Evaluation of the environmental sustainability of a flax spinning process through life cycle assessment: an Italian case study

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Abstract: The textile industry is a major contributor to the global economy, but it is also energy, emission, and material-intensive, leading to several environmental challenges. With rising energy costs, strict environmental regulations, and an uncertain context, it is paramount for textile companies to fully comprehend their environmental impact in order to improve their long-term sustainability level. It is widely recognized that the use of organic natural fibers could have a positive impact on this aspect. Among others, flax fiber is becoming increasingly popular due to the growing awareness of its environmentally sustainable nature. For instance, it requires little rainwater to grow, requires few inputs, and its harvesting and processing do not generate waste. To truly achieve sustainability goals, it is crucial to understand the actual environmental impact of the whole flax spinning process. Nevertheless, to the best of the authors' knowledge, no studies have been conducted on this topic. To fill this gap, the current paper analyzes the flax spinning process of Linificio e Canapificio Nazionale Srl Società Benefit, a leading company in this industry, by leveraging the life cycle assessment developed through the SimaPro software. Specifically, a 'gate-to-gate' approach was used considering a functional unit of 1 kg of finished 100% linen yarn. The primary data were gathered through on-site investigation and the environmental impacts were assessed using the ReCiPe (H) method. The results demonstrate that the flax spinning process drastically impacts on Human health protection area and that the most impacted midpoints are freshwater ecotoxicity, human carcinogenic toxicity, marine ecotoxicity, and freshwater eutrophication. Finally, the identified environmental hotspots are useful to shed light on potential opportunities for improvement from the manufacturer's perspective.

Keywords: Flax fiber; Spinning; Life cycle assessment; Environmental sustainability.

I. INTRODUCTION AND BACKGROUND

As it provides essential products for everyday life, including clothing and home textiles, as well as products for other industries (e.g., automotive), the textile sector is one of the largest contributors to the global economy [1,2]. Nevertheless, the industry's production and consumption at the worldwide level are on the rise, resulting in increased environmental pressures [3]. As proof of this, it is now widely recognized that this sector accounts for approximately 1.2 billion tons of greenhouse gas emissions per year. Just to give an idea, this value is much higher than the combined emissions from international flights and maritime shipping [4,5]. At each stage of its supply chain, huge quantities of energy, water and chemicals are used [6,7]. For instance, fuels are the primary source of energy for wet processing of textiles (i.e., bleaching, dyeing, and finishing), while electricity is the main one for yarn spinning [8]. Wet processing, along with the harvesting of some natural fibers (i.e., conventional cotton), is also a major contributor to water consumption, which is often contaminated with hazardous products [7, 8]. To counter all these problems, several legislations have been recently introduced by policymakers at both the process level and waste disposal and incineration level. At the same time, customers' awareness of the sustainability issue has increased [9,10]. In such a context, it is crucial for companies in the textile industry to fully understand their environmental impact in order to improve their long-term sustainability and continue to meet society's needs while ensuring the survival of the planet. To achieve this ambitious goal, the adoption of sustainable practices, such as reducing energy consumption, minimizing waste production, and using eco-friendly raw materials, could be a potential solution [6,11].

