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Life Cycle Assessment of an industrial laundry: A case study in the Italian context

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ABSTRACT

Industrial laundries need large amounts of energy and water and, thus, generate large amounts of wastewater, due to the core washing, drying and ironing processes and to the transport of linen and chemicals. The presented Life-Cycle Assessment (LCA) concerns an Italian industrial laundry, and is based on primary data collected from the facility, complemented by information from literature, supporting databases (Ecoinvent 3.8), and technical datasheets. The analysis covers the entire cycle of linen processing (material extraction and manufacturing, transport, logistics, laundry processes, wastewater treatment and reuse, packaging, and solid waste management). The defined Functional Unit (FU) is 1 kg of linen. The LCA, carried out by SimaPro 9.2 and ReCiPe 2016 H, indicates a total impact of 12.77 mPt/FU, chiefly deriving from washing (4.62 mPt), ironing (4.29 mPt), and drying (1.56 mPt). Detergents and washing agents contribute significantly to the impact of the washing phase. 'Fine particulate formation' is the most affected impact category (5.18 mPt). The initial results suggested that generating renewable energy on-site could reduce the environmental impact by 19.7%. Solar photovoltaic panels were installed in 2023, and the actual energy production exceeded expectations, indicating an even greater reduction in the laundry environmental footprint.

1. Introduction

The need to assess the impact of industrial laundries in the European Union (EU) is growing mostly due the development of new cleaning products (Golsteijn et al., 2015), involving the toxicological concern of wastewater as a potential pollution source for water bodies.

To address these concerns, the “Charter for Sustainable Cleaning” was developed and is being implemented in Europe by the International Association for Soaps, Detergents, and Maintenance Products (A.I.S.E) (Golsteijn et al., 2015). Launched in 2005 and updated in 2010, it provides a comprehensive, life cycle-based framework for promoting corporate sustainability. The activities and requirements covered by the Charter span a wide range of topics, including the safety of chemicals and products for people and the environment, as well as workplace health and safety, resource use, and consumer information.

There is increasing awareness of the importance of sustainable practices in the industrial laundry sector and of the key role that Life Cycle Assessment (LCA) plays in evaluating and improving the environmental performance of these processes (Romagnoli et al., 2023) The A.I.S.E. Charter supports two main objectives: to aid the cleaning and detergent industries in designing more sustainable products and to encourage consumers to adopt more sustainable washing, cleaning, and home maintenance practices (Golsteijn et al., 2015).

This trend has also led to the development of guidelines for ecolabels, specifically Type III ecolabels in line with ISO Standard 14025 and the Product Environmental Footprint (PEF) proposed by the European Commission (European Commission, 2021). During the pilot phase of this European certification (2016–2019), specific PEF Category Rules (PEFCR) for Heavy Duty Liquid Laundry Detergents were created (AISE, 2019).

The PEF method provides a standardized way to evaluate and compare the environmental performance of different products and has been integrated into several EU policies and regulations, such as the Taxonomy Regulation, the Sustainable Batteries Initiative, and the Green Consumption Pledge.

Similarly, for other types III ecolabel platforms connected to issuing

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EPD (Environmental Product Declaration), specific category rules for laundry detergents were developed, like the Product Category Rule (PCR) nr. 2011:10 for detergents and washing preparations (4.0.0) (EPD, 2020), still active.

The study by Lutterbeck et al. (2020) and by Melian et al. (Melián et al., 2023) highlighted the use of LCA models on hospital laundry wastewater treatments and Santiago et al. (2021) carried out a review of the available treatment options for laundry wastewater including LCA. Most of the treatment alternatives investigated demonstrated significant adverse impacts, suggesting that the environmental costs associated with these treatments might surpass their benefits. This is particularly concerning as such treatments could potentially worsen both the direct and the indirect toxicological effects of effluents. Moreover, the study highlighted the necessity of circumventing treatment systems that are energy-intensive, regardless of their efficacy in pollutant mitigation, due to the substantial environmental toll they impose.

Despite the dynamic nature of the industrial laundry sector, characterized by continual advancements in data availability, product innovation, and assessment methodologies, the absence of comprehensive and specific Life Cycle Inventory (LCI) data pertaining to detergent use within laundry systems poses a significant challenge. This gap in data specificity may compromise the integrity of environmental assessments in this domain. A recent review stressed that the lack of harmonized and detailed LCI data could hinder the reliability of LCA outcomes for resource-intensive industries, particularly those involving water and chemical use (Sabate and Kendall, 2024). Recent studies have underlined the importance of improving LCI data in similar contexts, including industrial systems linked to high water and chemical use (Cornago et al., 2022).

Within a specific LCA for laundry it would be essential to characterize the used products in terms of formula composition, recommended dosage, packaging material, product use indications (wash temperature selection and prewash incidence) and impact on/of wastewater treatment. The use of proxy or substitutional products for more than 20% of the population to face a lack of data to complete LCA could increase the study's uncertainty and affect the study and the sustainability strategy (Golsteijn et al., 2015).

Additionally, researchers have emphasized the role of advanced LCA tools in tackling uncertainty through data harmonization, a crucial factor for industrial laundry assessments (Kiemel et al., 2022).

This study focuses on the following critical areas:

- Establishing a comprehensive framework for LCA that includes the production and transport of cleaning agents, the laundering process itself, and the disposal of wastewater and lint. This approach ensures a thorough evaluation of the environmental footprint.
- Carefully selecting relevant impact categories and indicators to accurately assess the environmental impact of the laundry process. Key impact categories often include global warming potential, water use, and human toxicity, among others.
- Collecting and analysing primary data to enhance the accuracy and reliability of LCA results. This initiative aims to improve comparability between different LCAs, ensuring that assessments are both precise and reliable.
- Standardizing definitions and methodologies for assessing different industrial laundry processes. This consistency helps identify areas for improvement and guides decision-making to mitigate environmental impacts.
- Identifying environmental "hot-spots" using LCA to implement potential enhancements. This includes exploring better material substitutions and changes in operational behaviours to reduce the ecological footprint.

The primary objective of this paper is to develop a comprehensive LCA model for an industrial laundry located in Isola d'Elba, Tuscany, Italy, integrating Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA methodologies).

This model aims to detail an ecological profile through a sensitivity analysis, incorporating primary data sourced directly from the laundry. To ensure a holistic and robust evaluation, these data were integrated with information from the literature, detergent technical datasheets, and supporting database (Ecoinvent 3.8).

Recent analyses, particularly those exploring industrial systems' circular economy and emissions reductions, further emphasize this model's relevance (Fragkos, 2022).

To the authors' knowledge no comparable case studies can be found in the literature and the only found references concern specifically the analysis by LCA of laundry wastewater treatment.

