POLYTECHNIC INSTITUTE OF TURIN

Master's degree course in Environmental and Land Engineering

Master Thesis

Tape your way to sustainability: a Life Cycle Assessment of a sport tape made from conventional cotton and ways to minimize its environmental impact

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Summary

Many individuals engage in sports as either a hobby or a profession: approximately 40% of European adults report engaging in physical activity at least once a week. Despite the benefits of physical activity, sport-related injuries can occur, prompting individuals to use sport tapes to prevent further injuries and limit muscle and joint movements.

Sterkur, a company based in Amsterdam, produces tapes to be used for physiotherapy or personal use. Due to the wide range of tapes available, Sterkur aims to make a positive impact in the market and, at the same time, to provide a eco-friendly product. The objective of this thesis is to quantify the environmental impacts associated to the production of Sterkur's sport tape. The goal is not only to analyze the "cradle-to-grave" production processes but also to improve the tape's sustainability.

The method utilized in this study is the Life Cycle Assessment (LCA), with the OpenLCA software and the databases: Environmental Footprint and Ecoinvent. The functional unit used in this assessment is one sport tape. The inventory of each material used in the tape's production is thoroughly detailed in subsequent chapters, as is the Life Cycle Impact Assessment, which reveals that cotton has the highest impact on *climate change*, the sub-category *climate change - land use and land use change* , *acidification*, *terrestrial and marine eutrophications* and *water use.*

As such, the thesis proposes the substitution of traditional cotton with organic cotton as a more sustainable and environmentally friendly solution. The LCA confirms that organic cotton has lower impacts on the primary indicators considered in this report, which reduces the tape's overall impact. These findings represent a significant progress for Sterkur towards greater environmental responsibility. Furthermore, they demonstrate the extent to which traditional cotton plants, despite being a natural source, contribute significantly to the tape's environmental impact throughout its lifespan.

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~

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Chapter 1

Introduction

Sustainability can be defined as a state in which human activity is carried out in a manner that preserves the functions of the Earth's ecosystems, while maintaining the supply of non-replaceable goods and services, and promoting the indefinite perpetuation of all life forms. The concept of sustainability arose in response to growing global environmental risks such as ozone depletion, climate change, biodiversity loss, and alteration of the nitrogen cycle.

One approach for achieving sustainability is the concept of a circular economy, which seeks to promote the efficient reuse of resources, materials, and products, thereby reducing waste and increasing the lifespan and value of materials and products. The circular economy seeks to move away from the traditional, consumption-and-disposal-based linear model of production and towards a more sustainable, efficient, and circular model.

The circular economy is founded on three key principles. The first is to protect the environment by balancing the regulated usage of available resources and the renewable resource flow. The second is to optimize resource extraction by circulating products, parts, and materials to maximize their appearance in the technical and biological cycle. The third principle is to minimize negative externalities and eliminate toxic substances by either replacing or reducing them.

The European Commission's objectives for the circular economy, outlined in the 2020 action plan, include making products on the EU market more energy- and resource-efficient, repairable, and recyclable by 2030. The plan also aims to ensure that all companies are prepared to compete equally, that consumers have access to more sustainable products and are better protected from activities that damage the green transition, and that enterprises have the data they need to gain environmental sustainability and promote circularity.

To achieve these goals, the European Commission has proposed a list of measures, including:

1. Designing products to decrease the environmental impact.

2. Giving more and clearer information to consumers and to supply chain's participants about sustainability.

3. Forbidding the unsold products' demolition.
4. Promoting more sustainable business models
5. Increasing green public projects

In summary, the circular economy is a growing concept that aims to promote sustainability by reducing waste, extending the lifespan and value of materials and products, and optimizing resource extraction. The European Commission's objectives for the circular economy are ambitious, but they are (hopefully) achievable with a range of measures that include designing more sustainable products, providing clear information to consumers and supply chain participants, promoting sustainable business models, and increasing the number of green public projects.

To evaluate the effects of circular economy practices, the Life Cycle Assessment (LCA) is a useful tool.It is a scientifically-based tool which can measure and evaluate the potential environmental impacts and resources used throughout a product's life cycle, from raw material acquisition, via production and use phases, to waste management.

In this thesis the Life Cycle Assessment is used in the field of sport medical device. Therefore, this kind of products are largely used since many people practice sport as hobby or as professional, but the ones that make it the most are the Nordics.

Indeed, this thesis centers on a specific sport tape produced by Sterkur, an Amsterdam-based company that specializes in actively creating environmentally friendly products. The tape serves as the main subject of investigation.

Despite the benefits of physical activity, sport-related injuries can occur, prompting individuals to use sport tapes to prevent further injuries and limit muscle and joint movements. It is the typical accessory that athletes apply to carry out a therapeutic, preventive, and rehabilitative system.

Chapter 2

Methodology

Human activities are interconnected with the environment, leading to environmental impacts.

The methodology utilized in the thesis is based on Life Cycle Thinking (LCT) approach, employed in modern environmental policies and business decisions related to Sustainable Consumption and Production (SCP). Life Cycle Thinking supports a comprehensive evaluation of the environmental impact of a product or service across its entire life cycle.

Life Cycle Assessment (LCA) is a quantitative tool used for this purpose, standardized by ISO 14040-14044 and guidelines of the European Commision.

LCA helps to measure a range of environmental factors associated with goods and services. It is an objective tool to analyze and quantify the environmental consequences of products during their entire life cycle. This means that LCA evaluates the environmental impact of a product from the extraction of raw materials to production, use, and eventual disposal.

Overall, the use of LCA as a tool in Life Cycle Thinking helps to identify areas where improvements can be made in the production, use, and disposal of products or services, ultimately contributing to more sustainable and environmentally friendly practices.

The LCA methodology is divided in four steps:

1. Goal and scope definition

2. Inventory

3. Impact assessment stage

4. Interpretation and Improvement

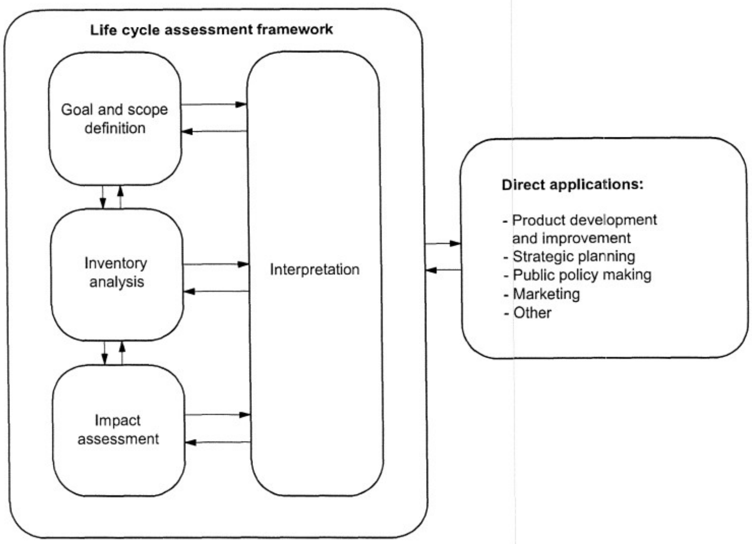


Figure 2.1: LCA framework, Figure taken by ISO 14040:2006:E.

Figure 2.1 helps to illustrate how Life Cycle Assessment (LCA) is a comprehensive and iterative approach that systematically evaluates the environmental impact of a product, process, or service. This approach involves compiling an inventory and analyzing all the products and processes within a system, covering the entire life cycle of the product from raw material extraction, manufacturing, transportation, operation, and disposal.

LCA allows designers and engineers to identify areas where improvements can be made to reduce the environmental impact of a product or service.

2.1 LCI guidelines

The guidelines and tools for conducting a Life Cycle Assessment (LCA) are established by the International Organization for Standardization (ISO) 14040/44 (2006) standard on Environmental Management – Life Cycle Assessment. This standard provides information on the principles and framework, requirements, and guidelines for conducting an LCA for companies, industries, and societies.

In addition to the ISO standard, the European Commission has produced a handbook on best practices in LCA, called the International Reference Life Cycle Data System (ILCD) Handbook. This handbook provides governments and businesses with a basis for ensuring the quality and consistency of LCA data, methods, and assessments. It provides technical guidance for conducting detailed LCA and forms the technical basis for developing product-specific criteria, guides, and tools. Moreover, the Product Environmental Footprint (PEF) is a method of Life Cycle Assessment used to quantify the environmental impacts of products.

LCA is a method for identifying and quantifying energy and materials used, as well as releases to the environment and their potential impacts throughout the entire life cycle of a product or service. The life cycle framework comprises products and elementary flows. Products evolve from elementary flows, which are defined in the ISO 14040 standard as materials or energy that enter the system from the environment and have not been previously transformed by humans, or materials or energy without subsequent human transformation.

Overall, the use of standard guidelines and tools such as ISO 14040/44 (2006) ILCD Handbook and PEF provides a consistent and rigorous approach to conducting LCA, which enables organizations to identify areas where they can improve the environmental performance of their products or services.

Carrying out a LCA requires a significant amount of detailed data, time, and expertise, which can be a limitation for some organizations. Despite its benefits, there are several limitations to consider when using LCA.

The first limitation is the robustness and applicability of the results, as LCA involves many assumptions and uncertainties in data collection and modeling, which can affect the reliability of the results. Therefore, it is essential to use appropriate data sources, consider uncertainties, and use sensitivity analysis to evaluate the robustness of the results.

The second limitation is that LCA loses its effectiveness when switching from a global to a local scale of environmental issues. This is because local conditions can vary significantly, and the environmental impacts of products or services can be highly dependent on the specific context in which they are used or produced. Therefore, it is crucial to consider the local context and use appropriate regional or national data when conducting LCAs at a local scale.

Finally, LCA is not a replacement for other environmental tools but complements them. It can be used in conjunction with other tools environmental risk assessment, and eco-design to provide a comprehensive understanding of the environmental impacts of products or services.

Therefore, it is essential to select the appropriate tool or combination of tools that best meet the objectives of the analysis.

2.2 Goal and scope definition

In conducting a Life Cycle Assessment (LCA), it is important to clearly state the study's intended application, audience, and reasons for carrying out the study.

This includes identifying to whom the results of the study will be communicated and whether the results will be used in comparative assertions intended for disclosure to the public. The scope of the study should be well-defined, ensuring that the breadth, depth, and level of detail of the analysis are compatible and sufficient to address the stated goal.