The use of eco-friendly raw materials, such as organic cotton and bast fibers (e.g., flax and hemp) is increasingly gaining prominence [12,13]. These fibers are biodegradable and generally have a lower carbon footprint compared to synthetic fibers like polyester and polyamide, as well as conventional natural fibers such as non-organic cotton and wool [14,15]. For instance, studies have shown that organic cotton emits less CO_2 and requires less water and energy than conventional cotton, while flax requires less energy and water than organic cotton [14]. Furthermore, wool outperforms cotton in various aspects, including recyclability and pesticide use, but it has a greater overall environmental impact due to its inability to absorb the emitted CO_2 [14,16]. Among others, flax fiber has gained momentum in textile applications in recent years due to its environmentally sustainable nature [17]. It does not require irrigation and does not pollute the soil or water, since it needs a low amount of nitrogen to grow and requires five times less fertilizer and pesticides than cotton [18]. Additionally, it enables zero-waste production, as all waste produced during scutching and subsequent steps (i.e., short fibers, seeds, etc.) can be recovered for the manufacturing of mats, paper sheets, or oils and paints, respectively [17,18]. Finally, due to its high strength, stiffness, and low elongation at break, flax fiber is currently used in the production of bio-composites [19,20]. These properties are in line with the principles of the circular economy. Therefore, a wider use of flax fiber can help improve the sustainability of the textile industry. Nevertheless, it is widely recognized that to truly achieve sustainability goals, taking a holistic perspective is crucial. By analyzing the whole process, it becomes possible to identify the main criticalities and find suitable solutions accordingly. To this end, the life cycle assessment (LCA) methodology can be adopted [12]. Despite of these potential benefits, to the best of the authors' knowledge, no LCA studies have been conducted on the whole flax spinning process. Previous LCA studies have focused on the analysis of the environmental impact of flax fiber production from growth/extraction stage to fiber ready for spinning, in comparison to other textile fibers [14], or on specific applications such as flax fiber reinforced composites [20].

Based on these premises, the current paper aims to conduct the LCA analysis of the flax spinning process of Linificio e Canapificio Nazionale Srl Società Benefit, a renowned leading company in this sector located in Villa d'Almè (BG). Specifically, a 'gate-to-gate' approach was adopted, considering a functional unit of 1 kg of finished 100% linen yarn suitable for the production of a long-sleeved 100% linen men's shirt. The SimaPro5 v. 9.3.0.3 software was used to achieve this goal. By doing so, the selected company can gain insights into the critical points of its production process in light of sustainability and, consequently, identify potential opportunities for improvement.

The remainder of this research is structured as follows: Section II introduces the materials and methods employed for the LCA analysis, while Section III presents and discusses the key outcomes of the research. Finally, conclusions and limitations are reported in Section IV, where future developments are also outlined.

II. Materials and methods

This study evaluates the environmental sustainability of the flax spinning process of Linificio e Canapificio Nazionale Srl Società Benefit. To this end, the LCA methodology (ISO 14044) was adopted. LCA is recognized as one of the most valuable tools for quantitatively assessing the sustainability of current technologies. It plays a crucial role in eco-design decision making and evaluating the environmental performance of newly developed technologies. With LCA, it is possible to analyze the environmental impact of products, processes, and services from a holistic perspective. This allows for the identification of potential areas for improvement and the development of strategies to reduce the environmental burden of human activities [21]. Following the guidelines of ISO 14040 and ISO 14044, the LCA method involves four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation of results. In this section, after briefly describing the flax spinning process under investigation, these steps are better introduced.

A. The flax spinning process

The spinning process of flax fiber is the first processing step to which the ready-made fiber (i.e., the fiber that has previously undergone the scutching and hackling processes) is subjected within the long and complex production chain of a long-sleeved men's shirt made of 100% linen.

The flax spinning process under investigation comprises five distinct steps: 1) Preparing is the step where flax fibers are processed through various mechanical operations into a semi-finished product called *roving*; 2) Bleaching is a chemical treatment that enhances fiber quality by removing all foreign substances that may adversely affect subsequent processing phases [17]; 3) Wet-spinning is the step in which the linen yarn is actually produced. It is called “wet” since the roving is passed through room temperature water to soften the fiber bundle [22], enabling the production of high-quality yarns [23]; 4) Drying comes after wet-spinning and is the phase in which yarns are dried using hot-air or radiofrequency dryers [17]; 5) Winding is the step to assemble the produced yarn into packages suitable for subsequent phases like weaving and knitting [24]. It also facilitates the removal of potential defects present in the final yarn [17]. At this point, the yarn spools are stored until they are transported to another company for the weaving stage.

B. Goal and scope definition

The goal of this work is to analyze the environmental impacts of the flax spinning process using the LCA method. In detail, this study aims to identify the environmental hotspots within the process and explore potential opportunities for improvement from the manufacturer’s perspective.

B1. Functional unit

This study specifically focuses on the spinning phase, which is responsible for yarn production. The functional unit was set at 1 kg of finished 100% linen yarn. Accordingly, all input flows, including materials and energy, were collected considering such a value.