2. Methods

This study was conducted using the LCA methodology, a standardized process for evaluating the environmental impact of production systems (Pelaracci et al., 2022). ISO 14040 and 14044 are the main international standards for conducting LCA studies (ISO, 2020a) (ISO, 2020b). While ISO 14040 outlines the general principles of LCA, including goals and scope, collecting data, and interpreting results, ISO 14044 offers more detailed guidelines for executing LCA studies. This includes ensuring data quality, maintaining transparency, and selecting appropriate methods for assessing and reporting environmental impacts. These standards establish a framework for conducting globally recognized LCA studies, enhancing their consistency and transparency.

The LCA methodology assesses the environmental impacts of a product or process throughout its entire life cycle - from material extraction to final disposal. It provides an ecological profile that reflects the environmental performance across all life cycle stages: production, transport, usage, and disposal. LCA aims to offer a holistic view of a product or process's environmental impacts and pinpoint opportunities for reducing these impacts (Lucchetti et al., 2019).

The development of the LCA model for this study was facilitated by the Ecoinvent 3.8 database (Wernet et al., 2016) and SimaPro 9.2 (Goedkoop et al., 2016).

The Life Cycle Impact Assessment (LCIA) method selected was ReCiPe Hierarchic (Huijbregts et al., 2017). The ReCiPe method for assessing the potential environmental impacts associated with renewable energy and climate change was created by the Dutch National Institute for Public Health and the Environment (RIVM). It is extensively utilized across various industries and in academic research. Employing a "cause-effect chain" approach, the ReCiPe method investigates the fundamental mechanisms leading to environmental impacts, thereby enhancing the understanding of a product or process environmental effects and highlighting opportunities for improvement. Offering a thorough and scientifically grounded framework for environmental impact evaluation, the ReCiPe method has gained broad acceptance, and it is now regarded as one of the most widely used LCIA methodologies.

The ReCiPe method represents the impact through impact categories expressed with mid- and end-point impact indicators. At the midpoint level ReCiPe has 18 impact categories, in terms of: *Climate change* [kg CO_2 equivalents], *Stratospheric ozone depletion* [kg CFC-11 equivalents], *Ionizing radiation* [kBq Cobalt-60 equivalents to air], *Ozone formation (human health)* [kg NOx equivalents], *Fine particulate matter formation* [kg $PM_{2.5}$ equivalents], *Ozone formation (terrestrial ecosystems)* [kg NOx equivalents], *Terrestrial acidification* [kg SO_2 equivalents], *Freshwater eutrophication* [kg P to freshwater equivalents], *Marine eutrophication* [kg N to marine equivalents], *Terrestrial ecotoxicity* [kg 1,4-dichlorobenzene (1,4-DCB) emitted], *Freshwater ecotoxicity* [kg 1,4-dichlorobenzene (1,4-DCB) emitted], *Marine ecotoxicity* [kg 1,4-dichlorobenzene (1,4-DCB) emitted], *Human carcinogenic toxicity* [kg 1,4-dichlorobenzene emitted], *Human non-carcinogenic toxicity* [kg 1,4-dichlorobenzene (1,4-DCB) emitted], *Land use* [$m^2 \cdot y$], *Mineral resource scarcity* [kg Copper equivalents], *Fossil resource scarcity* [kg oil equivalents], *Water use* [m^3 water consumed].

At the endpoint level the midpoint impact categories are multiplied by damage factors and aggregated into three endpoint categories expressed in terms of: *Human Health* [Disability - Adjusted Life Years (DALYs)], *Ecosystems* [annual loss of species], *Resource Depletion* [surplus costs of future resource production over an infinite timeframe in USD2013].

The consistency of the obtained results was evaluated through sensitivity and scenario analysis better described in section 5.2.

3. Case study

The LCA concerns the industrial laundry ILVA, located in Rio Marina (Italy) in the eastern area of the Elba Island. For over forty years ILVA has been supplying linen to restaurants and hotels and since 2021 has also extended the rental to private individuals in the surrounding areas by preparing suitable kits for the various needs. The production activity includes renting, washing, sanitizing, ironing and delivering linen.

Over the years, the company has grown considerably, requiring continuous investments in modern and efficient machinery.

4. Goal and scope definition

4.1. Goal of the study

The study takes a comprehensive approach to analyse the environmental impacts of the laundry process by examining every stage of the system through the lens of a system-wide Functional Unit. This approach ensures consistency, openness, and repeatability in the evaluation process. It explores energy and resource consumption throughout the laundry system, focusing on direct and indirect emissions, waste production, and resource use, particularly emphasizing the role of detergents. The analysis identifies critical parameters that contribute significantly to the environmental burden, highlighting areas that require specific monitoring and control.

By pinpointing these parameters, the study uncovers opportunities for improving the environmental performance of the laundry system. This includes optimizing detergent formulations, reducing energy consumption, and minimizing waste.

To achieve these objectives, the study customized an existing database (Ecoinvent 3.8) to tailor it to the specific needs of the laundry process. Supporting inventory databases were verified, streamlined, and completed to construct a comprehensive Life Cycle Inventory (LCI) for the products involved. Consistency and reliability of the results were ensured through a detailed sensitivity analysis, which specifically addressed the impact of primary energy sources and the type of detergents used as described in section 5.2. The outcomes of the study offer a reference point for evaluating and improving the environmental performance of laundry systems across various contexts.

Thus, the goal of this study was also to support potential external operators clearly and transparently clarifying the impact of industrial laundries in the Italian context.

The selected reference year was 2019 to consider standard data avoiding the issues related to COVID crisis which had led to non-standard procedures and management.

The baseline scenario is compared with an improved one introducing renewable energy technology (i.e. solar PV panel). The sensitivity analysis refers to change in logistics distance of the material transport and a potential change in the energy consumption of the core industrial processes of the laundry as described in section 5.2.

4.1.1. Functional Unit

According to ISO 14040-44, the Functional Unit (FU) is the reference unit for the quantitative measurement of the performance of a product or process. It represents the function or service the product or process provides and is pivotal for consistent comparisons among alternatives and to define the study boundaries (Guinée et al., 2002). Therefore, the Functional Unit should be carefully defined to reflect the actual use of the product or process and should be clearly stated in the study to allow for transparency and reproducibility. For this study, 1 kg of dried plain white 100% cotton linen for a standard washing cycle was chosen as the FU, as this activity is largely prevalent in the studied site.

4.1.2. System boundaries

The LCA model considered a cradle-to-gate system. Fig. 1 shows all the activities included within the system boundaries, grouped in upstream, core and downstream processes.

Upstream processes encompass the production of materials for the main operations, such as detergents, washing aids and packaging materials. The core processes include the transport and the industrial laundry activities: washing, drying, ironing, folding, and bagging.

Transport, a key component of core processes, is assessed considering the origin and distance of material procurement, the method of transport, and the volume of materials transported. This aspect also accounts for travels related to customer relations and administrative interactions. Soiled linen collection and clean linen distribution are efficiently managed in a single journey using trucks or vans.