The scope of the study encompasses the following elements: the product system under examination; the functions of the product system, or, in the case of comparative studies, the systems being compared; the functional unit; the system boundary; allocation procedures; selected impact categories and the methodology of impact assessment, as well as the subsequent interpretation to be used; data requirements; assumptions; limitations; initial data quality requirements; the type of critical review, if any; and the type and format of the report required for the study. LCA is an iterative technique, and as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study.

According to the ISO 14040:2006(E), a system may have multiple functions, and the function(s) selected for a study depend on the goal and scope of the Life Cycle Assessment (LCA).

2.2.1 *Functional unit*

The functional unit defines how the identified functions (performance characteristics) of the product are quantified.

The primary purpose of a functional unit is to provide a reference for which the inputs and outputs can be related. This reference is necessary to ensure comparability of LCA results. It is particularly critical to ensure comparability of LCA results when assessing different systems, to ensure that such comparisons are made on a common basis. Therefore, it's important to determine the reference flow in each product system, which is the amount of products needed to fulfill the intended function.

2.2.2 *System boundary*

Life Cycle Assessment (LCA) involves defining product systems as models that describe the key elements of physical systems.

The system boundary defines the unit processes to be included in the system. Ideally, the product system should be modeled in such a manner that inputs and outputs at its boundary are elementary flows.

However, resources need not be expended on the quantification of such inputs and outputs that will not significantly change the overall conclusions of the study. The choice of elements of the physical system to be modeled depends on the goal and scope definition of the study, its intended application and audience, the assumptions made, data and cost constraints, and cut-off criteria. The models used should be described, and the assumptions underlying those choices should be identified. The cut-off criteria used within a study should be clearly understood and described.

The criteria used in setting the system boundary are important for the degree of confidence in the results of a study and the possibility of reaching its goal. When setting the system boundary, several life cycle stages, unit processes, and flows should be taken into consideration, including the acquisition of raw materials, inputs and outputs in the main manufacturing/processing sequence, distribution/transportation, production and use of fuels, electricity and heat, use and maintenance of products, disposal of process wastes and products, recovery of used products (including reuse, recycling, and energy recovery), manufacture of ancillary materials, manufacture, maintenance, and decommissioning of capital equipment, and additional operations such as lighting and heating.

2.3 Life Cycle Inventory (LCI)

The inventory analysis is a critical phase of the Life Cycle Assessment (LCA) process that involves compiling and quantifying inputs and outputs for a given product system throughout its life cycle. This analysis also includes the end-of-life step, which aims to understand what happens to products after their use and quantify the associated environmental impacts.

The inventory phase involves collecting data on every process unit within the system boundaries, including consumption, emissions, and product quantity and weight.

This data can be primary or secondary, with primary data being measured on-site and secondary data being obtained from literature or databases.

A flow chart is typically used to define the system boundaries, with process units representing the different phases of the life cycle and interconnected by product, energy, and material flows.

Each process unit is connected to the ecosystem from which it obtains resources and releases waste (air emissions, water and soil, solid waste, products) as in the Figure 2.2. Software such as Gabi, SimaPro, and OpenLCA can facilitate the creation of this model.

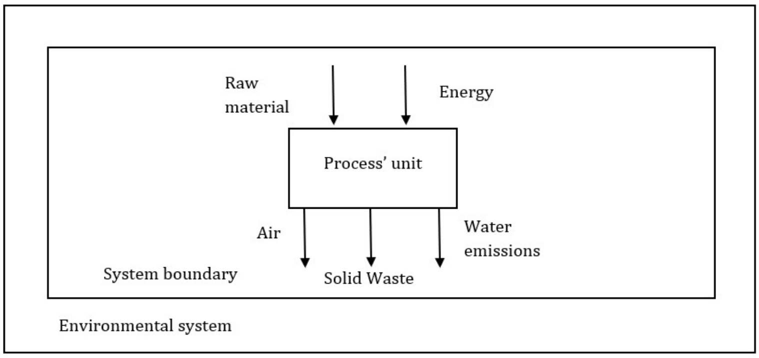


Figure 2.2: Input and Output flows considered in a LCA study.

An important aspect of end-of-life processes is recycling, which can take two forms: closed and open loop recycling. Closed loop recycling occurs when material flows to be recycled are re-entered into the same industrial process from which they originated. This type of recycling reduces the need for virgin materials and reduces waste. Open loop recycling, on the other hand, occurs when the origin and destination processes for recycling the materials differ. This type of recycling may require additional energy and resources for transportation and processing but can still reduce the need for virgin materials and waste. Both types of recycling can have environmental benefits and are considered in LCAs.

The steps to carry out are: data collection, data calculation and allocation of flows and releases, which are explain in the next paragraphs.

2.3.1 *Data collection*

Data for each unit process within the system's boundary can be classified under major headings, including energy inputs, raw material inputs, ancillary inputs, other physical inputs, products, co-products and waste, emissions to air, discharges to water and soil, and other environmental aspects. Data collection can be a resource-intensive process.

2.3.2 *Data calculation*

After data collection, calculation procedures are needed to generate the results of the inventory of the defined system for each unit process and for the defined functional unit of the product system that is to be modeled. These procedures include validation of the collected data, relating data to unit processes, and relating data to the reference flow of the functional unit.

2.3.3 *Allocation of flows and releases*

In many industrial processes, it is common to have multiple outputs or a non-linear relationship between raw material inputs and outputs. In fact, most industrial processes yield more than one product, and they recycle intermediate or discarded products as raw materials. When dealing with systems involving multiple products and recycling, allocation procedures should be considered to ensure accurate accounting of environmental impacts.

2.4 Life Cycle Impact Assessment (LCIA)

The purpose of Life Cycle Impact Assessment (LCIA) is to evaluate the environmental significance of a product system's Inventory results. This phase employs impact categories and category indicators to simplify and model LCI results, which are intended to reflect potential environmental impacts.

The ISO 14044 mandates two steps, classification and characterization, and provides two optional steps, normalization and weighting, for LCIA.

In the classification step, each environmental flow is assigned to a specific impact category.

In the characterization step, the impact of each emission is quantitatively modeled according to the underlying environmental mechanism.

Normalization relates different characterized impact scores to a common reference, while weighting reflects the relative importance of different environmental impact categories.

It is important to differentiate between impact and effect in this step, where the former is the physical outcome of a human activity, such as mineral extraction or substance release, while the latter can be estimated from the impact, under given assumptions and using appropriate models.

2.4.1 *Elements of LCIA*

The LCIA phase is a key component of LCA and involves the assessment of potential environmental impacts associated with the inventory data generated in the previous phase. In the Figure 2.3 the LCIA phase is reported, which can be divided into four main elements: characterization, normalization and weighting.

1. Characterization: This element involves the classification of the inventory data into impact categories, such as climate change, acidification, eutrophication, and human toxicity. The impact categories are defined based on the type of environmental impact being assessed.

2. Normalization: This element involves the scaling of the impact categories to a common reference point, such as global warming potential (GWP) or human toxicity potential (HTP). Normalization is used to facilitate comparison between different impact categories.

3. Weighting: This element involves the assignment of relative importance or significance to the impact categories based on value-choices made by the decision-makers. This is a subjective step and requires careful consideration of the values and perspectives of different stakeholders.

The level of detail, choice of impact categories evaluated, and methodologies used in the LCIA phase depend on the goal and scope of the study.

The LCIA results can be used to identify hotspots or areas of significant environmental impact, assess the effectiveness of different environmental management strategies, and inform decision-making processes.

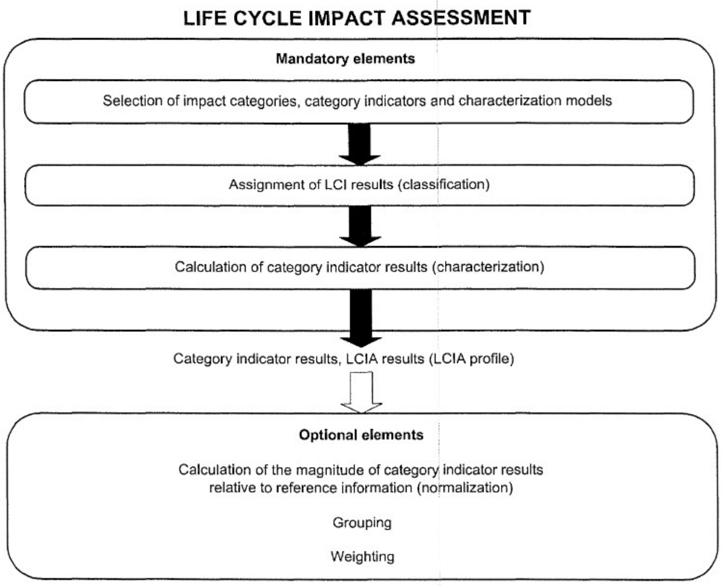


Figure 2.3: Elements of the LCIA phase, Figure taken from ISO 14040:2006(E).

2.4.2 *Limitation of LCIA*

Additionally, the LCIA results are dependent on the selection of impact categories and their associated indicators.

The selection of impact categories is subjective and can vary depending on the goal and scope of the study and the values and preferences of the stakeholders involved.

Moreover, the weighting of different impact categories is subjective and varies depending on the values and preferences of the stakeholders.

As a result, the interpretation and communication of the LCIA results require careful consideration of the underlying assumptions and uncertainties.

The limitations and uncertainties associated with the LCIA phase highlight the need for transparent reporting of the methods, assumptions, and data used in the LCA study, as well as the need for sensitivity and uncertainty analysis to assess the robustness of the results.

2.5 Interpretation and Improvement

The interpretation phase of LCA involves analyzing the results of the inventory analysis and impact assessment, or in the case of LCI studies, the inventory analysis alone. The goal of interpretation is to provide conclusions, limitations, and recommendations that are consistent with the study's defined scope and objectives. It's important to note that LCIA results are relative and indicate potential environmental effects, rather than predicting actual impacts on category endpoints, exceeding thresholds, safety margins, or risks.

The interpretation phase aims to provide decision-makers with a comprehensive and consistent presentation of the LCA results that is easily understandable. This phase may involve an iterative process of reviewing and revising the study's scope, as well as the quality of data collected, to ensure that they align with the study's defined goals.

Overall, the findings of the life cycle interpretation should reflect the results of the evaluation element, and take the form of conclusions and recommendations that are consistent with the study's defined scope and objectives.

Chapter 3

Application to Sterkur company: LCA of a sport tape

All the products we use in our daily lives are created using raw materials that have an impact on the environment and our health, depending on the extraction and production processes involved.

Sterkur, a company based in Amsterdam, aims to make a positive difference by prioritizing the planet and using the most natural raw materials for its physiotherapy products. It offers a range of physiotherapy products, including sport tapes classic, kinesiology tapes, professional rugby tapes, stretch bands, and trigger point ball.