B2. Assumptions

Some assumptions were made in this work to enable the implementation of the LCA: (i) as directly collected on-site, data were considered as reliable; therefore, no uncertainty analysis was performed, (ii) the process was not evaluated from a technical standpoint. Rather, it was assumed to be as described and shown by the company during the scheduled visits, (iii) waste from the spinning process was not included in the modeling as it was deemed to be of insignificant magnitude for the production process under analysis.

B3. System boundary

The aim of this paper is to analyze the environmental impacts of the flax spinning process. Consequently, the system boundary was limited to this specific phase within the whole supply chain for the production of a long-sleeved 100% linen men’s shirt. Overall, the study follows a ‘gate-to-gate’ approach, meaning it focuses solely on a particular step in the life cycle of a long-sleeved 100% linen men’s shirt (i.e., from the entry to the exit of the company under consideration). Moreover, all processes, from the transportation of flax fibers ready for spinning to the storage of the finished product, were considered. Instead, the outbound transportation of the finished product was excluded. Figure 1 provides a graphical representation of the system boundary for this investigation.

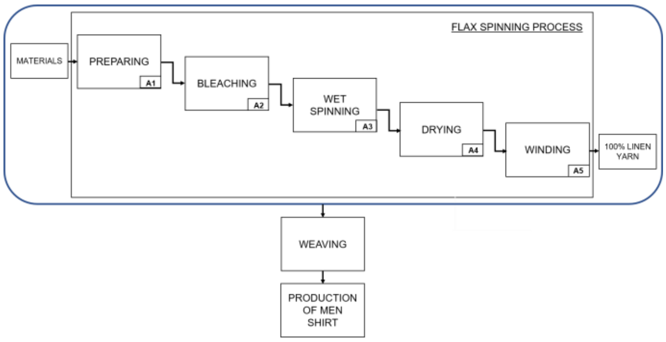

Figure 1. System boundary of the study

C. Life cycle inventory analysis

The life cycle inventory is a crucial procedure for assessing the environmental impact of a system, as it allows for the quantification of all inputs required and outputs produced within the system boundaries. This includes the use of resources such as raw materials and energy, as well as the release of substances into air, water, and soil. To compile a comprehensive list of these inputs and outputs, the production process was mapped out using a versatile modeling technique, namely the IDEF0 methodology. This methodology enables the accurate identification of all inputs, outputs, controls, and mechanisms involved in the process activities [25]. Figure 2 represents the result of this analysis. Specifically, five main inputs were considered, namely electricity, packaging, transport, chemicals and process. The item “process” encompasses flax fiber and water used to simplify the modeling.

In this study, the raw material for the manufacturing of 1 kg of 100% linen yarn is represented by flax fibers that have already undergone the scutching and hackling processes together with energy, water, and chemicals. Other inputs are packaging and transports. All data were gathered considering the functional unit of the study. To ensure the accuracy of the results, primary data of raw materials were directly collected on-site with the support of the company's sustainability and innovation manager. Instead, secondary data were retrieved from the international database Ecoinvent v.3.6. Additionally, information regarding energy use was obtained directly from the supplier, while data about energy mix (share of energy from renewable sources) were provided by Gestore dei Servizi Energetici – GSE S.p.A (https://www.gse.it/). For chemicals, data within the Material Safety Data Sheets (MSDSs) were used as they provide information regarding their specific composition. With respect to packaging, in the absence of precise data, pallets were excluded because they are generally used to handle all goods produced by the company, thus including also those not directly covered by this work. Concerning transports, they were modeled on the software by using the same type of transport vehicle, i.e., a medium-sized (16-32 tons) EURO 5 truck, but with different distances based on the material transported. For the transport of scutching flax, a distance of 1073 km was entered. The fiber used by the company, in fact, comes entirely from Normandy that is one of the largest producer of flax fiber at the European level [26]. For other input materials, an average distance of 100 km was assumed. With respect to one of the outflows, namely the waste produced, it is crucial to remember that it was not considered in the analysis since most of it always finds a new application. Finally, the LCA study was modeled in SimaPro5 v. 9.3.0.3 software, and the results from characterization were exported and analyzed using Excel.