The downstream processes include the management of the generated solid waste and wastewater. After adequate reclamation treatment, wastewater is partially recycled in continuous washing machines.

4.2. Life Cycle Inventory analysis and data quality

The inventory was framed and aligned to the EPD Product Category Rules (PCR) for Professional Laundry and Cleaning Services of Items (EPD, 2020).

4.2.1. Upstream processes: material production

The type and origin of the products used by ILVA in 2019 are listed in Table 1 where the amounts are expressed in kg/year and in kg/FU.

The details of chemical products (cleaning agents and washing aids) used by ILVA in 2019 are listed in Table 2, including the chemicals used in wastewater treatment.

4.2.2. Core processes

The core processes include the transport for the provision of materials, the activities carried out for the complete cycle of linen treatment, the transport of clean and dirty linen, the disposal of solid waste and the management and reclamation of wastewater.

Table 3 reports the origin and distance to be covered for the delivery of the different materials.

To quantify the impact of the transport of materials, the distance covered from the provider to ILVA was determined as well as the impact related to ferry boats (needed to reach the island). ILVA uses ferry boats from the TOREMAR company, which are 113 m long and consume 780 L/km of bunker fuel.

The activities included in the complete cycle of linen processing are:

- Sorting and washing of soiled linen;
- Pressing;
- Drying;
- Sponge folding;
- Ironing;
- Bagging.

The delivered linen is first sorted and stored per homogeneous categories in polypropylene bags. From there, it is picked up and sent to the continuous washer, which performs a specific programme for each linen category.

The laundry treats different kinds of linen (on the whole 2,641,000 kg in 2019) by specific cleaning programmes based on the Sinner's Circle (1960), to optimize the four variables of washing: Temperature, Chemistry, Time, Mechanical Action. The guiding principle is that if the

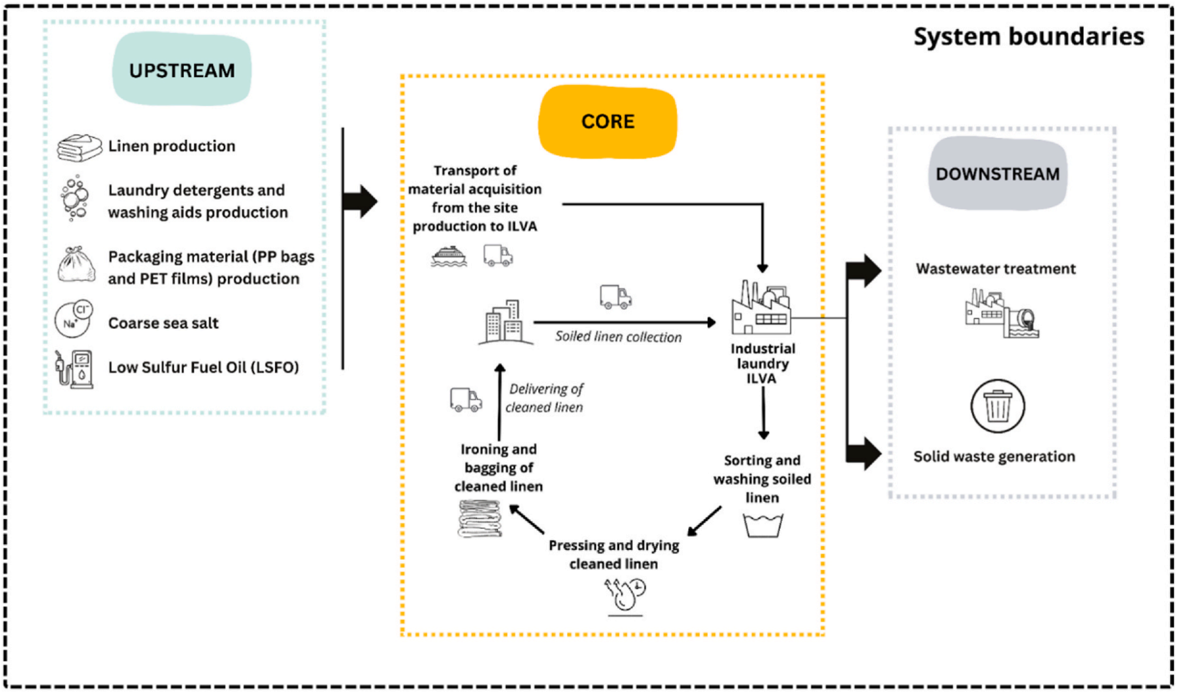


Fig. 1. Structure of the laundry system modeled in the SimaPro software.

Table 1
Upstream processes: amounts of materials per year and FU.

Materials	Origin	Amount [kg/year]	Amount [kg/FU]
New cotton linen	Northern Italy	52,840	0.021
Cleaning agents	Vimercate (MB), Italy	42,682	0.017
Washing aids	Prato (PO), Italy	74,370	0.030
Polyethylene film	Casalromano (MN), Italy	10,147	0.004
Low sulphur fuel oil (LSFO)	Pesaro (PU), Italy	286,360	0.116
Raw sea salt (NaCl)	Margherita di Savoia (BT), Italy	32,140	0.013
Polypropylene bags	Noventa di Piave (VE), Italy	6900	0.003

value of one of the variables decreases, the values of the three others must increase. The programmes are defined applying this theory to search for the optimal combination of the four elements.

Each cleaning programme uses a defined amount of detergents and washing aids, allowing for a complete cleaning and hygienization of the treated lining.

The continuous batch washer (Power Trans Kannegiesser) is 14 m long and divided into 18 chambers, separated by a helicoidal wall, allowing for washing a great amount and variety of linen. The process includes three steps within each chamber: pre-washing, washing and rinsing. In the first one the input of water, sodium hypochlorite and detergents allows for bleaching. Water from bleaching is discharged, and new water, with higher doses of detergents, is used for the washing phase after heating. For rinsing, water is flushed and discharged after filtration, to remove the fibres released by linen, and the pH is adjusted to 5.5. Such pH is optimal to achieve good ironing results. In every chamber, a beating system allows for continuous swinging with a 250° rotation every 120 s, after which a complete drum rotation occurs and the linen (60 kg) passes from one chamber to the following one. The recovery of water from the different washing steps allows for reducing water consumption to 5 L/kg linen.

After leaving the last chamber of the continuous batch washer the linen undergoes pressing (280 atm, corresponding to 40 kg/cm^2 of linen) for a first removal of excess water (about 70%). The removed water is collected in three tanks (T1, T2, T3) to be recycled in the following washing operations. The residual moisture of linen after pressing is about 30%.

The following step is thermal drying (95 °C) in desiccators with heat recovery. A specific valve allows the recovery of 40% of the energy from

Table 2
Kinds and amounts of chemicals (detergents, washing aids and chemicals for wastewater treatment) used by ILVA in 2019.