This thesis focuses on the environmental impact of Sterkur's sport tape classic. Sterkur recognizes that its products depend on natural resources, such as rubber trees and cotton plants. As a responsible measure, Sterkur engages in replanting and repairing the land it uses for each roll of sports tape to minimize its environmental impact. By doing so, Sterkur aims to reduce the negative effects of natural resource use and promote sustainable practices in its company.

Furthermore, Sterkur's tapes present differences compared to others in the market. Some other tapes may be composed of elastane, which can contain synthetic fibers like polyester or nylon that are not biodegradable like cotton, and may require significant resources for production. In addition, synthetic fibers can release microplastics into the environment.

Other tapes may be made of synthetic adhesives, such as polyester, and may contain harmful substances like PVC. The production of these materials can also require significant resources, and their disposal can pose an environmental problem if not handled correctly.

To evaluate the product's entire life cycle, from production to disposal, a life cycle assessment will be conducted.

Chapter 4

Sport tape: goal and scope definition

4.1 Goal definition

The reason why the thesis includes the methodology of Life Cycle Assessment (LCA) is rooted in sustainability theory. LCA is a tool used to evaluate the potential environmental impacts of a product by considering the different life cycle phases, including raw material extraction and processing, manufacturing, and disposal. By identifying the critical phase of the product's life cycle that generates the major impacts, companies can design a plan to reduce those impacts.

OpenLCA, an open-source and free software for sustainability and Life Cycle Assessment, is used in this thesis to conduct the LCA case study following international standards.

The software allows for fast calculations using the largest set of data available.

The thesis is motivated by a strong interest in the field of Life Cycle Assessment (LCA). By conducting an LCA for their products, companies can identify specific processes and areas where improvements can be made to minimize their impact on the environment, atmosphere, and human health.

Sterkur is a company that has recognized the importance of sustainability and has taken steps towards producing more eco-friendly products. Specifically, they have started using natural sources for their sports tapes, trigger point balls, and stretch loops. This transition towards sustainable products demonstrates Sterkur's commitment to reducing their environmental impact and improving the overall sustainability of their products.

The case study in this thesis focuses on a sport tape and evaluates each process from "cradle-to-grave" using LCA. Despite the sport tape being made from natural sources, the aim is to identify the phase of the life cycle responsible for the main impacts and determine ways to lower those impacts.

4.1.1 *What a sport tape is*

Figure 4.1: Representation of a sport tape, picture taken by Sterkur.

The function of sport tapes is to provide support, compression, and limit the motion of certain muscles and joints during physical activity. Sport tape is commonly used by athletes and active individuals to prevent or reduce the risk of injury, as well as to support an injured or weak body part during physical activity. Additionally, sport tapes can also aid in the recovery process by promoting healing and reducing pain and inflammation in the affected area.

The tape is typically 10 meters in length and 3.75 centimeters wide, and a single roll is typically used for two workouts by a sporty person. However, after the application, the tape only lasts for one workout and must be removed and disposed of.

The sport tape is classified as a dipping product, similar to gloves, nipples, balloons, and toys.

Figure 4.2: Application of a sport tape, picture taken by Sterkur.

4.2 Scope definition

4.2.1 *Functional unit*

The term "functional unit" is used to describe the specific quantity or function of a product that is being evaluated in an LCA.

In this case, the functional unit is defined as one sport tape (10 meters in length and 3.75 centimeters wide), which serves as a reference to compare the environmental impacts of different tapes.

By using the same functional unit, it is possible to make meaningful comparisons between different products and evaluate their relative environmental performance.

4.2.2 *System boundaries and assumptions*

The analysis of the sport tape's supply chain is dependent on the boundaries that define the extent of the chain being studied. Since all components of the sport tapes are manufactured in China, Sterkur does not have direct control over their production.

The LCA methodology provides a comprehensive view of the examined situation, identifying critical points in the system and highlighting the potential impact of interventions. However, depending on the system boundaries set, indirect consequences may not be included in the analysis.

The LCA conducted for this thesis follows a cradle-to-grave approach, covering the main processes involved in the production of the sport tape, as well as its incineration at the end of its life. The use phase of the sport tape is not considered since it does not involve any energy or material consumption, nor does it result in emissions.

The sport tape is composed of three primary materials: textile cotton, adhesive, and cardboard packaging.

The cardboard packaging is also present in the inner core of each sport tape. The Figure 4.3 provides a visual representation of the essential materials that make up a sport tape.

In addition, the thesis is based on certain assumptions due to the lack of data. It is also important to acknowledge the limitations of the study and potential sources of uncertainty that may affect the results. In the case of the sport tape LCA, the assumptions made regarding the location of production and the use of secondary data may introduce some uncertainties, but as long as they are clearly stated and justified, the study can still provide valuable insights for the improvement of the product's environmental performance.

Initially, it was assumed that China is the main country involved in the production of sport tapes, however, in reality, other countries are also involved in this process. For the sake of simplicity, the assumption was made that China is the reference nation, and therefore, transport, energy, and emissions were considered to be from China.

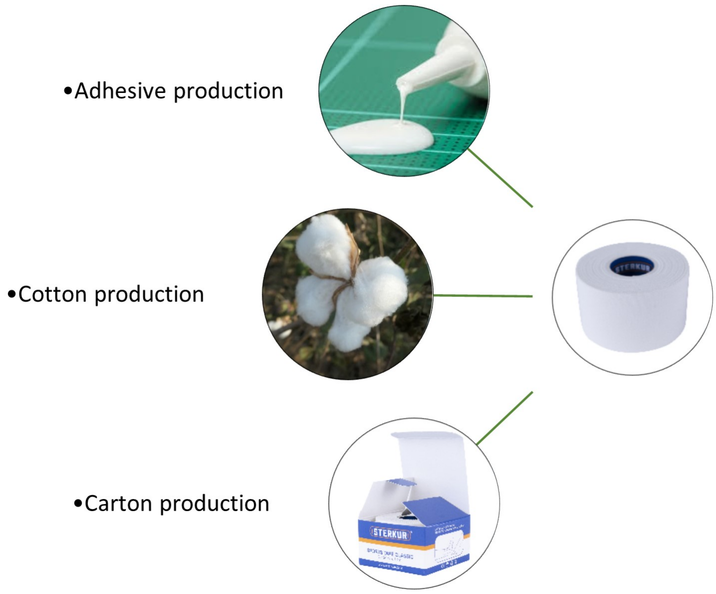


Figure 4.3: Flow chart of a sport tape by Sterkur.

The process of collecting data involved obtaining primary data from Sterkur regarding the quantities of materials used in the production of the sport tape, including the assembly of cotton and adhesive to create the tape and the carton's quantity. In cases where primary data was not available, secondary data was sourced from literature and databases related to upstream processes involved in the production of materials such as cotton, adhesive, and carton, as well as downstream processes like tape incineration.

For certain aspects of the study, secondary data was sourced from literature related to condom production in Europe, which included information on energy consumption and emissions. In cases where the Environmental Footprint database did not contain relevant data, the Ecoinvent database was used as an alternative source of information. Additionally, for processes where data was only available in a global context and not specific to China, the global data was considered. Transportation, emissions, and energy were also taken into account for selected processes in the database.

4.2.3 *Impact categories*

Several impact assessment methodologies can be applied in the European context, such as Environmental Footprint, CML, ReCiPe, and selected methods recommended by the ILCD.

The Environmental Footprint (EF 3.0) method was used in this thesis.

The results obtained from the LCA analysis are divided into indicators, which synthesize the environmental effects associated with the materials and energy flows in the input/output of the study system. The environmental indicators used in the thesis are in the Table 4.1.

Indicator	**Description**	**Unit**
Climate change	A measure of greenhouse gas emissions such as CO2 and methane. These emissions are causing an increase in the absorption of radiation emitted by earth, increasing the natural greenhouse effect	kg CO2 equivalent
Climate change-land use and land use change	Representation of the occupation of land. It is a sub-category of climate change.	kg CO2 equivalent
Acidification	Potential acidification of soils and water due to the release of gases	kg mol H+
Eutrophication-freshwater	It indicates the enrichment through nutritional elements of the freshwater ecosystem, due to the emission of nitrogen or phospor containing compounds	kg P-eq
Eutrophication–marine	It indicates the enrichment through nutritional elements of the water ecosystem, due to the emission of nitrogen containing compounds	Kg N eq
Eutrophication– terrestrial	It indicates the enrichment through nutritional elements of the terrestrial ecosystem, due to the emission of nitrogen containing compounds	mol N eq
Water use	Indicates the water involved, directly and indirectly in any phase of product's life. It includes the groundwater, river and surface water used for irrigation.	m3 world deprived

Table 4.1: Reference indicators used for the interpretation of the results.

Chapter 5

Sport tape: Life cycle inventory

5.1 Production Phase

To start the LCI, Sterkur provided the weights of each component of one sport tape, that weights 84.7 g, as shown in the Figure 5.1.

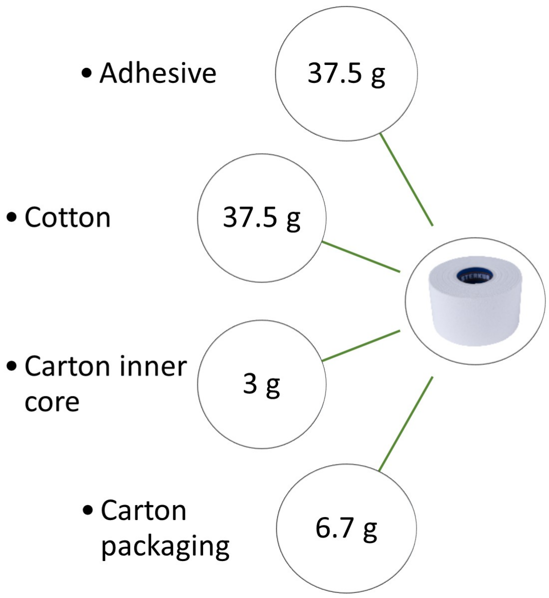


Figure 5.1: Sport tape's components' weights.

5.1.1 *Adhesive*

The adhesive used by Sterkur undergoes several processes before becoming part of the sport tape. However, due to the lack of information on the production process of the adhesive from the company, obtaining data on the adhesive used was a major challenge during the thesis.

Despite this, through extensive research, it was discovered that the adhesive used in Sterkur's tape is cement rubber. Cement rubber is a mixture of solid rubber in a volatile solvent that dissolves it. When the cement is applied, the solvents evaporate, leaving the rubber as the adhesive.