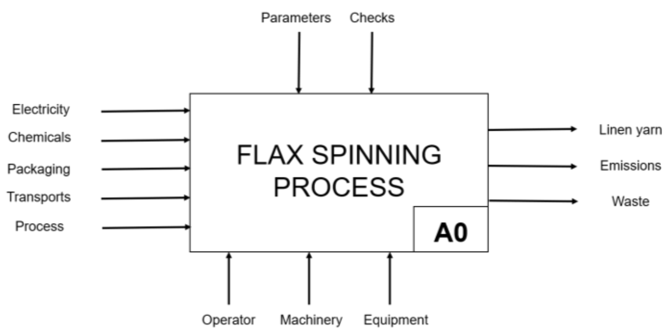

Figure 2. IDEF0 of the flax spinning process at hand

D. Life cycle impact assessment

The ReCiPe 2016 (H) method was used for the life cycle impact assessment as it is one of the most commonly applied methods for identifying parameters role and analyzing research findings [27]. In greater detail, this method combines the midpoint and endpoint methodologies based on a consistent environmental cause-effect chain [28]. The midpoint represents a series of environmental issues that are then aggregated into three endpoints (i.e., protection areas). The former consists of 18 different categories, including global warming, stratospheric ozone depletion, ionizing radiation, ozone formation-human health, fine particulate formation, ozone formation-terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption. It allows for measuring the impact of a specific effect before the damage occurs to one of the protection areas. The latter models the impact of each inventory voice to the protection areas (i.e., human health, ecosystem health, and resource availability).

III. Results and discussion

This section presents and discusses the key results obtained from the analysis conducted using SimaPro. It is divided into two subsections: the first focuses on the outcomes of the endpoint analysis, while the second examines the results of the midpoint analysis.

A. Endpoint analysis

Normalization in percentage points enables the comparison of the impact of each item relative to others for each midpoint analyzed. Therefore, the results of 100% normalized endpoints are presented in Figure 3. Examining the values thoroughly, it should be noted that the largest contribution to the impacts is due to Electricity and Process in all three damage categories. However, to determine the damage category most affected by the flax spinning process, it is necessary to normalize the impacts using ecopoints whose score is obtained from the combined results of an LCA with respect to the impact categories investigated. The more ecopoints a category gets, the worse its environmental impact. For example, 100 ecopoints represent the environmental impact equivalent to that of 1 EU citizen in a year. This approach allows the outcomes to be expressed in the same unit of measurement (mPt), facilitating comparison [29]. Figure 4 shows that the greatest damage is to "Human Health" (362.7 mPt), impacted 55% by Electricity, 38% by Process and the remaining 7% by Chemicals, Packaging and Transport. Then follows the "Ecosystems" protection area (13.5 mPt), mainly impacted by the Process (57%) and the Electricity (36%). Finally, there is the "Resource availability" protection area (2.3 mPt) due to Electricity (41%) and Process (27%).

Overall, it is possible to claim that Electricity and Process are the two most impactful inputs in terms of magnitude. In terms of milliecopoints, Electricity plays the predominant role, followed by Process. This highlights the need for the company to focus on these inputs in order to improve its sustainability. To reduce its environmental impact, the firm could consider several measures in the near future. First, it could prioritize the adoption of renewable energy sources, such as solar energy, in line with the International Energy Agency (IEA)'s analysis on past years and future prospects of this promising energy source [30]. Secondly, the sustainability of flax fiber could be further improved by implementing precision farming, that is a scientific method to improve crop management using satellites and IT [31]. By doing so, fertilizers, soil, organic substance levels, etc. are managed on a case-by-case basis, according to the space-time dimension considered [31].