Chemical products	Description	Amount [kg/year]	Amount [kg/FU]
Component A	Washing aid preventing foam formation in the presence of high detergent load	50	0.000020
Duxil Perfekt	Atomized powder detergent to remove grease	11,750	0.004757
Epicare Des	Hand disinfectant for daily use	10	0.000004
Oxyguard Bright Alpha	Liquid detergent for bleaching, alternative to Bright Beta	4000	0.001619
Oxyguard Bright Beta	Bleaching agent, working at low temperature	11,440	0.004632
Oxyguard Emulsion	Detergent based on surfactants for removing dirt. Used with Bright Beta o Bright Alpha	9040	0.003660
Ozonit Bnl	Liquid bleaching agent based on peracetic acid, active at low/medium temperature	528	0.000214
Sericol Perfect	Surfactant based liquid detergent	400	0.000162
Softenit Blue	Concentrated fabric softening with scented essences	4750	0.001923
Corn Starch	To refine table lining	2650	0.001073
Acetic Acid	To regulate pH	15,650	0.006336
Sodium Hypochlorite	Bleaching agent for pre-cleaning	44,200	0.017895
Sodium Hydroxide	To regulate pH in the continuous batch washer	8900	0.003603
Aluminum Polychloride	Sewage sludge conditioning	2600	0.001053
TOTAL		**115,968**	**0.046951**

Table 3
Core processes: origin and distance run for delivery of the different materials.

Raw materials	Origin	Distance [km/year]
New cotton linen	Northern Italy	386
Cleaning agents	Vimercate (MB), Italy	393
Washing aids	Prato (PO), Italy	196
Polyethylene film	Casalromano (MN), Italy	349
Low sulphur fuel oil (LSFO)	Pesaro (PU), Italy	424
Raw sea salt (NaCl)	Margherita di Savoia (BT), Italy	672
Polypropylene bags	Noventa di Piave (VE), Italy	458

the drum, using only water-saturated air. Sponges are completely dried, so the air is released at 95 °C, while the remaining linen is kept moist to optimize ironing, so the air temperature is 60 °C. Each drying cycle generates considerable amounts of textile fibre wastes separated by an inox filter automatically cleaned by compressed air.

Then, linen is manually moved and sponges are placed in the towel folding machines (four machines operate at the ILVA facility) as they don't need ironing, while the remaining material undergoes ironing. The ironing operations are carried out by three elements, in sequence: feeders, flatwork ironers and folders. To introduce linen in the ironing system, ILVA has two kinds of feeders: the first one, equipped with grippers, deals with large items, while the second one involves manual operation to place the linen over the belts.

The high-power flatwork ironers are able to maintain the quality of the textile finishing and exploit electric power. The basins of the flatwork ironers are heated at 170 °C by the boiler steam (12 bar) and the rollers and fans extract steam from the linen. The operators check possible damages to linen and reject spoilt material before folding. The last step of the ironing line is carried out by the folders, delivering predefined amounts of linen for bagging via dedicated transport belts. An air-flow integrated technology guarantees the folding precision, and a servo-assisted function controls the amount of linen sent to bagging.

The bagging machine is totally automated and uses microporous thermoformable polyethylene, which does not keep moisture and allows for safe transport. The polyethylene reels are entered in the machine which wraps the items according to their size, based on the photocell signal.

Tables 4 and 5 report the flows of energy and materials per each working phase.

Energy comes partly from the national electric network and partly from low sulphur fuel oil (LSFO) which feeds two large boilers (2.3 MW each), producing 18.2 kg of steam at 180 °C per kg of LSFO. The steam is used for the continuous batch washer, for the desiccator and for the flatwork ironers. The return condensates from the flatwork ironers are recycled to the boilers after cooling from 105 °C (too high temperature) to 98 °C by a heat exchanger. The water heated by the exchanger is used in the rinsing step performed by the continuous batch washer.

The national electric network provides the power for the electric component of the laundry machines (409 MWh in 2019).

The water demand is covered 50% by the local aqueduct (Rio Marina, Venelle well) and the remaining 50% by wastewater reclamation and recycling, as detailed in subsection 4.2.3.2.

In the model for the core processes the consumption of energy, water, LSFO, detergents and washing aids is included. For the washing aids a good correspondence was found between the products used by ILVA and the chemicals in Ecoinvent database, while detergents are complex mixtures, under industrial secret, so some assumptions were made to cope with missing information. The detergents used for less than 2% of the total were neglected; the most used ones have been "simulated" selecting the hazardous components from the Safety Data Sheet and collecting information on the most similar compounds in Ecoinvent.

4.2.2.1. Transport. All the vehicles picking up and delivering linen have been considered, as well as the company cars. The kilometres travelled in 2019 were determined based on fuel bills (Table 6).

ILVA vehicles use mostly diesel fuel (80%) and, to a smaller amount, gasoline. Trucks can carry up to 33 laundry carts (3.5–7.5 tons) while vans can carry up to 15 (2 tons). Each laundry cart carries 130 kg of linen, on average. Both trucks and vans have been assumed to belong to Euro 4, as most of the vehicles of such categories circulate in Italy. Even if they are obsolete, they are still commonly used for many years because they cover short distances and for few months per year. Vans are the most used vehicles because picking up and delivery within Elba Island mainly occur on secondary streets, and vans allow easier driving in such conditions, while larger trucks (7.5–16 tons, also Euro 4) have been assumed to be used primarily for transporting materials as chemicals.

4.2.3. Downstream processes

4.2.3.1. Wastewater management. Wastewater is discharged from the continuous batch washer and conveyed to the wastewater treatment plant (WWTP) and, then, to the reclamation unit, consisting of filtration on activated carbon, ultrafiltration (membrane cutoff = 0.2 μm), and reverse osmosis (membrane cutoff = 0.0002 μm).

From the first feed tank, wastewater is pumped to a rotary drum screen to remove the released linen fibres (solid waste) from the liquid phase. On average, 25 kg of solid waste is produced every 10 days.

Then, the effluent is pumped to an equalisation tank, which collects the 24 h flow, from which 9 m^3/h are fed to the activated sludge reactor, consisting of four in-series tanks. Wastewater flows from one tank to the next by gravity. Oxygen is supplied by air compressors also providing the needed mixing. Nitrogen is added, when needed, by dosing urea.

After secondary settling, part of the sewage sludge is recirculated to keep the defined solid concentration in the activated sludge reactor and the waste sludge undergoes filter pressing after aluminium polychloride conditioning, for dewatering. The waste sludge is disposed of as solid waste (see section 4.2.3.3).

