.1%	0.1%	0.2%	75.6%
Photochemical ozone formation	kg NMVOC eq	77.4%	1.4%	1.8%	19.5%
Resource use, fossil	MJ	75.6%	0.7%	1.9%	21.8%
Resource use, minerals and metals	kg Sb eq	54.0%	0.1%	<0.01%	46.0%
Water scarcity	m3 depriv.	65.7%	<0.01%	1.3%	32.9%

Table 28. Results by life cycle phase, lateral drape (REUSABLE – worst-case scenario: end of life to landfill)

Impact category	Unit	Product and packaging production	Transport to laundry	Laundering and sterilization	Collection and delivery to customers	End of life
Acidification	mol H+ eq	0.8%	0.2%	82.5%	16.3%	0.1%
Climate change	kg CO_2 eq	0.5%	0.1%	84.8%	12.2%	2.4%
Freshwater ecotoxicity	CTUe	1.0%	<0.01%	96.7%	2.2%	<0.01%
Particulate matter	disease inc.	0.7%	0.5%	66.1%	32.3%	0.3%
Marine eutrophication	kg N eq	1.0%	0.2%	78.7%	19.9%	0.2%
Freshwater eutrophication	kg P eq	0.7%	<0.01%	98.5%	0.7%	<0.01%
Terrestrial eutrophication	mol N eq	0.8%	0.3%	76.0%	22.8%	0.2%
Human toxicity, carcinogenic effects	CTUh	0.9%	<0.01%	96.5%	2.6%	<0.01%
Human toxicity, non-carcinogenic effects	CTUh	0.8%	0.3%	75.2%	22.0%	1.7%
Ionizing radiation	kBq U-235 eq	1.1%	<0.01%	96.3%	2.6%	<0.01%
Land use	Pt	0.4%	<0.01%	99.3%	0.1%	0.2%
Ozone layer depletion	kg CFC11 eq	14.2%	0.1%	79.5%	6.3%	<0.01%
Photochemical ozone formation	kg NMVOC eq	0.6%	0.2%	81.7%	17.1%	0.4%
Resource use, fossil	MJ	0.5%	0.1%	90.2%	9.1%	<0.01%
Resource use, minerals and metals	kg Sb eq	4.0%	0.1%	86.7%	9.1%	0.1%
Water scarcity	m^3 depriv.	0.2%	<0.01%	99.8%	0.1%	<0.01%

Table 29. Results by life cycle phase, Foot drape (DISPOSABLE)

Impact category	Unit	Product and packaging production	Sterilization	Transport to customers	End of life
Acidification	mol H+ eq	70,5%	0,9%	0,5%	28,0%
Climate change	kg CO_2 eq	68,3%	1,3%	0,7%	29,8%
Freshwater ecotoxicity	CTUe	99,7%	0,1%	0,1%	0,1%
Particulate matter	disease inc.	87,5%	2,8%	0,3%	9,4%
Marine eutrophication	kg N eq	75,6%	1,8%	0,5%	22,1%
Freshwater eutrophication	kg P eq	79,9%	<0,01%	0,4%	19,6%
Terrestrial eutrophication	mol N eq	74,0%	1,9%	0,5%	23,7%
Human toxicity, carcinogenic effects	CTUh	55,4%	0,1%	0,4%	44,1%
Human toxicity, non-carcinogenic effects	CTUh	83,8%	2,7%	0,6%	12,9%
Ionizing radiation	kBq U-235 eq	59,5%	0,1%	0,3%	40,1%
Land use	Pt	70,1%	<0,01%	0,2%	29,7%
Ozone layer depletion	kg CFC11 eq	10,9%	0,1%	<0,01%	89,0%
Photochemical ozone formation	kg NMVOC eq	76,2%	1,5%	0,5%	21,8%
Resource use, fossil	MJ	74,7%	0,8%	0,5%	24,0%
Resource use, minerals and metals	kg Sb eq	33,1%	0,1%	<0,01%	66,8%
Water scarcity	m^3 depriv.	59,6%	<0,01%	0,4%	40,0%

Table 30. Results by life cycle phase, Foot drape (REUSABLE – worst-case scenario: end of life to landfill)