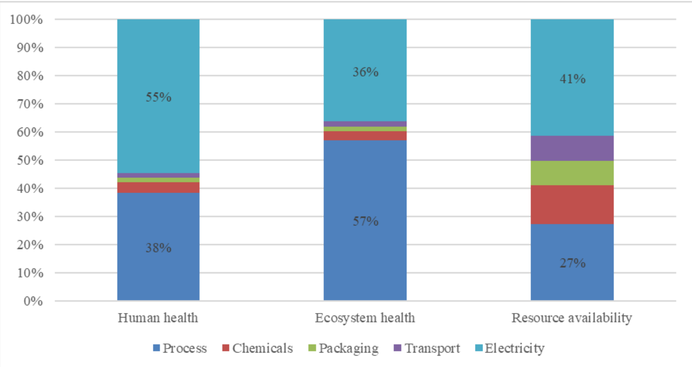

Figure 3: 100% normalized endpoints

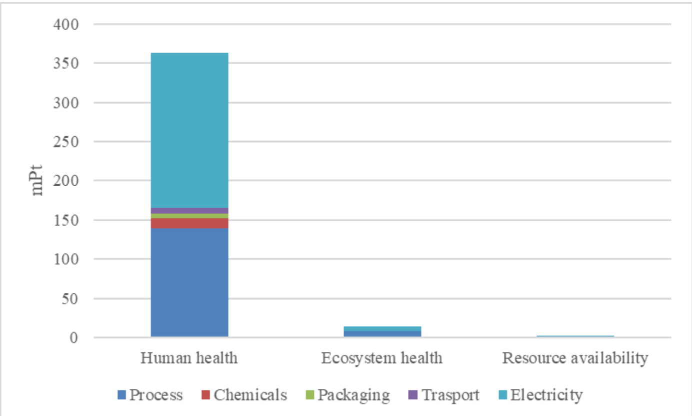

Figure 4: Normalized endpoints (in ecopoints)

B. Midpoint analysis

First of all, it is crucial to analyze the results at a less aggregate level to understand the magnitude of the impact of each input on every impact category. Figure 5 confirms, as anticipated by the endpoints' analysis, that the most impactful inputs are Electricity and Process for the majority of the impact categories. Subsequently, the results of the midpoints were normalized into ecopoints (Figure 6) to enhance their comparability. The outcomes show a predominance of impacts on freshwater eutrophication, freshwater and marine ecotoxicity, which grouped damage "Ecosystems", and human carcinogenic toxicity, which damages "Human Health". At this point, it was decided to delve into a detailed analysis of the four midpoints that are most impacted by the flax spinning process, as well as the midpoints that compose at the aggregate level the most impacted protection area, namely "Human Health".

B1. Midpoints composing Human health endpoint

With regard to the impact category "Global Warming", expressed in kg of CO_2 eq, it emerges that the largest impact is related to Electricity (44%) followed by Process (41%). This is due to the fact that the use of conventional energy sources predominates in the process (81% conventional energy versus 19% renewable energy). Even in the case of "Fine particulate formation", expressed in kg of PM2.5 eq., the impact is mainly attributed to Electricity (72%). Fossil fuels, burned for heating and powering production processes, contribute to the formation of particulate matter that worsens air quality. As for "Ozone Formation", characterized by values in kg of NOx eq., once again the main impact comes from Electricity (48%), followed by Process (42%). The formation of ozone in the troposphere, known as negative ozone, due to fossil energy sources, increases in the air that humans breathe and consequently has harmful effects on human and environmental health. Concerning "Ionizing Radiation", whose characterization factor is the kg of Cobalt-60 eq., it was found that the greatest impact is attributed to Electricity (56%), as well as Packaging (25%) and Process (13%). While it is evident that fossil energy contributes to ionizing electromagnetic radiation emissions, the impact of packaging may not be immediately apparent. This can be explained by the fact that many industries currently utilize irradiation as a process for producing packaging to ensure optimal conservation of products. Nevertheless, the company is increasingly adopting environmentally sustainable practices by incorporating recycled and recyclable materials with a lower environmental impact into its packaging (approximately 27% in 2022). As regards "Stratospheric Ozone depletion", expressed in kg of equivalent trichlorofluoromethane, the greatest impact is attributed to the Process (93%). The impact is mainly generated by emissions into water and, accordingly, into the atmosphere. The emission of chlorides, which are part of the substances called ODS (Ozone Depleting Substances), also leads to the release of chlorine atoms that damage the ozone layer. Finally, concerning "Human carcinogenic toxicity", characterized by kg 1.4 dichlorobenzene eq., it mainly originates from Process (60%) and Electricity (23%). It is also worth noting that this midpoint is affected by the flax spinning process along with the ones discussed in the subsequent subsection.