The effluent from secondary settling is conveyed to a storage tank, pumped through sand filtration, and then transferred to the water reclamation unit. 50% of the effluent from the reclamation unit is mixed with the municipal well water in an 80 m^3 basin. It is pumped to a resin softener to remove excess calcium and magnesium. NaCl regenerates the resins after being used for 400 m^3. The remaining 50% of the effluent is discharged into the municipal sewer network along with the concentrates from membrane filtration, complying with the limits in force.

Table 4
Flows of energy and materials of each working equipment/phase per year at ILVA in 2019.

Processes	Energy [kWh/year]	Low sulphur fuel oil [kg/year]	Water [m^3/year]	Cleaning agents [kg/year]	Washing aids [kg/year]	Polyethylene film [kg/year]
Sorting and washing of soiled linen	52,394	52.11	14,258	42,682	74,370	–
Pressing cleaned linen	14,970	–	–	–	–	–
Drying of cleaned linen	107,520	86,067	–	–	–	–
Sponge folding	15,940	–	–	–	–	–
Ironing	205,880	148,182	–	–	–	–
Bagging	12,323	–	–	–	–	10,147

Table 5

Flows of energy and materials of each working equipment/phase per FU at ILVA in 2019.

Processes	Energy [kWh/FU]	Low sulphur fuel oil [kg/FU]	Water [m^3/FU]	Cleaning agents [kg/FU]	Washing aids [kg/FU]	Polyethylene film [kg/FU]
Sorting and washing of soiled linen	0.0212	0.0211	0.0058	0.0173	0.0301	–
Pressing cleaned linen	0.0061	–	–	–	–	–
Drying of cleaned linen	0.0435	0.0348	–	–	–	–
Sponge folding	0.0065	–	–	–	–	–
Ironing	0.0834	0.0600	–	–	–	–
Bagging	0.0050	–	–	–	–	0.0041

Table 6

Transports for picking up and delivering linen: amount per year and FU.

Transport of cleaned/soiled linen	Fuel	Distance [km/year]	Distance [km/FU]
Truck	Diesel	49,246	0.020
Van	Diesel	194,827	0.079

Tables 7 and 8 show the amounts of energy and materials used in 2019 in the operation of the wastewater treatment plant and of the reclamation unit, per year and per Functional Unit, respectively.

4.2.3.2. Solid waste management. The different process steps generate waste needing for a correct disposal. The types and amounts of solid waste produces by ILVA are reported in Table 9, per year and per Functional Unit.

First, the different kinds of plastic containers (barrels, bottles, etc.) are separately collected and disposed of by the local waste organisation. The 1000 L tanks of the chemicals are collected, on demand, by the supplier. The purchased linen is delivered in cardboard boxes which are separately collected and disposed of by the local waste organisation. In 2019, 52,840 kg of linen was purchased, and 2657 cardboard boxes were delivered, totalling a weight of 2762 kg. The cardboard boxes have not been included in the calculations, as the amount is negligible with respect to the Functional Unit.

On the laundry demand, the hydraulic oils and lubricants used in the adaptors and in the machines are collected, when exhausted, by the local consortium for exhausted oils (CONOU).

Dewatered sewage sludge is further naturally dried in a closed storage for a whole year during which its water content decreases by 30%. In 2019 the amount of sewage sludge disposed of by a specialised company was 8500 kg.

Linen for touristic use undergoes frequent, intensive washing operations and loses up to 30% in weight. The released cotton fibres accumulate in wastewater (from which they are collected by rotary drum screens, as described above), but also in the filters of the machines. The amount of cotton scrap collected from the machine filters is about 35 kg every four days, corresponding to 1154 kg per year.

Exhausted linen, whose quality no longer complies with customer requirements, are managed as waste and sold to produce mops.

4.2.4. Assumptions

Modelling involved a series of assumptions:

Table 7

Amounts of energy, water and materials used for wastewater treatment per year (2019).

Processes	Energy [kWh/year]	Water [L/year]	Urea [kg/year]	Sea salt [kg/year]
Wastewater treatment	90,170	17,258	540	–
Wastewater reclamation	6318	4558	–	32,140

Table 8

Amounts of energy, water and materials used for wastewater treatment per FU.

Processes	Energy [kWh/FU]	Water [L/FU]	Urea [kg/FU]	Sea salt [kg/FU]
Wastewater treatment	0.036506	0.006987	0.000219	–
Wastewater reclamation	0.002558	0.001845	–	0.013012

Table 9

Type and amount of solid waste produced by ILVA per year and per FU.

Type of waste	Amount [kg/year]	Amount [kg/FU]
Cotton scraps	1154.05	0.0004672
Sludge	8500.00	0.0034413
Exhausted linen	150,202.00	0.0608106
Exhausted oil	200.00	0.0000810

- The linen undergoing re-washing after checking by specialised operators (normally around 5%) was not taken into account, as well as the detergents used for less than 2% of the total;
- The analysis focused only on white, plain linen, which was washed by standard procedure. Special treatments occasionally carried out were not considered;
- Regular maintenance operations performed annually were not considered because they change from one year to another. In fact, the ageing of each machine spare part is different and any standard assumption would be non-representative;
- Where specific information was missing, the average value of the concerned datum was used;
- For the vehicles used by suppliers, the worst case (Euro 4 engines) was assumed, unless other specific information was available;
- As described in subsection 4.2.2, the detergents were modeled based on their composition (Safety sheets), referring to the Ecoinvent database.

5. Results and discussion

5.1. Baseline scenario

The Single Score value representing the overall environmental footprint of ILVA industrial processes is 12.77 mPt/FU (1 kg of plain white 100% cotton linen for a standard washing cycle), corresponding to an impact of 33,725,570.00 mPt for the whole settlement in 2019.The highest values for each impact category are due to the core processes, specifically, washing and ironing, accounting for 36% and 34%, respectively. Within this representation, one environmental point Pt represents a unit of environmental impact describing one person's average environmental impact in one year. This standardization helps to understand and contextualize the environmental impacts of products, processes, or systems by comparing them to an average individual's annual environmental footprint.

For the washing process, the greatest impact is due to the use of detergents and washing aids, while for the ironing line the greatest impact is due to the consumption of energy, *i.e.* of LSFO and electricity. Fig. 2 shows the percent contribution of the different activities to the overall environmental impact in the baseline scenario.

Fig. 3 depicts the impact values for the midpoint categories in ReCiPe (2016) (Huijbregts et al., 2017).

The categories of major concern are *Global warming & human health*, *Fine particulate matter emissions*, *Human cancerogenic toxicity*, *Human non-carcinogenic toxicity*, and *Fossil resource scarcity*, and, among these, the prevailing one is *Fine particulate matter emissions* (5.18 mPt) whose emissions are related to energy consumption and derive chiefly from washing, ironing and drying. This category includes all the particulate precursors, such as sulphur dioxide, ammonia and nitrogen oxide. Within washing operations the most impactful items are the production of LSFO, of electric power and of washing aids, especially of sodium hypochlorite. The primary environmental impact of drying and ironing stems from the consumption of LSFO and electricity. Sulphur dioxide is generated from fossil fuel energy production and accounts for 57% of the fine particulate formation. $PM_{2.5}$ is emitted mainly in the production of detergents and washing aids and contributes 23% of the overall fine particulate. 19% is due to nitrogen oxides (NO_x) from the industrial combustion of LSFO and from the production of electric power. Ammonia accounts for 1% of fine particulate emissions. The increase of fine particulate concentration in the atmosphere raises the incidence of respiratory disease, reflecting in the *Human health* endpoint (Kowalska et al., 2019).