The adhesive used by Sterkur is a solvent-based pressure-sensitive adhesive formulated with natural rubber, hydrocarbon resins, synthetic rubbers, calcium carbonate, and zinc oxide emulsified with aliphatic and aromatic hydrocarbon solvents. The solvents used are heptane and toluene, where at the beginning of the process, the solids make up 71% +/- 3% of the adhesive's weight, while the liquids make up the remaining 29%, which are solvents.

The adhesive itself weighs 37.5 g and has the percentages of components listed in the Figure 5.2 before being mixed with solvents. Instead, the calcium carbonate and zinc oxide are not considered in the thesis because they would be a very low amount and data are not available neither from Sterkur, nor from literature.

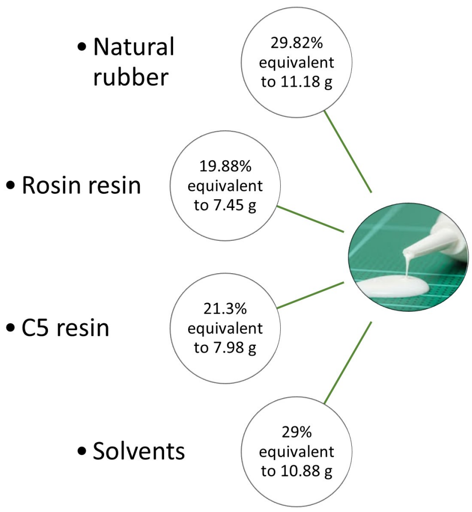


Figure 5.2: Percentages of adhesive's components in liquid form.

After exposure to high temperatures, the solvents in the adhesive evaporate, causing the liquid part to disappear. As a result, the solid part of the adhesive becomes 100% of its composition. This is illustrated in the Figure 5.3, which shows the composition of the adhesive in its solid form.

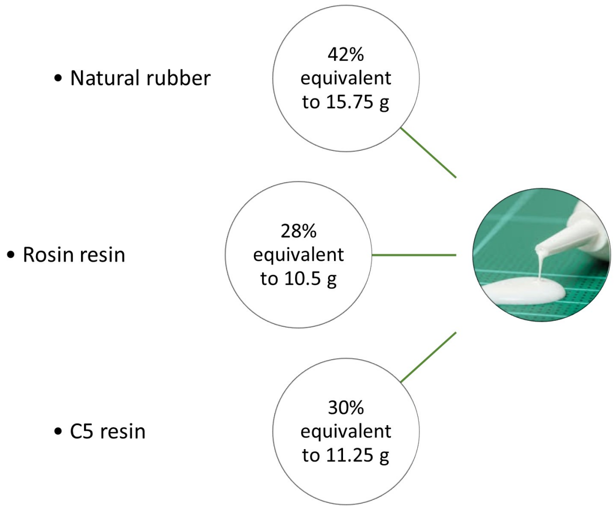


Figure 5.3: Percentages of adhesive's components in solid form.

Natural rubber

The latex that forms the basis of the Sterkur adhesive is a crucial component. It is sourced from the natural rubber tree, Havea brasiliensis, which is mainly grown in China. Rubber trees are fast-growing, perennial crops that occupy a relatively small area compared to other land-use types. The trees take around seven years to mature before they can be tapped for their latex.

Figure 5.4: Rubber trees in China, picture taken by Sterkur.

The importance of natural rubber is increasing due to its high level of supplier country concentration, with 91% coming from just five countries on two continents. It is a global requirement with the growth of the economy and is essential for the European industry, particularly for vehicle tires. The natural rubber industry is heavily dominated by micro farming.

However, there are also some disadvantages associated with natural rubber. There is a weak supply and demand equilibrium, a long supply chain with many intermediaries, and very limited traceability. The supply is also heavily impacted by climate change, disease, and trade disruptions, which can result in significant volatility. Moreover, there is high environmental pressure on limited geographical areas.

Considering the high import dependency and significant identified risks of supply disruptions, natural rubber "is a critical raw material for the future" [1]. It is economically and strategically important for the European economy, but there is a high-risk associated with its supply. [2]

Thanks to the archive version "Growth and production of rubber" [3] the entire process that the rubber plant undergoes to become latex is known. Rubber trees have similar growth requirements to oil palm and are often grown in the same areas. The trees need deep soils, stable high temperatures, and continuous moisture, while soil fertility is less important than physical soil properties.

Annual rainfall in the region where latex is harvested should be between 1,800 and 2,500 mm and remain continuous throughout the year, except for a 2-3 month low-rainfall season. Rubber crops tolerate a variety of soils, but well-drained and well-aerated, permeable soils with a loamy or sandy clay texture are preferred. On slopes above 5%, contour planting is recommended, while slopes above 25% should not be planted.

Nitrogen is usually supplied by a leguminous cover crop or by the mineralization of organic matter in the soil. For immature rubber, total fertilizer application over the first six years from planting is around 200-250 kg N/ha, 250-260 kg P2O5/ha, 130-170 kg K20/ha, and 20-50 kg MgO/ha, depending on the soil type and cover crop. Fertilizer recommendations for mature rubber (year 7 to 25) are estimated at 15-25 kg N/ha/year, 20 kg P2O5/ha/year, 60-150 kg K2O/ha/year, and 10 kg MgO/ha/year (IFA, 1992). In order to generate income during the first year of establishment, most small rubber plantations utilize an intercropping system with food crops.

To collect the latex from the rubber trees, a system called tapping is used. During tapping, an anti-coagulant is added to the latex and it flows into a cup fixed to the tree, which can hold either 500 ml or 1200 ml of latex. The tapper usually begins the cuts in fixed number of trees and returns to the first trees after 5 to 6 hours, once the latex flow has stopped. The combination of latex and cup dregs is used to collect the latex, as it is shown in the Figure 5.5.

Figure 5.5: Latex cup dregs system, picture taken by Sterkur.

After the latex cups are filled with rubber, they are emptied into a bucket and brought to a collection point where the thickness of the latex is measured using a density meter. The latex is then filtered and stored in tanks made of aluminum or galvanized iron. If necessary, ammonia is added to prevent coagulation caused by rain. Once the collection tank is full, it is transported to the factory for processing. Ammonia is added to the tank to stabilize the latex during transport.

At the factory, the latex is measured for the amount of anti-coagulant used and the amount of ammonium is adjusted in the storage tanks. The latex may be diluted with water to obtain a constant dry rubber content. The normal percentage of high rubber content in concentrated latex is around 60%. The latex is homogenized in large containers with a capacity of 5000 to 20000 liters and manufactured into different commercial products.

In certain industries, such as the surgical field and the makers of adhesive, concentrated liquid latex is preferred. To create the concentrated latex, the harvested latex is centrifuged to expel the serum or aqueous substances. The separation process is based on different specific gravities of the various components. Finally, the latex is stabilized by adding ammonia.

There are two processes involved in obtaining natural rubber: production of fresh latex and production of concentrated latex. The first process, which was previously referred to as "Natural rubber, at plant, production mix, per kg," includes various activities such as fertilizer application, land use, transportation, and direct emissions. The inputs and outputs of this process are depicted in the Figure 5.6.

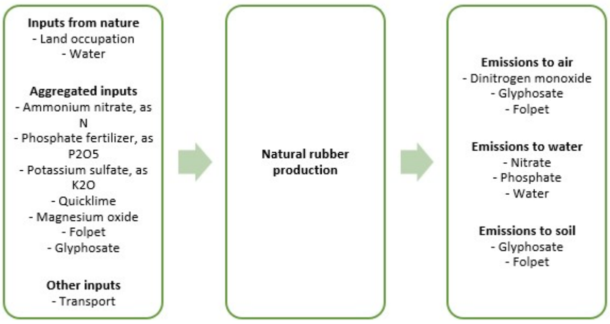


Figure 5.6: Natural rubber production from Ecoinvent database.

However, the subsequent processes of preparing ribbed smoked sheets and drying them in a smoked house were not considered in Sterkur's analysis, as the latex arrives at the facility in liquid form to create adhesive.

Instead, Sterkur focuses on the vulcanization and molding processes after obtaining the concentrated liquid latex. Vulcanization is performed to improve the mechanical and electrical properties of the rubber, enhancing its rigidity, durability, lifespan, function, and strength. On the other hand, molding involves the transformation of rubber into a usable product by compressing, transferring, or injecting raw material into a metal mold cavity.

In the absence of a proper dataset, to analyze the concentrated liquid latex, the Life Cycle Assessment of a natural rubber condom was referred to [4] . The condoms in this case are produced in Malaysia and sent to Germany.

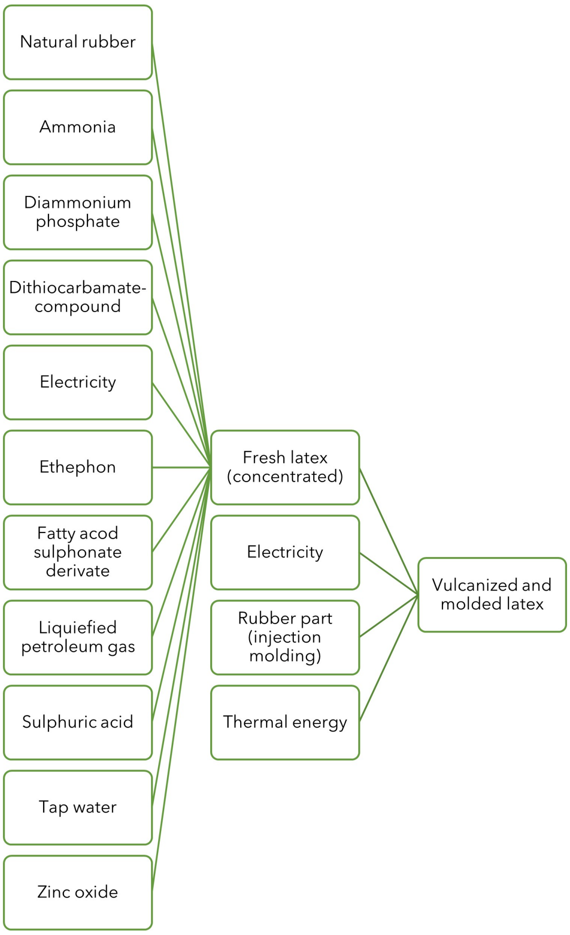


Figure 5.7: Overall picture to achieve the vulcanized and molded latex, next to be mixed with the rest of adhesive's components. Taken from the Life Cycle Assessment of a natural rubber condom [4].

Starting from the natural rubber production, the input and output flows used in the LCA model, with relative quantities and reference dataset are reported in the Table 5.1.