B2. Midpoints most impacted by the flax spinning process

Regarding "Freshwater eutrophication", expressed in kg of phosphorus equivalent, almost all of the impact is attributed to Process (95%), primarily due to flax fibers and emissions into water. This is because phosphorus and nitrogen, essential nutrients for flax cultivation, are released into the aquatic environment. The midpoint "Freshwater ecotoxicity" (kg 1.4 dichlorobenzene eq.) is mostly affected by Process (90%) since emissions into water degrade its quality. The same is exactly for 'Marine ecotoxicity' (kg 1.4 dichlorobenzene eq.). Overall, it is important to note that the company has a process water purifier in place to monitor all discharges.

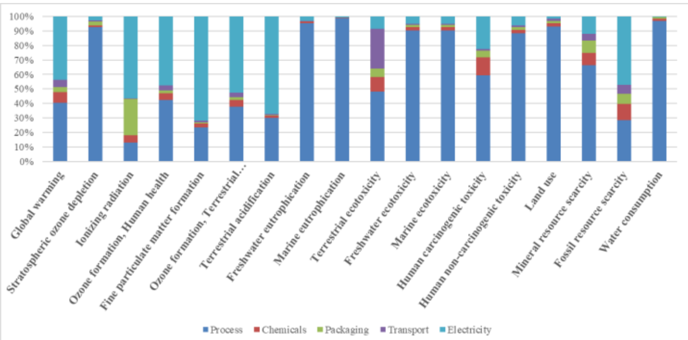

Figure 5: 100% normalized midpoints

IV. Conclusion

To effectively pursue sustainability goals, robust tools are required to assist decision-making in identifying the best solutions to support sustainable development. In this paper, the LCA methodology was adopted to evaluate the environmental impact

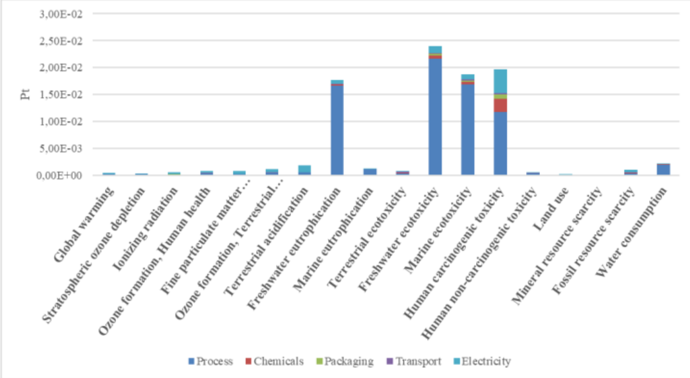

Figure 6: Normalized midpoints (Pt)

of flax spinning at Linificio e Canapificio Nazionale Srl Società Benefit, using the SimaPro software. The impact categories and the protection areas were analyzed with the aim of identifying critical inputs and proposing improvement solutions to the company.

By considering both midpoints and endpoints, it was found that the greatest contribution comes from Electricity and Process, while the impacts of Packaging, Transport and Chemicals are relatively less significant. Based on the obtained results, potential solutions can be defined to provide the company with valuable advice for improving its environmental performance. The main proposal is to prioritize renewable sources, especially solar energy. Additionally, the sustainability of flax fiber could be improved through precision farming techniques. Finally, the integration of collaborative robots into the production process could be considered to reduce resource consumption and waste.

It is important to note that all of these proposals require thorough technical and economic feasibility analyses before implementation. Furthermore, in the near future, a comprehensive investigation into the blockchain technology used by Linificio e Canapificio Nazionale Srl Società Benefit could be conducted to explore how digitalization can contribute to fostering sustainability.

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