The second ranking impact category is *Global warming & human health*, with 4.41 mPt, also caused by the consumption of energy and of LSFO in washing, drying and ironing operations, but with a considerable contribution from the production of chemicals as detergents and washing aids.

Global warming has a series of consequences: it fosters the diffusion of illnesses, it damages agriculture, thus reducing the availability of food and causing, indirectly, malnutrition problems, but also threatening some terrestrial species (Sanghi and Mendelsohn, 2008). That's why it reflects not only on *Human health* endpoint but also, to a lesser extent, on *Terrestrial ecosystems* endpoint.

Lower, but detectable, impacts were found also for *Human carcinogenic toxicity* and *Human non-carcinogenic toxicity* because of the production of detergents and washing aids, affecting the *Human health* endpoint (Hauschild et al., 2024).

In the end, the use of LSFO and the production of electric power involve the consumption of fossil resources and, thus, affects the category *Fossil resource scarcity* and the endpoint *Resource depletion*.

As a result, the endpoint category *Human Health* is the most affected by the impact (11.67 mPt), followed by *Resource depletion* (0.45 mPt) and, lastly, by *Ecosystems* (0.66 mPt), as shown in Fig. 4, where the contribution of the different sources to the overall endpoint impact categories is reported in mPt (a) and in % (b).

For *Human Health*, the most impactful activities are washing, ironing, and, to a lesser extent, drying. Wastewater treatment and transport have a minor impact, chiefly related to energy consumption and the use of chemicals. On the other hand, the discharge of non-treated wastewater, besides being illegal, would involve much higher impacts, also on the value of other indicators and the on-site treatment and recycling of wastewater is surely a good strategy to reduce the environmental impact of the laundry, allowing for saving both water and energy (Jørgensen et al., 2004).

Table S1 in Supplementary Material reports the results at the midpoint categories from the LCIA using ReCiPe H 2016 (Huijbregts et al., 2017).

5.2. Sensitivity analysis

The sensitivity analysis was conducted to assess the reliability of the data and assumptions underlying the study, ensuring the validity of the results. The analysis considered three scenarios:

- Alternative detergent type;
- Changes in material logistics for the laundry;
- Potential reduction in electricity consumption.

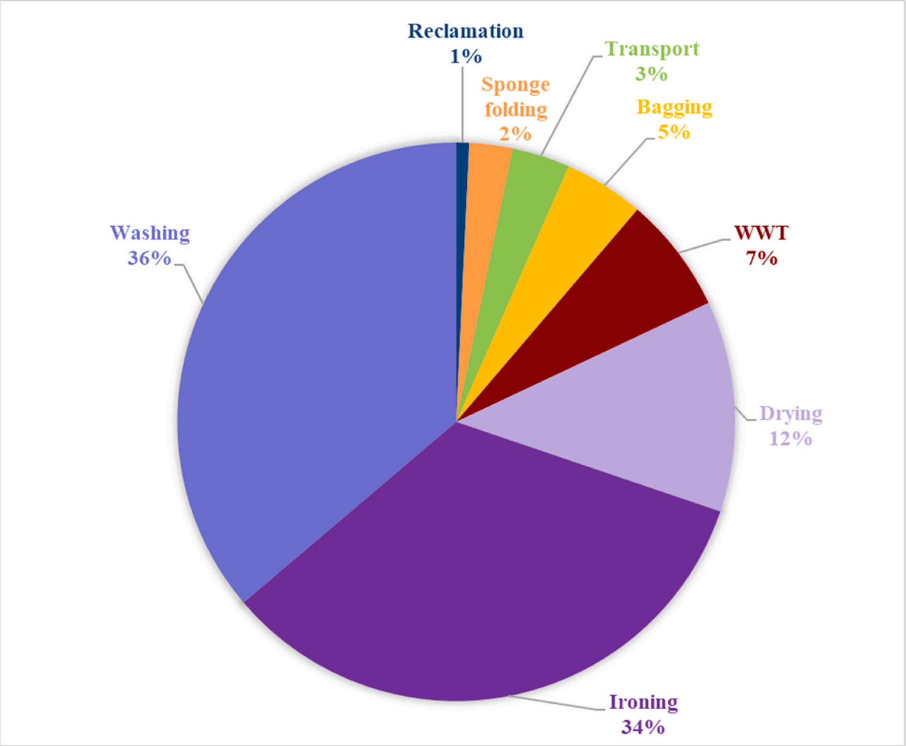


Fig. 2. Percent incidence of the various activities on the environmental impact of the entire cycle of linen processing performed by ILVA (baseline scenario).

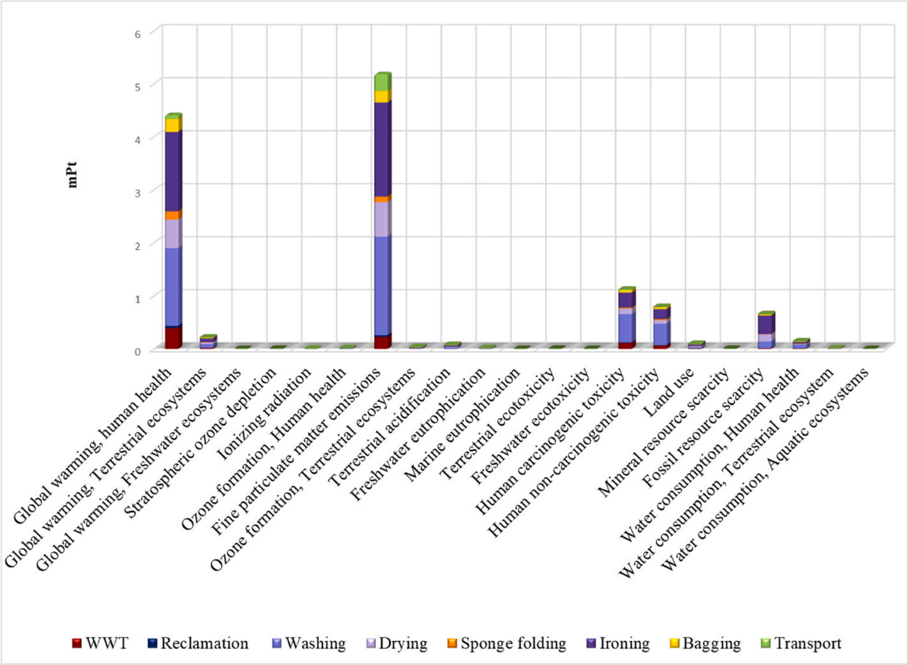
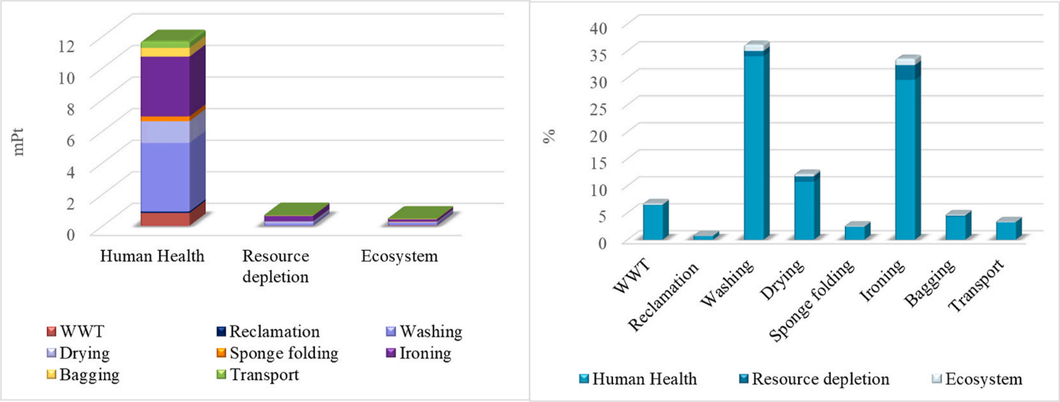