Output flows	**Quantity**	**Unit of measure**	**Reference Dataset**
Fresh latex (concentrated)	1	t	
Skim block rubber	0.06	t	(Ecoinvent)
Wastewater	6.20	m3	Water (waste water, treated) (EF)
Unspecified mass	0.01	t	Waste (unspecified) (EF)
Input flows			
Fresh dried latex	2.17	t	Natural rubber production mixed at plant (EF)
Water	5.09	m3	Tap water technology mix at user (EF)
Electricity	93.44	kWh	Electricity grid mix 1 kV-60kV, consumption mix, to consumer, AC, technology mix – CN (EF)
DAP (for magnesium precipitation)	2.17	kg	Diammonium phosphate at plant (EF)
Ammonia	4.33	kg	Ammonia, as 100% NH3 production, production mix, at plant, technology mix, 100% active substance (EF)
Tmtd	0.28	kg	Dithiocarbamate-compound RER| production | Cut-off, S (Ecoinvent)
Lauric acid	1.08	kg	Fatty acid RER| fatty acid production, from coconut oil | Cut-off, S (EF)
Sulfuric acid (coagulant)	4.33	kg	Iron oxide, yellow pigment, Production mix, at plant, Technology mix, Fe III oxide (EF)
Ethephon	0.51	kg	Ethephon (emission in soil) (Ecoinvent)

Table 5.1: Fresh concentrated latex inventory.

Thanks to the Polito's report it has been possible knowing the electricity consumption for the vulcanization of the latex, based on the *Pirelli patent (2005)*, which estimation is 2.14 kWh per kg, and the heat, thanks to the report by the *Department of Alternative Energy Development and Efficiency (2007)*, that corresponds to 0.68 MJ per kg.

In the Table 5.2 the inventory is reported to proceed to vulcanization and molding's process.

Output flow	Quantity	Unit of measure	Reference Dataset
Vulcanized and molded latex	0.01118	kg	
Input flows			
Fresh latex (concentrated)	0.0118	kg	See the Table 5.1
Injection moulding	0.0118	kg	Injection moulding rubber, production mix, at plant, plastic injection moulding – EU-28+EFTA (EF)
Thermal energy	0.68*0.01118	MJ	Thermal energy from natural gas, production mix, at heat plant – CN (EF)
Electricity	2.14*0.0118	kWh	Electricity from natural gas, production mix, at power, at power plant, AC. Mix of direct and CHP, 1 kV-60kV – CN (EF)

Table 5.2: Inventory to vulcanize and mold the latex before mixing with solvents.

Rosin resin

There are 3 species of pine that are available for rosin production. They are Pinus roxburghii, Pinus wallichiana, Pinus keysia. However, only chir pine (Pinus roxburghii) is widely used for resin on commercial base.

The way of harvesting is to tap standing pine trees, that is, making a cut which exposes the surface of the wood, and the resin will flow out. There are 4 methods of tapping pine trees, which are (chronological order):

1. Box method (most damaged one).
2. Cup and lip method.
3. Rill method (improved one).
4. Bore hole method (least damaged and latest one).

The crude resin collected from the pine trees will be heated at 95°C for 4-5 hours after bigger-sized impurities are removed. Further, the crude resin will be filtered to remove smaller-sized dirt and particles. The resin is then cooked in the distillation kettle for 1-2 hours by indirect steam. The molten resin remains inside the copper tubes and steam remains in the outside. In this process the turpentine oil and moisture present in the resin get evaporated and condense in the condenser. Turpentine oil is collected in a separator. The rosin left in the distillation kettle is taken out at 165°C and collected. Rosin chiefly consists of various resin acids, especially abietic acid. Abietic acid will be polymerized. Such polymerizations are typically carried out in solvent like ethanol, acetone, and ether(solvent-based), to produce a water-resistant, homogenous coating.

In the sport tape the main components of the adhesive are natural rubber and tackifier (both natural and synthetic). In this case natural tackifier is rosin resin and synthetic tackifier is C5 petroleum resin (see next paragraph).

At room temperature, natural rubber is blended with tackifier to produce permanent tack. Zinc oxide was added to accelerate esterification (for polymerization of abietic acid) of rosin.

Afterwards, the adhesive is coated onto the fabric (here the white sport tapes) to provide strength and protect the adhesive from degradation by environmental factors including humidity, temperature, and ultraviolet light.

In Ecoinvent database the rosin resin was found referring to the production of paper, because it is typically used for this purpose. So it was approximated to this use.

Flow	**Quantity**	**Unit of measure**	**Reference Dataset**
Rosin resin	7.45	g	Rosin size production, RoW (Ecoinvent)

Table 5.3: Rosin resin inventory.

C5 resin

The C5 resin is an aliphatic hydrocarbon resin, made from C5 piperylene and its derivatives. C5 resin is aliphatic in nature and is, fully compatible with natural rubber, most olefins, and many specific elastomers of low polarity. It has a light yellow to light brown color and possess excellent heat stability.

Hydrocarbon resins are used as tackifiers, performance modifiers and homogenizing agents. They are most often use for the manufacture of rubbers, coatings, printing inks and adhesives (particularly synthetic rubbers that are less tacky than natural rubber).

Mostly, they are selling for hot melts, PSA tapes and labels. Thanks to "polymerdatabase.com" it was found that the aim of these resins is to improve tack, peel strength and increase the glass transition temperature which gets better shear strength, they reduce VOCs and provide improved mildew and water resistance.

In the available databases the specific C5 resin is not present, but it has been substituted with the C9 resin, which has similar properties.

The C9 has a low molecular weight, as C5, and is an aromatic hydrocarbon resin. Its composition depends on hydrocarbon feedstock. Compared to C5 resin, it has a much higher melt viscosity, is of darker color and has softening point ranging from about 100 to 150°C. C9 resin is versatile and compatible with many polymers.

C5 and C9 resin are commercially available, these are often colorless and have improved heat and color stability, they are more expensive and thus, only used if superior heat and color stability is necessary.

Flow	**Quantity**	**Unit of measure**	**Reference Dataset**
C5 resin	7.98	g	Aromatic hydrocarbons, C9-C16; technology mix; production mix, at plant; BP 165-290°C (EF)

Table 5.4: C5 resin inventory before mixing with solvents.

5.1.2 *Cotton*

Sterkur sources its cotton for the sport tape from China, which is the largest producer of cotton in the world. The primary growing regions in China are the Northwest, Yellow River Basin, and Yangtze River Basin, where farmers cultivate upland cotton (Gossypium hirsutum) and long staple cotton (G. barbadense). The cotton growing season in China typically experiences daily air temperatures ranging from 18-25°C.

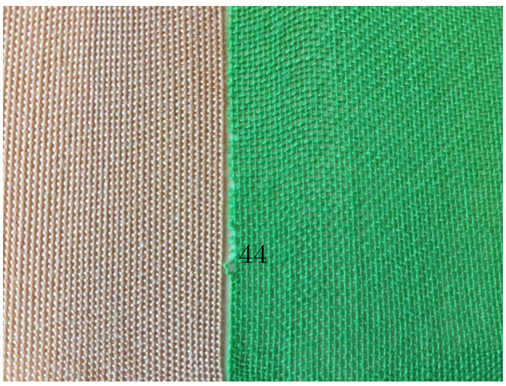
Figure 5.8: Closed Chinese cotton, picture taken by Sterkur.

The production process of woven cotton for the market begins with the cultivation of the seed, which grows into a plant, and then harvests by hand - Figure 5.9a- followed by the formation of fibres which are transported to the farm – Figure 5.9b- , then spun into yarn - Figure 5.9c, and finally woven into textile to create the finished cotton product - Figure 5.9d.

(a) *Cotton harvesting by hand, China, picture of Sterkur's founder*

(b) *Picking cotton from the ground to the farm, picture taken by Sterkur*

(c) *Yarn cotton, picture of "craftsbliss.com"*



(d) *Textile woven cotton, picture taken by Sterkur*

Figure 5.9: Cotton chain.

This chain is shown in the Figure 5.10 in terms of components involved.

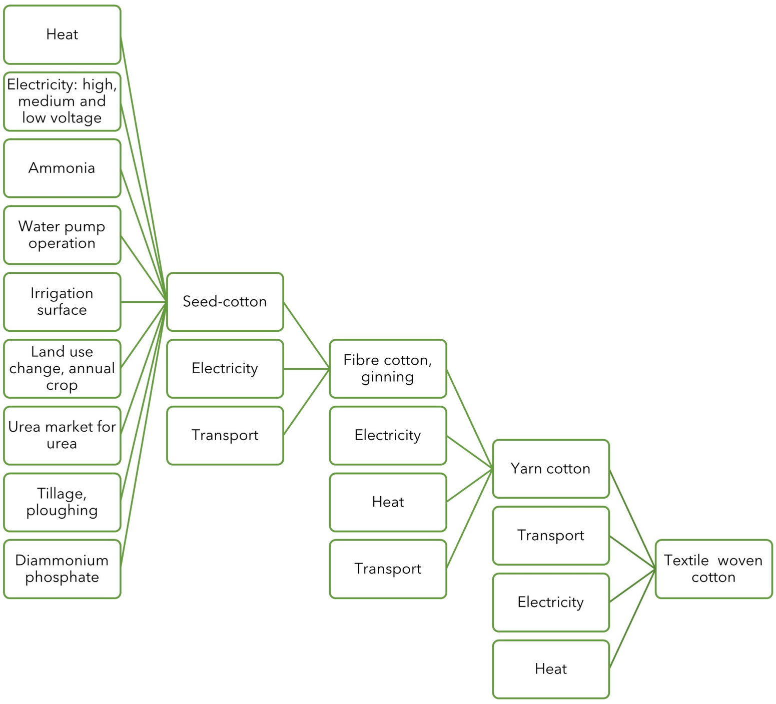


Figure 5.10: Textile woven cotton supply chain.

The inventory is reported in the Table 5.5 , where the processes reported in the upper Figure **??** are implied and the cotton is taken with respect to a global average, because China is not present in the EF and Ecoinvent datasets.

Flow	**Quantity**	**Unit of measure**	**Reference Dataset**
Woven cotton	37.5	g	1 kg Textile, woven cotton GLO| market for | Cut-off, S (Ecoinvent)

Table 5.5: Inventory of woven cotton for the production of one tape.

5.1.3 *Solvents*

The adhesive used in the sport tape manufactured by Sterkur contains solvents, which make up 29% of the adhesive's composition before being mixed with the other components. These solvents evaporate during the process of mixing and coating the sport tape through a coating machine.

The solvents used in the sport tape are heptane and toluene. Heptane belongs to the alkane group and is almost insoluble in water. It is an excellent solvent for non-polar substances, fats, and oils, and is commonly used in the production of paints, varnishes, and adhesives. Some synthetic rubbers are also produced in solution using heptane.