Impact category	Unit	Product and packaging production	Transport to laundry	Laundering and sterilization	Collection and delivery to customers	End of life
Acidification	mol H+ eq	0.7%	0.2%	82.6%	16.4%	0.1%
Climate change	kg CO_2 eq	0.4%	0.1%	84.8%	12.2%	2.4%
Freshwater ecotoxicity	CTUe	0.6%	<0.01%	97.1%	2.2%	<0.01%
Particulate matter	disease inc.	0.6%	0.5%	66.3%	32.4%	0.3%
Marine eutrophication	kg N eq	0.6%	0.2%	79.0%	20.0%	0.2%
Freshwater eutrophication	kg P eq	0.5%	<0.01%	98.8%	0.7%	<0.01%
Terrestrial eutrophication	mol N eq	0.6%	0.3%	76.1%	22.9%	0.2%
Human toxicity, carcinogenic effects	CTUh	0.5%	<0.01%	96.9%	2.6%	<0.01%
Human toxicity, non-carcinogenic effects	CTUh	0.6%	0.3%	75.4%	22.0%	1.7%
Ionizing radiation	kBq U-235 eq	0.9%	<0.01%	96.5%	2.6%	<0.01%
Land use	Pt	0.1%	<0.01%	99.6%	0.1%	0.2%
Ozone layer depletion	kg CFC11 eq	14.9%	0.1%	78.8%	6.2%	<0.01%
Photochemical ozone formation	kg NMVOC eq	0.6%	0.2%	81.7%	17.1%	0.4%
Resource use, fossil	MJ	0.4%	0.1%	90.3%	9.1%	<0.01%
Resource use, minerals and metals	kg Sb eq	3.2%	0.1%	87.4%	9.2%	0.1%
Water scarcity	m^3 depriv.	<0.01%	<0.01%	99.9%	0.1%	<0.01%

4.2. Impact of costs

Based on the data presented above, which make it possible to assess both the costs and the revenues (income) that may arise from the operations evaluated over the life cycle, the different items (pieces) that make up the set of gowns and drapes used in operating rooms can be compared.

The cost and revenue components analyzed are as follows:

- Costs for the purchase of items (textiles), which for TTR are borne by the laundries and for TNT by healthcare organizations;
- Costs for rental, laundering, and sterilization services, which represent the value of the service sold by the laundries and borne by healthcare organizations;
- Disposal costs (for the different scenarios analyzed, which also include various treatment options for recycling). In this case, the reported value represents the net income resulting from the different operations using the life cycle costing approach:
    - for incineration, transport and treatment costs are considered, together with revenues from the sale of electricity and heat; as in the LCA analysis, the only treatment scenario assumed for TNT is incineration with energy recovery;
    - for landfilling, transport and disposal management costs are considered;
    - for mechanical recycling, transport and treatment costs are considered, together with the economic benefit resulting from resource savings due to the substitution of virgin raw materials with recycled content (for TTR, the saved virgin material component is assumed to be polystyrene, assimilated to PET);
    - for chemical recycling (pyrolysis technology assumed), transport and treatment costs are considered, together with the economic benefit from resource savings, as for mechanical recycling;
- The benefit (in terms of avoided costs) deriving from raw material savings due to the reduced need to produce new TNT items, resulting from the choice to use the rental, laundering, and sterilization service for TTR, which have a longer life cycle than TNT.

It should be noted that one limitation of the study concerns the chemical recycling scenario, which—based on the literature source used (a study conducted by the JRC of the European Union, see bibliography)—represents a costly technology (especially in terms of capital investment), resulting in a non-positive net outcome. However, as this is a rapidly evolving technology and valid alternatives to the assumed process (pyrolysis) are available—such as pyrolysis combined with gasification and technologies based on dissolution, glycolysis, and methanolysis—ongoing analyses and research report positive net results (in the literature, from EUR 0.5 to 1 per kg treated), which could significantly change the outcome of the assumed scenario. For the purposes of this study, however, the most conservative scenario was adopted.