Fig. 3. Normalized, Single Score results for the different midpoint impact categories.



(a)

(b)

Fig. 4. Normalized, Single Score results for the endpoint impact categories, in mPt (a) and in percentage (b).

For the second and third cases, sensitivity was evaluated using the *sensitivity ratio* (SR) approach proposed by Clavreul et al. (2012). The SR equation quantifies the relationship between changes in a parameter's value and the corresponding changes in the results. An SR value of 1 indicates a proportional relationship: a 10% increase in the parameter results in a 10% change in the outcome. Higher SR values signify greater sensitivity of the final LCA result to the parameter.

5.2.1. *Alternative detergent scenario*

Sensitivity analysis for detergents assessed the robustness of the Life Cycle Inventory (LCI) data. The Baseline Scenario, based on the current detergent data, was compared with an Alternative Scenario using the proxy soap dataset from the Ecoinvent database. Results, presented in Fig. 5, show a marginally higher environmental impact in the Alternative Scenario (+11%) compared to the Baseline Scenario. This emphasizes the robustness of the baseline dataset and the novelty of integrating detergent-specific environmental parameters into a comprehensive LCA for industrial laundries.

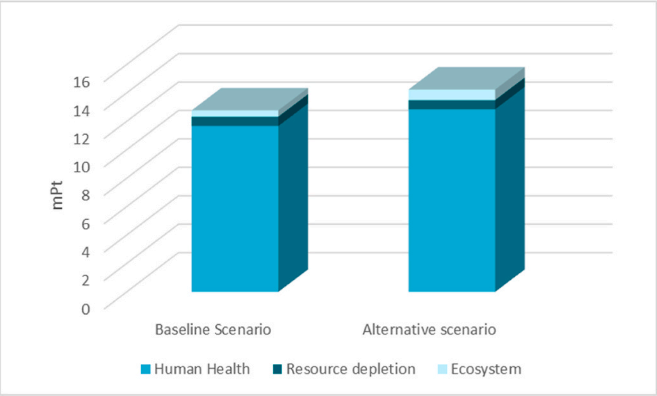


Fig. 5. Results of the sensitivity analysis for detergents. In the alternative scenario data derive from the proxy Soap dataset in Ecoinvent database.

5.2.2. *Transport distance scenario*

Three levels of variation in transport distances between suppliers and ILVA were analyzed: 50%, 100%, and 200% increases in the reference distance of 2034 km. Table 10 summarizes the results. The sensitivity analysis revealed that variations in transport distance had minimal impact on the overall result, with SR values consistently below 1. This outcome reflects the low contribution of transport to the total environmental impact. While the sensitivity was negligible, minor variability in transport contributions may arise due to uncertainties in actual travel distances.

5.2.3. *Electricity consumption scenario*

Electricity consumption was varied by 5%, 10%, and 20% above the baseline value of 0.2535 kWh to assess its impact sensitivity. Table 11 summarizes the results. Although electricity accounts for 30% of the total environmental impact, the sensitivity analysis indicated low sensitivity (SR $<$ 1). Nevertheless, electricity remains a major contributor to carbon emissions, and its reduction represents a substantial opportunity to mitigate environmental impact. The integration of renewable energy sources, such as solar power, would be an effective measure in reducing these emissions.

The sensitivity analysis confirmed that variations in detergent type, transport distances, and electricity consumption have a limited impact on the overall environmental results of the LCA. The detergent scenario showed only an 11% increase in environmental impact when switching to an alternative dataset, supporting the robustness of the Baseline Scenario's more specific data. Variations in transport distances and electricity consumption both exhibited sensitivity ratios below 1, indicating low influence on the overall results despite the inclusion of these parameters in the LCA model.

These findings emphasize the stability and reliability of the underlying assumptions and methodological choices in the analysis. Specifically, the results suggest that the system's environmental performance is primarily driven by other factors beyond those considered in the sensitivity analysis. However, the study highlights the importance of consistent and accurate data for significant contributors, such as electricity consumption, which accounted for a substantial portion of the overall impact despite low sensitivity to minor variations.

Overall, the sensitivity analysis provides confidence in the validity of the study's conclusions and supports the robustness of the evaluated scenarios, strengthening the case for the adopted methodologies and assumptions. Future studies could further refine the model by exploring additional variables or employing advanced uncertainty analysis to ensure comprehensive understanding and reliability.

5.3. *Improved scenario*

The results obtained and the sensitivity analysis served as the foundation for exploring potential actions to reduce the environmental impact of laundry operations. The option of substituting or reducing the use of detergents and washing aids was dismissed due to the limited information in the database, which would compromise the model's reliability, and because significant optimization efforts have already been made. On the other hand, according to Fontana et al. (2024) the use of eco-labelled and concentrated detergents would allow for substantial decrease in CO_2 emissions and in the consumption of the detergents themselves, but would involve higher water demand for the dilution.