Toluene, on the other hand, is a volatile organic compound that consists of carbon and hydrogen. It is a colorless liquid at room temperature and pressure and can naturally occur in fossil fuels [5] .

Toluene is commonly found in different consumer products such as adhesive tape, buttons made of polystyrene-based resins, and products made of synthetic leather. It is typically used in the production of paints, rubbers, lacquers, glues, and adhesives to aid in the drying, dissolving, and thinning of other substances.

Since Sterkur does not provide specific quantities of each solvent and literature does not provide clear information, it has been assumed that they are equally divided. Materials entering the process are included, as well as energy uses, infrastructure, transports, and emissions.

Flows	**Quantity**	**Unit of measure**	**Reference Dataset**
Heptane	5.44	g	Heptane GLO| market for | Cut-off, S (Ecoinvent)
Toluene	5.44	g	Toluene production, production mix, at plant, technology mix, 100% active substance (EF)

Table 5.6: Solvent inventory for the production of one tape.

5.1.4 *Carton*

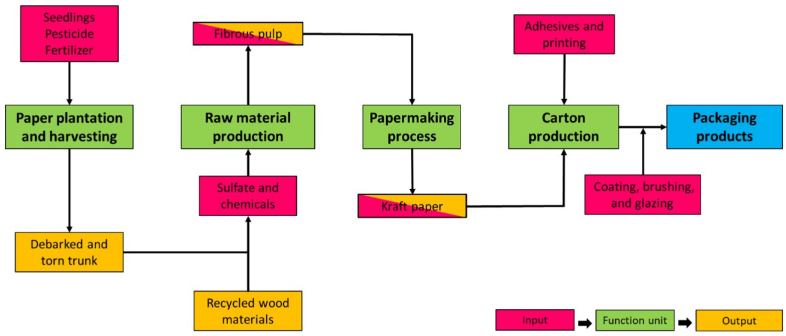


Figure 5.11: Production chain of carton. Boxes in green are the 4 different phases. Boxes in red are the resource used for production and processing, and boxes in yellow. Picture taken by Sterkur.

Carton is one of the most important packaging materials for the products. One of the functions of it is to contain and to stabilize the allocation of the products. Sterkur uses two kinds of carton: one is the big outer carton named corrugated container, and the other is the small inner carton box named paperboard box. The fluting structure of corrugated container serves as a stable cushion for the products through long-distance transportation. The paperboard boxes contain the products individually.

In the first phase of paper plantation and harvesting, seedlings are planted and cultivated with the assistance of pesticides and fertilizers (varied by places). Trees are harvested and stripped before shipped to the paper mill.

In the second phase of raw material production, chemicals are added to break down wood chips to form virgin fibrous pulp during raw material production. The third phase is the papermaking process. Kraft paper is made after the pulp being cleaned, refined, and dried in a paper machine.

In the last phase of carton production, adhesives, and printing as well as additives are added. For corrugated containers, corrugator is used to make kraft paper fluted and transform it with other unfluted Kraft paper into corrugated containers.

For paperboard boxes, the paperboard machine stacks layers of kraft paper with different composition and properties of pulp. Pressing and drying processes then reduce the water content of the paperboard. The final steps of coating, brushing, and glazing will make the final product of paperboard.

Figure 5.12: Final packaging of Sterkur sport tape, picture taken by Sterkur.

In the software, the flows considered are in the table below.

Flows	**Quantity**	**Unit of measure**	**Reference Dataset**
Carton inner-core	3	g	Carton box, production mix, at plant, Kraft Pulping Process, pulp pressing and drying, box manufacturing, CN
Carton packaging	6.7	g	Carton box, production mix, at plant, Kraft Pulping Process, pulp pressing and drying, box manufacturing, CN

Table 5.7: Carton inventory for the production of one tape.

5.1.5 *Sport tape*

The raw components used to produce the sport tape are transported to the main facility located in Nantong, China. Here, the latex and resins are blended together to create the adhesive mixture. The adhesive is then mixed with a solvent compound in a barrel - Figure 5.13, and the cotton arrives at the facility as a textile material.

Figure 5.13: Barrels of adhesive and solvents, picture taken by Sterkur.

The final step in the production process involves the coating procedure using the Coating Machine reported in the website "*Ofuri.com*", also known as Pilot.

In the Figure 5.14 provided, the left green cells represent the flows involved in creating the adhesive mixture, while the red cell encompasses the flows related to the coating process.

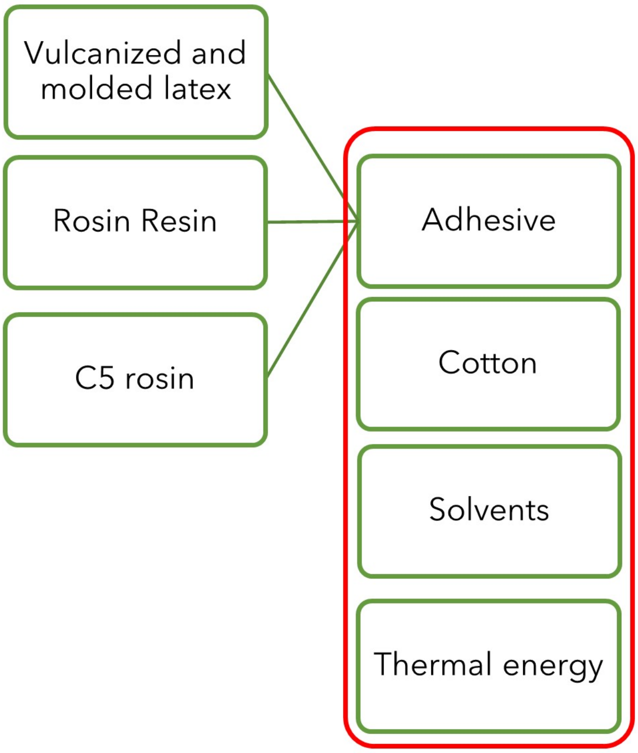


Figure 5.14: Scheme of the last processes to create the sport tape.

The machine applies layers of cotton, adhesive, and solvents to create the sport tape. The cotton passes through the machine, where the adhesive and solvents are applied. The machine is equipped with multiple heating components that induce three different temperatures to allow the solvents to evaporate from the adhesive. This process results in the complete evaporation of the liquid part, leaving behind a 100% solid product.

The Table 5.8 shows the inputs and outputs for the LCA model. It has been determined that the solvents evaporate during the coating process, which means they are emitted into the air.

Output flows	Quantity	Unit of measure	Reference Dataset
Coated tape	75	g	
Heptane	5.44	g	Emissions to air (Ecoinvent)
Toluene	5.44	g	Emissions to air (Ecoinvent)
Input flows			
Vulcanized and molded latex	0.0118	kg	See Table 5.2
Rosin resin	7.45	g	See Table 5.3
Aromatic hydrocarbon C9-16 Resin	7.98	g	See Table 5.4
Thermal energy	45/1044	kWh	Energy carriers and technologies/heat and steam (EF)
Solvents	10.88	g	See Table 5.6

Table 5.8: Inventory for the coating process of a sport tape.

The power of the coating machine corresponds to 45 KW, and it produces 6 meters of sport tapes per minute, so 360 meters per hour.

The rolls contained in 10 meters are 29, to obtain the rolls produced in one hour:

$$36 \text{ meters}*29 \text{ rolls} = 1044 \text{ rolls per hour}$$

The coating machine produces 1044 rolls per hour by 45 KW power.

The final stage involves the use of cutting machine - Figure 5.15 - to separate the tapes. However, the electricity consumed during this process was not included in the LCA analysis as it was considered negligible by Sterkur. Additionally, no waste is generated during this step.

Figure 5.15: Cutting machine, picture taken by Sterkur.

The Table 5.9 shows the data used for the inventory of the final sport tape, which weighs 84.7 grams and includes information on packaging and transportation. The tapes are transported from Nantong, in China to the port of Shanghai, where they are carried by barges to the port of Rotterdam, a distance of approximately 22223 kilometers. From Rotterdam, the tapes are transported by lorry to Sterkur's storage in Amsterdam, which is approximately 80 kilometers away.

Output flow	**Quantity**	**Unit of measure**	**Reference Dataset**
Sport tape	84.7	g	
Input flows			
Sport tape (coating process)	75	g	
Carton packaging	6.7	g	See Table 5.7
Carton inner core	3	g	See Table 5.7
Transport by ship	0.08470*222223	kg*km	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo – GLO (EF)
Transport by lorry	0.08470*80	kg * km	Articulated lorry transport, Total weight 7.5-12 t, mix Euro 0-5, consumption mix, to consumer – EU- 28+3 (EF)

Table 5.9: Sport tape's inventory.

Finally, the tapes are sold to customers either through the company's website, with 5% going to Belgium and 95% to the Netherlands, or directly to physiotherapists using DHL. However, the transports during this process was not included in the LCA analysis as it was considered negligible by Sterkur.

5.2 Use and Disposal Phase

The use of sport tape has minimal impact during its use phase, as it only needs to be applied to the ankle once. Consequently, it is excluded from the Life Cycle Assessment (LCA).

However, it must be disposed of properly after use. Due to hygiene concerns (blood and sweat), sport tape cannot be reused or recycled and should be discarded in residual waste bins for incineration in the Netherlands. In the country, all waste incineration facilities are categorized as Waste-to-Energy (WtE) plants, which produce electricity and heat by burning waste.

The Dutch waste management policy mainly focuses on incineration, with the landfilling of municipal solid waste being prohibited. The high population density and limited availability of land in the country contribute to this emphasis.

It is practically impossible to avoid waste management, as it would accumulate in homes and businesses. Landfilling is no longer a viable option due to its impact on the environment, which includes hazardous pollution of the air, water, and soil. The least preferred option for waste disposal is to discharge waste into water bodies or bury it in landfills, both of which lead to environmental degradation. [6]

EU Directive 2008/50/EC contains air quality legislation, which is transposed into Dutch national law through the 'Wet Milieubeheer.' The directive aims to minimize the negative effects of ambient air pollution on human health and the environment. Member States are obligated to monitor and evaluate ambient air quality and make this information accessible to the public.

The following Table 5.10 outlines the input and output flows associated with the disposal phase of the tape. These flows are used to assess the environmental and human impacts resulting from incinerating the tape.

Output flow	**Quantity**	**Unit of measure**	**Reference Dataset**
End-of-life sport tape	0.08470	kg	
Incineration good	0.08470	kg	Wastes
Input flows			
Sport tape	0.08470	kg	See Table 5.9
Trasport	0.08470*30	kg*km	Articulated lorry transport

Table 5.10: Inventory of the end-of-life of a tape.