IMPORTANT. When interpreting the values, it should be kept in mind that the comparison is carried out—as in the LCA analysis—with respect to the function performed by the item, which corresponds to the number of laundering and sterilization cycles assumed for TTR in all scenarios of this study. Therefore, to guarantee the same performance as 1 TTR item, 60 TNT items are required (functional unit – FU).

Table 31 and Figure 23 present comparisons of the total life cycle cost for the different items analyzed. As stated previously, the end-of-life (EoL) scenario for TNT is incineration, whereas for TTR four alternative scenarios are considered (incineration, landfilling, mechanical recycling, chemical recycling). As can be observed, the comparison shows significant differences, ranging between 20% and 50% for some items, representing a positive result. A further noteworthy aspect is that the total value does not show significant differences among the four end-of-life scenarios. As will be discussed later, this is due to the substantial benefits arising from resource savings (lower costs for

purchasing virgin raw materials to produce TNT) associated with the rental, laundering, and sterilization service for TTR.

Table 31: Total life cycle costs, comparison between disposable and reusable– EUR/FU

Item	TNT (disposable) – 60 items	TTR – 1 item reused for 60 cycles			
		TTR EoL – incineration	TTR EoL – landfill	TTR EoL – mechanical recycling	TTR EoL – chemical recycling
Reinforced gown – LL size	162.91	128.64	128.61	128.49	128.68
Reinforced gown – XL size	168.69	137.94	137.90	137.78	137.98
Standard gown – LL size	137.64	72.05	72.02	71.92	72.08
Standard gown – XL size	151.17	77.59	77.56	77.45	77.63
Main operating table drape	217.21	195.34	195.29	195.09	195.41
Lateral drape (surgical drape)	80.13	63.66	63.64	63.58	120.16
Pillowcase (surgical drape)	85.83	120.13	120.10	119.99	120.16
Head drape	391.13	413.09	413.03	412.80	413.16
Foot drape	387.79	307.34	307.29	307.11	307.40

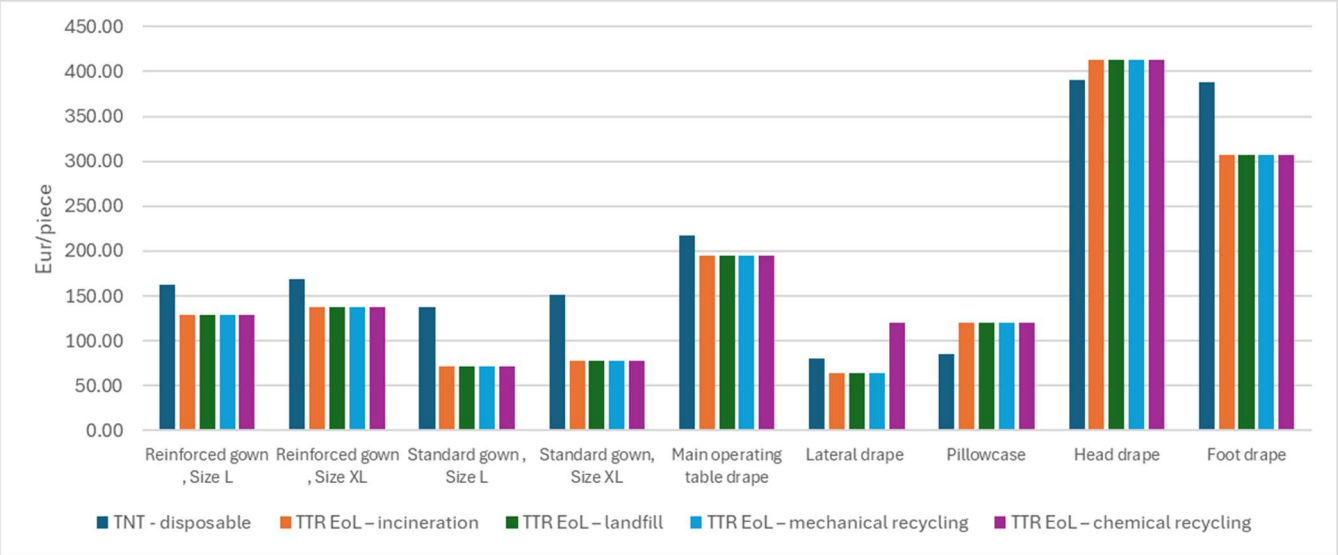


Figure 22. Comparison of life cycle costs between single-use and reusable items – EUR/FU

In the following tables, the comparisons are presented considering costs across the different life cycle phases. Table 32 shows the costs for TNT, which refer only to the fabric production phase and end-of-life management (incineration scenario).