Table 10
Results of the sensitivity analysis for the transport of materials.[a]

Scenario	Distance [km]	Impact [mPt]	Variation (km)	Variation (mPt)	SR[a]
Present value	2034	12.8	0	0	
50% increase	3051	13.1	1017	0.3	0.0468
100% increase	4068	13.4	2034	0.6	0.0469
200% increase	6102	14.0	4068	1.2	0.0471

[a] Sensitivity ratio (SR) as suggested by Clavreul et al. (2012)

Replacing LSFO was not feasible, as it would require a complete overhaul of the ILVA site's combustion plant, and Elba Island lacks the infrastructure for receiving and distributing methane gas. Therefore, the most viable option identified was the self-generation of renewable energy by installing photovoltaic panels.

A specialised enterprise provided a preliminary design to cover all available surfaces with photovoltaic panels capable of generating 241 kW. The improved scenario was created using the methods and assumptions applied for the baseline one, and the impacts were calculated by considering the construction and installation of solar panels. The resulting global impact was quantified in 10.3 mPt/FU, with a decrease of 19.7% to the baseline scenario, despite non-covering the whole energy demand of the laundry (Fig. 6). This significant reduction highlights the novelty of integrating on-site renewable energy production into industrial laundry systems as a pioneering approach to mitigate carbon emissions while maintaining operational efficiency.

In 2023 the photovoltaic panels were installed and put in operation. The energy production from April 2023 (when ILVA started to work regularly after the low activity winter season) to December 2023 was 182.5 MWh, higher than expected from the evaluated preliminary project, and covered, on the whole, 28.8% of the total consumption and, on average, 31.1%. The transition to renewable energy demonstrates a scalable and replicable pathway for industrial laundries to substantially reduce carbon emissions and environmental footprints. We can thus estimate a significant improvement in the environmental performance of ILVA laundry. Of course, not all the energy produced is consumed, depending on the seasonal production and demand. The consumption ranged between 48% (in December) and 100% (from June to September), and the remaining energy was contributed to the local electric network, thus positively impacting the area. When practically available, the prospect is to apply new technologies to store within ILVA the energy exceeding the demand to optimize its use and induce an additional benefit in terms of environmental impact.

These strategies underscore the study's novel contribution to integrating renewable energy solutions within industrial laundry operations, providing a model for sustainability that can be adapted to other high-impact industrial sectors.

6. Conclusion

This LCA model was designed to assess the environmental impact of an Italian laundry operation through sensitivity analysis, leveraging primary data collected directly from the laundry. This assessment was supported by SimaPro 9.2 software and an inventory created from primary data, detergent technical datasheets, and the Ecoinvent 3.8 database.

The analysis identified critical environmental hotspots, emphasizing the contributions of energy consumption, particularly in the washing, drying, and ironing processes, and the use of detergents and washing aids. The most affected impact categories include global warming, human health, fine particulate formation, carcinogenic and non-carcinogenic human toxicity, and fossil resource scarcity. Among these, the human health endpoint emerged as the most significantly impacted, driven primarily by the emissions and energy use associated with the core industrial processes.

A key opportunity for mitigating these impacts lies in reducing energy consumption and transitioning to renewable energy sources. This study highlighted the integration of on-site photovoltaic panels as a transformative step, resulting in a 19.7% reduction in environmental impacts, which was further validated by the higher-than-expected

Table 11
Results of the sensitivity analysis for electricity consumption.

Scenario	Consumed energy (kWh)	Impact [mPt]	Variation (kWh)	Variation (mPt)	SR*
Present value	0.2535	12.8	0	0	–
5% increase	0.2662	12.9	0.0127	0.1	0.156
10% increase	0.2789	13.1	0.0254	0.3	0.234
20% increase	0.3042	13.5	0.0507	0.7	0.273

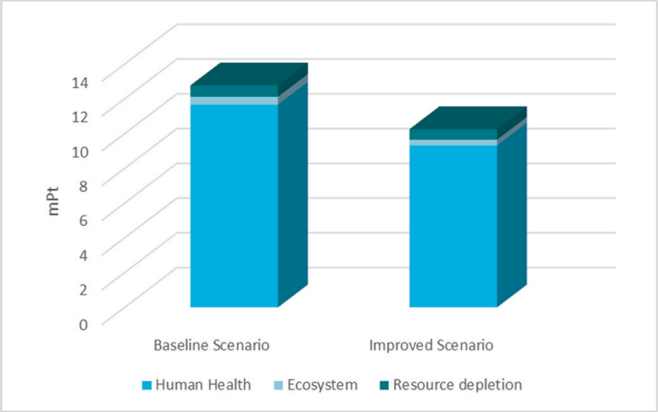


Fig. 6. Comparison between the impact calculated for the baseline scenario and for the improved one, based on the production of solar energy to cover part of the energy demand.

energy production observed in 2023. Solar energy contributed over 30% of the facility's energy demand, showcasing its potential for substantial emissions reduction. This represents a novel and scalable approach to embedding sustainability in industrial operations while maintaining high efficiency.

While energy consumption emerged as the most significant contributor to environmental burdens, the contribution of chemicals such as detergents and washing aids was also notable, though accompanied by a degree of uncertainty. Sensitivity analysis revealed that variations in detergent composition, transport distances, and electricity consumption had minimal effects on overall impacts, underscoring the robustness of the results. This demonstrates that addressing major contributors, like energy efficiency and renewable energy integration, holds the greatest potential for reducing the facility's environmental footprint.

Furthermore, the study underscores the importance of adopting holistic environmental strategies, integrating data-driven decision-making, and leveraging advanced LCA methodologies. By focusing on renewable energy solutions, the ILVA laundry facility sets an example for implementing replicable sustainability measures within the industrial laundry sector. The findings from this study pave the way for developing Type III environmental labels in alignment with ISO 14025 standards, through platforms like the Environmental Product Declaration (EPD) and the European Product Environmental Footprint (PEF).

In addition, the insights gained from this comprehensive LCA contribute to a deeper understanding of environmentally sustainable practices, offering actionable benchmarks for improving industrial performance. The integration of renewable energy solutions not only addresses current environmental challenges but also provides a flexible framework adaptable to other high-impact industrial sectors. This study highlights the value of combining renewable energy production, such as solar photovoltaics, with targeted process improvements, establishing a model of sustainability that balances environmental, economic, and operational considerations effectively.

Finally, the results of this research emphasize that sustainability in industrial processes is achievable through innovative strategies and data-driven actions. This serves as an actionable blueprint for other industries aiming to reduce carbon emissions, minimize environmental impacts, and align operations with global sustainability goals. The case of ILVA demonstrates how proactive measures can drive meaningful change, providing a scalable, replicable solution to address pressing environmental challenges across industrial contexts.

CRediT authorship contribution statement

Valeria Mezzanotte: Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Sara Venturelli:** Investigation, Formal analysis, Data curation. **Riccardo Paoli:** Validation, Software, Data curation. **Elena Collina:** Validation, Supervision, Data curation, Conceptualization. **Francesco Romagnoli:** Supervision, Software, Methodology.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used Chat GPT in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2024.100246.

Data availability

Data will be made available on request.

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