Chapter 6

Sport tape: Life Cycle Impact Assessment method

6.1 Production phase

The impact assessment is an important step in evaluating the environmental performance of a product. It involves translating the data from the inventory analysis into impact indicators that are understandable and relevant to decision-makers. The LCIA methodology follows a set of guidelines provided by ISO 14040 and ISO 14044, which ensure a standardized and consistent approach to impact assessment.

In this thesis, the Environmental Footprint Mid-point indicator has been used as the impact assessment method. This method predicts indicator values based on the emissions generated during the life cycle of the product.

It is important to note that LCIA results are potential impacts and should not be used to predict actual impacts, safety margins, or risks. However, they can be used to identify areas for improvement in the product's life cycle.

So, the overall indicators and relative results of the production of one sport tape are in Table 6.1.

To gain a better understanding of the impact categories and which process has the greatest impact, the Figure 6.1 reports the indicators of the tape production.

Indicator	**Impact result**	**Unit**
Climate change	0.56767	kg CO2 equivalent
Climate change-land use and land use change	0.04545	kg CO2 equivalent
Acidification	0.00665	mol H+ eq
Eutrophication, freshwater	0.00028	kg P eq
Eutrophication, marine	0.00781	kg N eq
Eutrophication, terrestrial	0.02413	mol N eq
Water use	6.46857	m3 deprivation

Table 6.1: LCIA of the production of one sport tape.

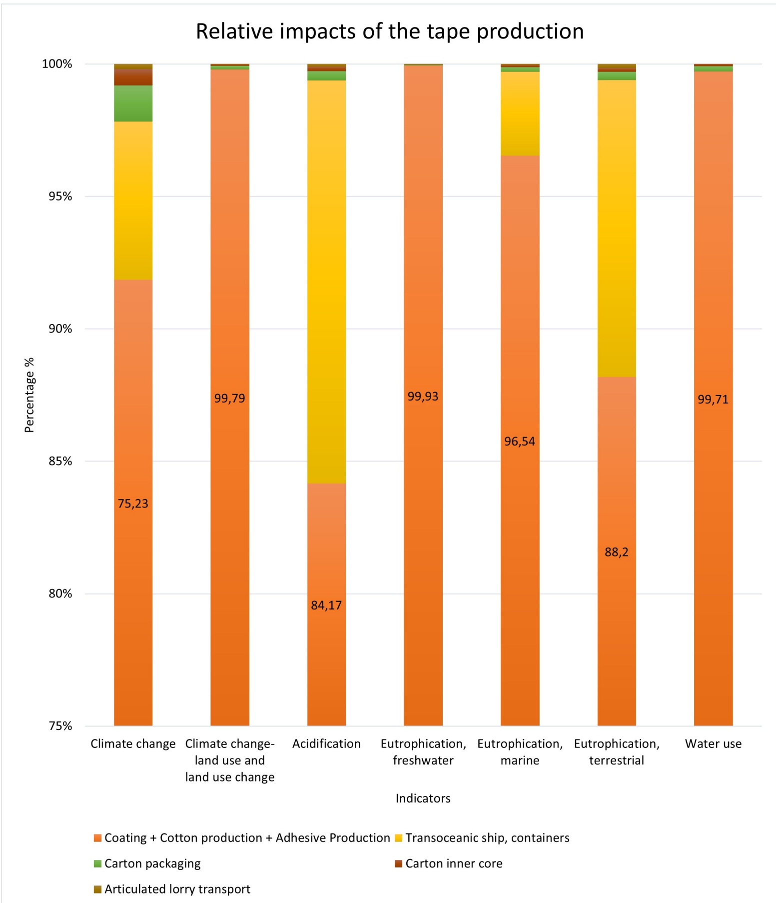


Figure 6.1: Impacts for the production of a sport tape.

The analysis of all the impact categories indicates that the cotton and the adhesive production with the coating have the greatest environmental impact.

The transport with transoceanic ship has a limited impact on *climate change* (almost 5% of the total impact), while the packaging and the transport by lorry result having negligible impacts for all the analyzed impact categories. The coated cotton with the adhesive has been further analyzed to determine which material and corresponding process has the most significant impact.

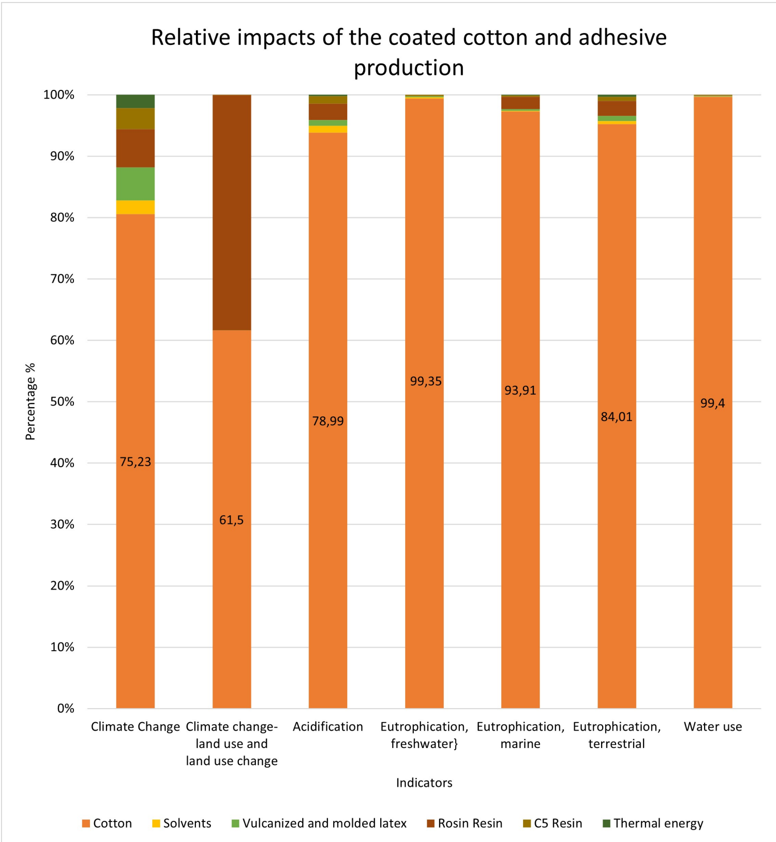


Figure 6.2: Impacts of the production of the coated cotton and adhesive.

According to the results, cotton has the highest impact on categories among all the materials used in the sport tape.

The JRC Technical Reports, "*Suggestions for updating the Product Environmental Footprint (PEF) method*" [7] , provided valuable information on the most robust categories.

As a result, the categories that were identified as the less robust (see Appendix A.1) were excluded, and the robust (type I, see Appendix A.3) and medium (type II, see Appendix A.2 and A.3) were taken into account . Consequently, the analysis focused on *climate change* (as a robustness type I), *acidification*, and the three categories of *eutrophication* (as robustness type II).

6.2 Comparison between production and end-of-life

Tables have been generated to provide further analysis of the impact of cotton throughout the entire lifespan of the sport tape.

The Tables 6.2 , 6.3 that follow, list the entire life cycle of the sport tape, which encompasses the previously reported production stage and the end-of-life phase (incineration of the sport tape).

Finally, they display the overall result of sport tape that incorporates all of the aforementioned components.

Indicator	**Cotton production**	**Sport tape (cotton+ adhesive+ coating+ packaging)**	**Unit of measure**
Climate change	0.42704	0.56767	kgCO2 eq.
Climate change - Land use and land use change	0.02795	0.04545	kgCO2 eq.
Acidification	0.00525	0.00665	mol H+ eq
Eutrophication, freshwater	0.00028	0.00028	kg P eq
Eutrophication, marine	0.00733	0.00781	kg N eq
Eutrophication, terrestrial	0.02027	0.02413	mol N eq

Table 6.2: Environmental impacts of a sport tape during the production phase of its life cycle. The contribution of cotton production is highlighted in the first column.

Indicator	**Incineration**	**Sport tape Life cycle (from cradle-to-grave)**	**Unit of measure**
Climate change	0.1782	0.74621	kgCO2 eq.
Climage change - Land use and land use change	-4.67751E-6	0.04545	kgCO2 eq.
Acidification	-0.000225	0.00643	mol H+ eq
Eutrophication, freshwater	-7.51655E-8	0.00028	kg P eq
Eutrophication, marine	-4.40749E-5	0.00777	kg N eq
Eutrophication, terrestrial	-0.00038	0.02375	mol N eq

Table 6.3: Environmental impacts of a sport tape during the entire life, from cradle-to-grave. The contribution of incineration is highlighted in the first column.

The impact of waste incineration on the environment is evident in the case of *climate change*, with a contribution of 23.88% in relation to the entire life of the sport tape.

This means that waste incineration during the end-of-life phase contributes to the impact of the sport tape on *climate change*.

However, it is worth noting that this impact is specific to the *climate change* impact category and may not necessarily be reflected in other impact categories. The negative results of incineration, related to the other indicators, are due to the positive impact that it has on environment.

Since in the Netherlands, all waste incinerators are referred to as Waste-to-Energy (WtE) plants, the facilities generate electricity and heat by burning waste.

Compared to alternative energy sources, which are often based on fossil fuels, WtE plants can prevent externalities associated with such energy sources.

This has been a significant selling point for waste incinerators that incorporate energy recovery, as opposed to relying on landfills.

Chapter 7

Interpretation and Improvement

The cotton used in the LCA analysis is the woven cotton from Ecoinvent database, which represents a consumption mix of product in a given geography, connecting suppliers with consumers of the same product in the same geographical area. This cotton is a natural textile made through weaving and is unprocessed.

The activity ends with the supply of "textile, woven cotton" to the consumers, and transport is included while losses during transportation are assumed negligible and not included in the analysis. A global average for cotton as a market activity was used in the analysis because specific data for Chinese cotton was not available, and since Sterkur sport tape is made with traditional cotton, a conventional global average data was chosen.

Although natural sources of sport tape have relatively low impacts, there is still room for improvement to make the product more sustainable.

A study conducted in June 2021 [8] suggests that by 2040, half of the world's cotton growing regions could face drastic changes to temperatures and water availability, and exposure to extreme weather events, if carbon emissions continue to soar.

Raw material extraction accounts for 23% of total apparel and footwear GHG emissions, and cotton, which accounts for 24% of total fiber by volume, is estimated to be responsible for 14% of these emissions.

Agriculture is also contributing to the loss of topsoil, and an estimated 1/3 of the world's soil is already degraded.

7.1 Conventional cotton

Water quantity

Cotton production can contribute to excessive water consumption if managed poorly, depending on the location and methods used.