Table 33 reports the costs for TTR, which include fabric production, the rental, laundering, and sterilization service, and the four-alternative end-of-life scenarios. The last column presents the estimated savings credited to TTR, resulting from the avoided cost of producing raw materials for TNT that are replaced by the reusable product.

Table 32: Life cycle cost analysis of disposable TNT, by life cycle phase – EUR/FU (60 items)

Item	Product manufacturing (textile)	End of life	Resource use savings
Reinforced gown – LL size	154.14	8.77	0
Reinforced gown – XL size	159.39	9.30	0
Standard gown – LL size	137.97	6.55	0
Standard gown – XL size	143.64	7.53	0
Main operating table drape	201.30	15.91	0
Lateral drape (surgical drape)	76.86	3.27	0
Pillowcase (surgical drape)	76.86	8.97	0
Head drape	373.32	17.81	0
Foot drape	373.32	14.47	0

Table 33: Life cycle cost analysis of reusable TTR – EUR/FU

Item	Average raw material cost as a share of service cost – % value	Service cost before end of life	End of life - incineration scenario	End of life - landfill scenario	End of life - mechanical recycling scenario	End of life - chemical recycling scenario	Resource use savings
Reinforced gown – LL size	21%	137.76	0.10	0.07	-0.05	0.14	-9.22
Reinforced gown – XL size	21%	147.60	0.11	0.07	-0.06	0.15	-9.77
Standard gown – LL size	21%	78.84	0.09	0.06	-0.05	0.12	-6.88
Standard gown – XL size	21%	85.41	0.09	0.06	-0.05	0.13	-7.91
Main operating table drape	22%	211.89	0.16	0.11	-0.09	0.23	-16.72
Lateral drape (surgical drape)	37%	67.04	0.05	0.04	-0.03	0.07	-3.44
Pillowcase (surgical drape)	12%	129.46	0.09	0.06	-0.05	0.13	-9.42
Head drape	28%	431.61	0.19	0.13	-0.10	0.26	-18.71
Foot drape	27%	322.39	0.15	0.10	-0.08	0.21	-15.20

The difference in value among the various items depends on the different sizes and average weights considered for the purposes of this study. The results also show that end-of-life scenarios highlight a greater benefit for the mechanical recycling option. Chemical recycling emerges as the most cost-intensive option, taking into account the assumptions previously described for this scenario.

Overall, the results indicate that the life cycle cost analysis yields better outcomes for TTR than for TNT for all items composing the set used in operating rooms. When considering the externalities generated by the processes analyzed, two effects should be highlighted. As previously noted, these were not included in the calculations in order to avoid double counting. Drapes show a higher service value (€/kg) compared to other items. This result is mainly due to the lower average weight of drapes relative to their unit price (€/item), which increases the value when expressed per kilogram. In addition, drapes require more intensive and costly laundering and sterilization processes, due to their larger dimensions and their specific use in the operating room.

As a result, the service value is proportionally higher, reflecting both the operational cost of treatment and the valuation of the material relative to its actual weight.

Assessment Using the Eco-Cost Method

The environmental impacts of the two solutions considered in the comparative analysis generate environmental effects that can be subject to economic valuation based on the expected damage and the reduction in environmental quality. Methodologies are available to perform this type of assessment, such as the eco-cost method (Delft University of Technology, Sustainability Impact Metrics, www.ecocostvalue.com), which can be combined with LCA analyses. This method is based on estimating the costs incurred to repair environmental damage caused by pollution and can be used to carry out a monetary valuation of environmental effects, applicable as parameters for comparing products or services in public procurement tenders.

To provide an order of magnitude for the case under examination, considering a standard gown size XL, the difference in the climate change indicator (GWP) between the two solutions (see Section 4.1.1) amounts to 14.51 kg CO_2eq (additional greenhouse gas emissions attributable to TNT). The average value of 1 kg of CO_2eq is estimated to range from a minimum of EUR 0.06/kg (reference: average CO_2 price on the European ETS mandatory trading market) to a maximum of EUR 0.09/kg (value defined at the European level in the cost–benefit analysis manual for public works). Assuming that these values represent an acceptable approximation of the costs required to prevent (mitigation measures, e.g., investments in renewable electricity generation plants) or repair the damage resulting from climate change effects (adaptation measures), the environmental cost (externality) of a standard TNT gown could range between EUR 0.87 per item and EUR 1.30 per item.

Similar assessments can also be carried out for the other environmental impacts presented in Section 4.1.1.

Assessment of Social Costs Over the Life Cycle

The LCC method used—based on the evaluation of direct (conventional) and indirect (environmental) costs for comparing different types of textiles—does not consider other types of costs that could be associated with the services analyzed. One potentially relevant cost relates to the use phase of the products. In this case as well, similarly to environmental externalities, the social value of the impact is attributed to an additional activity required by the choice of TNT, namely the operations carried out by healthcare staff or designated personnel to manage and dispose of these textiles at end of life. There are few studies available on this aspect; however, an analysis conducted by a company supplying products and technologies for industrial laundering (Steven J. Tinker, 2022) produced comparative estimates of costs incurred in certain healthcare facilities.

Among the evaluations, a saving associated with avoided end-of-life management operations within hospitals (year 2020) was identified in the case of choosing reusable textiles, estimated at approximately 30 US cents per ASD (*patient-day*, adjusted value). Updating this value to 2023 and converting it to euros, this corresponds to approximately EUR 0.33 per ASD. In this case as well, this represents an approximate estimate of avoided social costs (in terms of reduced labor costs associated with the number of patients) when reusable textiles are used.

5. INTERPRETATION OF THE LIFE CYCLE

In an LCA study, contribution analysis and thus life cycle interpretation aim to identify the critical points of the life cycle under examination and, in this study in particular, the phases that contribute most significantly—from both an environmental and economic perspective—to the overall impacts of disposable and reusable items. The goal of this analysis is to identify the scenario requiring greater attention and the preferred option, considering both environmental performance and costs. Sensitivity[4] analyses are used to highlight the extent of the dependency between one or more variable parameters and the system under study, and they are also useful for evaluating alternative scenarios. The considerations presented in the following sections refer to the functional unit.

5.1.Sensitivity analysis

Four sensitivity analyses were carried out on the variation in environmental impacts based on the characteristics of the fabrics analyzed and the packaging used for collection and delivery by laundries. Specifically, the following assumptions were made:

- Influence of the PU or PTFE membrane in reinforced gowns
- Consideration of potential recycled content
- Variation in service life;
- Use of recycled packaging

As indicated in the inventory analysis, the representative reinforced gown for the life cycle of reusable technical textiles (TTR) was modeled with a composition assuming polyurethane membrane in half of the cases and PTFE membrane in the other half (baseline scenario, corresponding to the worst-case end-of-life scenario: landfilling). Overall, the contribution analysis shows that, whether one extreme or the other is assumed, the environmental impacts in the main impact categories do not vary significantly:

Table 34: Impact of the choice of membrane saddle in trilaminate

	PU SCENARIO	BASE SCENARIO	PTFE SCENARIO
SINGLE SCORE INDICATORE	1.0442	1.0439	1.0437
	0.02%		-0.02%
Climate change	14.494	14.491	14.488
	0.02%		-0.02%
Particulate matter	2.51E-07	2.51E-07	2.51E-07
	0.06%		-0.06%
Photochemical ozone formation	0.04131	0.04131	0.04130
	0.02%		-0.02%
Fossil resource use	252.74	252.69	252.65
	0.02%		-0.02%
Water scarcity	15.249	15.245	15.242
	0.02%		-0.02%

A possible reduction in impact may result from the presence of recycled fabric in products: looking ahead, there is the possibility that the supply chain will turn to the market for recovered polyester microfiber. This scenario was analyzed by integrating the recycled content into the model according to the PEF methodology (par. 4.4.8.6, Zampori and Pant, 2019), using the processes in the Ecoinvent database to model the material recovery processes. If we look at the reduction in impact, only in relation to the manufacture of the item, the use of recycled material can lead to reductions ranging from -42% (Climate Change indicator) to -95% (Mineral Resource Use indicator). However, the

[4] Sensitivity analysis: Systematic procedure for estimating the effects on results caused by the method used or the data employed (par. 3.31 ISO 14040)

results of the analysis show a minimal reduction in impact due to the low incidence of article production on the life cycle analyzed (less than 0.5% reduction).

Table 35: Sensitivity analysis on the incidence of recycled material (single score indicator).

Article	Reusable, basic scenario	Reusable, recycled content
Reinforced gown	1.0439 pt	1.0420 pt
		-0.18%
Standard gown	0.8945 pt	0.8926 pt
		-0.22%

The useful life of reusable garments depends on various parameters, relating to the characteristics of the fabric or the different uses to which it is put; it is not uncommon for garments in this category to be lost or damaged during their life cycle, reducing the number of washing cycles to which statistical reference is made; the variation in impact was therefore analyzed as the number of cycles varied from a minimum of 20 to a maximum of 100; in general, the results show that this variation would lead to fluctuations of around two or three percentage points:

Table 36: Analysis of changes in useful life

	Reduced impact compared to equivalent single-use products		
	20 CYCLES	**60 CYCLES**	**100 CYCLES**
TTR reinforced gown, size L	-48.4%	-51.2%	-51.6%
TTR reinforced gown, size XL	-47.7%	-50.6%	-51.0%
TTR standard gown, size L	-45.0%	-47.9%	-48.3%
TTR standard gown, size XL	-48.1%	-50.8%	-51.2%
TTR Main operating table drape	-50.5%	-53.1%	-53.5%
TTR Lateral drape	-41.6%	-45.1%	-45.5%
TTR mayo pillowcase	-52.1%	-54.7%	-55.1%
TTR head drape	-47.6%	-50.4%	-50.7%
TTR foot drape	-51.0%	-53.6%	-54.0%

The use of plastic packaging is one of the biggest challenges for this type of product, since the sterilization process itself requires items to be packaged in such a way as to minimize contamination. The volumes of plastic, particularly polyethylene, used throughout the life cycle are significant; however, there is ongoing positive discussion about the possible use of recycled material, which would significantly reduce various environmental impacts, primarily resource use and global warming, which are particularly affected using virgin polymers. In this regard, a sensitivity analysis has been carried out on the two items that have the greatest impact, namely gowns and drapes. The analysis shows that, if plastic film or bags made from recycled polyethylene are used, the environmental impact per item can be reduced by more than 30%.

Table 37. Analysis of the use of recycled packaging

	Reusable, base scenario	Reusable, recycled packaging content
Reinforced gown	0.0011 pt	0.0008 pt
		-27%
Head drape	0.0020 pt	0.0014 pt
		-27%

5.2.Data quality assessment

The European Recommendation on PEF requires compliance with a series of characteristics of the data used to calculate the life cycle impact, which concern their ability to meet the established requirements (ISO 14040:2006). Based on these criteria, a **semi-quantitative assessment** of the overall data quality of the dataset used for all major processes must be carried out. This step lends credibility to the study results and helps to understand whether the dataset resulting from the data collection phase needs to be improved.

In this study, the requirements and quality of the data were assessed according to the methodology proposed by the European Commission (Recommendation 2021/2279), based on the following four criteria:

- **technological representativeness (TeR)**
- **geographical representativeness (GeR)**
- **temporal representativeness (TiR)**
- **accuracy (P)**

The methodology provides five different grades (from excellent to poor). The overall assessment of data quality (DQR) is semi-quantitative and is calculated by adding up the assessment achieved for each of the quality criteria, divided by the total number of criteria:

$$DQR = (TER + GR + TiR + P) / 4$$

Data quality rating (DQR) corresponds to a level of data quality defined as follows:

DQR ≤ 1.6: excellent quality

DQR from 1.6 to 2.0: very good quality

DQR from 2.0 to 3.0: good quality

DQR from 3.0 to 4.0: satisfactory quality

DQR> 4: poor quality

The quality score was calculated using the criteria set out in the PEF Recommendation. The overall average data quality was **very good** (DQR of 1.75) for data specific to the primary context and **good** (2.42) for background processes built with generic (secondary) data. In general, in the first case, all activity-related data collected for the study were evaluated, while in the second case, all data processes used in the model were evaluated.

5.3.Assessment of the validity of the model

The validity of the model was assessed during the development of the LCA in order to analyze its completeness, accuracy, precision, and consistency. The assessment served to identify the need for additional data collection, to review the assumptions made, and, in general, the methodological choices made. The assessment included the completeness, sensitivity, and consistency checks required by Recommendation 2021/2279 on PEF.

Sensitivity check

Several analyses were performed to ensure the consistency of the study results. The main ones are presented in section 5.1.

Completeness check

This is a qualitative procedure that ensures the completeness of the use of information and data at each main stage of the life cycle and their availability for interpretation. It is a useful check to ensure that no key aspects have been overlooked and that all data are available and complete. The check was carried out mainly by comparing all the sample

companies, the bilateral body EBLI and the trade association Assosistema, involving experts in the field and analyzing available studies.

All processes within each individual stage of the life cycle were modeled to represent each specific situation. All available data for each process unit and specific data provided directly by manufacturers of the items and laundries were verified. Below is the table used as a guide for the check, which includes an assessment of the need to supplement the data with external information (see result in the last column).

Table 38: Completeness checklist

Stages	Processes	Data collected in the field?	Data integrated with external information (literature/database)	Complete data?
Fabric production	Production of microfiber, trilaminate, double-sided laminates, etc.	No	Yes	Yes
Product manufacturing	utting, sewing, hemming, joining, and other operations	Yes	Sì	Yes
Transport from manufacturer to laundry	Transport	Yes	No	Yes
Use phase	Distribution (collection and delivery)	Yes	No	Yes
	Washing of reusable items	Yes	No	Yes
End of life	End of life	No	Yes	Yes

Consistency check

The consistency check consisted of a qualitative procedure used to determine whether the data quality requirements, assumptions, and methods used were consistent with the study's objective and scope.

Table 39: Consistency check table

Consistency check		Justification
Is the data quality sufficient?	Yes	The data quality assessment methodology proposed by the European Commission was used, and the result obtained was Very Good for specific data and Good for generic data.
Is the selection method consistent?	Yes	The methodological choices were made in accordance with ISO 14040 and ISO 14044 standards and the Recommendation developed by the European Commission for the PEF scheme.
Is the impact assessment consistent?	Yes	The impact assessment methodology, which involved characterizing the results from an environmental and economic point of view, was applied consistently and was appropriate for the objective and scope of the study.
Has the assessment of inconsistencies been carried out?	Yes	The graphical analysis of the flows in the tree networks, in which it was verified that there were no process loops, incorrect attributes, or flows that were unlikely to be possible, did not reveal any inconsistencies.

ABBREVIATIONS

CAPEX: Capital Expenditure

DPC: Dispositivi di Protezione Collettivi (Collective Protection Devices)

DPI: Dispositivi di Protezione Individuale (Personal Protective Equipment)

DQR: Data Quality Requirements

ePTFE: Expanded Polytetrafluoroethylene

ETSA: European Textile Services Association

ESF: European Safety Federation

E-LCC: Environmental Life Cycle Costing

GeR: Geographic Representativeness

GWP: Global Warming Potential

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCCA: Life Cycle Costing Analysis

LDPE: Low-Density Polyethylene

NHS: National Health System

OPEX: Operational Expenditure

P: Precision

PEF: Product Environmental Footprint

PES: Polyester

PP: Polipropilene

PTFE: Politetrafluoroetilene

PU: Poliuretano

SETAC: Society of Environmental Toxicology and Chemistry

SMMMS: Sterile Surgical Gowns Composed of Five Layers

TeR: Technological Representativeness

TiR: Temporal Representativeness

TNT: Tessuto Non Tessuto (Non-Woven Fabric)

TTR: Tessuti Tecnici Riutilizzabili (Reusable Technical Fabrics)

FU: Functional Unit

BIBLIOGRAPHY

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