On a global scale, the average water footprint of seed cotton is 3,644 cubic meters per tonne, equivalent to almost 1.5 Olympic swimming pools [9].

This water usage and pollution are affected by several factors, including the irrigation methods used, types and quantities of fertilizers and pesticides, and soil types. Around 60% of cotton is grown in irrigated fields, while 40% is grown under rain-fed conditions.

If not well managed, cotton production can significantly consume and pollute water resources. Irrigation farmers use groundwater and/or surface water, which can deplete freshwater resources if not regulated or managed properly, especially in regions experiencing water scarcity.

According to the first global analysis of climate risks to cotton production, water scarcity and extreme rainfall events are expected to increase the risk of cotton production in the most productive growing regions by 2040. Approximately 50% of global cotton-growing regions will be exposed to increased drought risk, exacerbating the already existing scrutiny on cotton's water footprint. This may impact yields, cause conflict, and societal unrest.

The use of fertilizers in cotton production can also lead to eutrophication, which is the enrichment of water with nitrogen and can impact drinking water sources for humans, animals, and aquatic life, similar to many other crops.

Use of pesticides and fertilisers

Figure 7.1: "Animal-drawn intertillage and fertilization" [10].

Cotton production can have significant environmental impacts when not grown sustainably. The "*cottonguide.org*" explains that cotton is the major user of pesticides and petroleum-based fertilizers, although their use has declined in recent years. Despite cotton occupying only 2.5% of the world's arable land, it accounts for 10% of all agricultural chemicals, including pesticides and fertilizers. In 2009, cotton producers represented 6.2% of total global pesticide sales and 14.1% of insecticide sales for all crops. The inappropriate use of pesticides and fertilizers can lead to water pollution, soil degradation, and harm to human health and biodiversity. Additionally, fertilizer production and use contribute to greenhouse gas emissions.

Incomes of smallholder farmers

The "*cottonguide.org*" explains that smallholder cotton farmers, who make up over 60% of the world's cotton production, are among the most impoverished and vulnerable populations worldwide. About 90% of these farmers, estimated at 100 million, are located in developing nations and cultivate cotton on plots of land smaller than two hectares.

Most smallholder cotton farmers live below the poverty line, earning insufficient income from the sale of their cotton to meet their basic needs, including food, healthcare, and tools. These farmers often have significant debts, largely due to high input expenses, such as fertilizers and pesticides. Coupled with other market dynamics, this can perpetuate the cycle of poverty for many.

More sustainable cotton has the potential to uplift millions of people out of poverty by providing stable income and better working conditions. Cotton is a critical rotation crop for smallholder farmers, used for fibre, fuel, and food, such as cottonseed oil. The cash income generated from cotton production is essential for improving their quality of life.

Forces labour and child labour

According to a 2016 report by the "*US Department of Labor*", child labor and forced labor were present in the cotton production process in 18 countries, including some of the top six cotton-producing nations, such as China, India, Pakistan, and Brazil. In 2018, the USA prohibited the import of cotton from Turkmenistan due to the discovery of state-enforced forced labor.

Soil depletion

Figure 7.2: Soil erosion, by " fao".

Similar to other crops, cotton farming practices can lead to various environmental issues such as land clearing, soil erosion, and contamination. These practices can cause a loss of soil biodiversity and fertility, which can ultimately result in productivity decline.

However, sustainable cotton production practices can help improve soil health and reduce greenhouse gas emissions through more sustainable farming methods. By implementing sustainable practices such as reduced tillage and cover cropping, farmers can prevent soil erosion and maintain soil fertility.

Adapting to land use pressures of the future

As "cottonguide.org" reports, the demand for food, water, and energy is projected to increase with the world population expected to reach 9 billion by 2030. This could pose a challenge to the feasibility of various crops, including cotton. The growing demand for food could increase by 40%, water by 35%, and energy by 50%, leading to increased pressure to shift land use from fibers, such as cotton, to food and fuel production.

Although the area under cotton cultivation has been decreasing, improved yields and productivity have been observed. Average global cotton yields have increased from 230 kilograms of lint per hectare in the 1950s to 780 kilograms of lint per hectare in 2013/14. Land use efficiency could further improve through better growing practices.

However, the impacts of climate change will increasingly affect the quantity and quality of cotton. Approximately 50% of global cotton growing regions face severe risks from more frequent floods, droughts, extreme heat, and storms if carbon emissions continue to rise. These challenges could create difficulties throughout the supply chain of agricultural commodities, including cotton.

Uncertain market

The price of cotton is subject to volatility, and this can be attributed to several factors such as national regulations, stockpiling, and government subsidies for farmers. This, combined with other uncertainties, can create an unpredictable market for farmers, making cotton less appealing to grow.

The financialization of cotton is a lesser-known problem that significantly affects the stability of cotton markets. While these markets were once used to manage risks, they are now seen as a source of profit in times of low returns in conventional stock markets and investments. As a result, significant fluctuations in price occur, creating instability in the cotton prices that farmers can receive at any given time. This is despite having no real connection to physical supply and demand.

7.2 Organic cotton

Figure 7.3: Organic cotton [11].

To address these issues, organic cotton can be used as a substitute for traditional cotton. Crop rotation, green manure, composting, reduced tillage, and recycling of crop residue in the soil can reduce soil erosion and enhance soil structure, making nutrients more easily available to crops and increasing the abundance of soil fauna.

In organic agriculture, chemicals are prohibited, and farmers use natural sources of fertility, such as compost, animal manure, green manure, and biodiversity to improve soil structure and water infiltration.

Organic cotton is predominantly grown by smallholder farmers as part of a rotation system with an average of nine other crops, while conventional cotton is grown as a monoculture and is heavily reliant on chemical inputs that are detrimental to biodiversity. Organic farming systems with better nutrient-retentive abilities greatly reduce the risk of groundwater pollution, and the higher amounts of soil organic matter in these systems result in improved water efficiency.

Organic farming practices offer a sustainable alternative to conventional farming by relying on natural processes, biodiversity, and cycles adapted to local conditions rather than external inputs that can have harmful effects on soil, ecosystems, and people. For example, instead of using synthetic nitrogen fertilizers that contribute to greenhouse gas emissions and affect soil and water quality, organic farmers utilize crop rotation and green manures to naturally build soil health.

By prioritizing place-based practices over external inputs, organic farming promotes the health of people and the land, offering long-term resilience over short-term yields. This approach ensures a sustainable future for every stakeholder in the global supply chain, from farmers to suppliers and brands.

Organic farming practices can reduce energy consumption by up to 30-70% per unit land by avoiding the use and manufacturing of synthetic inputs. [11]

Overall, organic farming practices have many benefits for the environment, soil health, and human health. They reduce energy consumption, improve soil structure and water infiltration, and reduce the risk of groundwater pollution. Organic cotton is grown as part of a rotation system with an average of nine other crops, which is beneficial for biodiversity. However, the conversion period to organic farming can be a significant burden for farmers, and access to non-GM seeds and organic inputs is limited. To move towards organic cotton production, it is essential to invest in research, farmer training, and improved access to seed. Companies must commit to fair pricing and traceability to the farm level, while governments can offer incentives to promote organic agriculture.

The following paragraphs will better explain the advantages of organic cotton and have "*Organic Cotton Crop Guide-A manual for practitioners in the tropics*" [12] as reference.

Organic crop rotation

Figure 7.4: Example of crop rotation of cotton and chili [13].

Crop rotation involves changing the type of crop grown on a particular piece of land from year to year. This can include cyclical rotations, where the same sequence of crops is repeated on a field indefinitely, as well as noncyclical rotations, where the sequence of crops varies irregularly to meet evolving business and management goals. Each field has its own rotation, and farmers manage a set of rotations.

Effective crop rotation requires long-term strategic planning. However, planning does not necessarily involve identifying which crop will be grown on a field year in advance. Specific plans can become disrupted by weather, changes in the market, labor supply, and other factors. Lack of planning can lead to serious problems, such as soilborne disease buildup or imbalances in soil nutrients, which can result in an inability to meet market demands or incur additional labor and expense. These problems can take several years to develop and can catch even experienced growers by surprise.

Although rotating among a diversity of cash and cover crops has numerous advantages, it poses substantial management challenges. The number of crops and crop families grown can be large, creating a huge number of potential crop sequences from which to choose.

Crop rotation is an important aspect of farm management, involving the use of biological principles to balance production and management. Expert farmers must consider market options, field biology, labor, equipment, and logistics when designing and executing crop rotations. These rotations typically include key cash crops, filler or break crops, and cover crops, and must be managed across multiple fields and beds to ensure profitability and soil quality.

While model rotations suggest that every crop is grown on a fixed schedule on every field, in reality, each field tends to have its own distinct sequence of crops, tillage, and amendments. Thus, each field has a unique cropping history. Some farms may have a few fields that follow a fixed rotation, but most rely on interchangeable short sequences to achieve their crop rotation objectives. These short sequences are based on biological principles and may vary from season to season.

Variation in acreage, field characteristics, and shifting business decisions result in multiple rotations or crop sequences on most organic farms. The challenge of a good crop rotation system is to grow the type and quantity of crops needed to ensure profitability while continually building soil quality for long-term productivity. The rotation of botanical families of crops prevents the buildup of pest populations and alters pest habitats, and fields may also be deliberately rotated through a fallow to manage a weed or pest problem.

Cover crops are often used for building soil fertility and health but make no direct contribution to cash flow. Farms with limited acreage may rely on compost or other soil amendments rather than cover crops. Farmers with large land bases often include longer-term, soil-restoring perennial cover or hay crops in their rotations.

During a field season, a bed or field may be planted with a series of different short-season crops. Sometimes, growers make multiple plantings of a crop in the same bed within a given growing season due to market demand or other farm practicalities, but the same crop or sequence is rarely replanted in the same bed or field the following year to avoid pest and disease outbreaks. Cover crops may be planted to follow or precede a cash crop and occupy a field only for the winter or a portion of the growing season. In all cases, experts are very conscious that intensive cropping needs careful biological monitoring and management.

Crop rotations require a comprehensive approach that takes into consideration both the entire farm and each individual field, and that balances field- and farm-scale decisions. On successful farms, rotation planning is a responsive, rolling process. Expert farmers continually balance annual and multiyear (short- and long-term) decisions, optimizing business decisions for annual returns and cash flow. In any given season, market opportunities and logistical needs may override biological concerns.

Organic farmers rely on rotations and long-term soil quality to deal with problems and ensure the productivity of fields, more than they rely on fertilizers and pest control products. Expert farmers manage multiple, interacting factors as they implement crop rotations, and many push and test the biological principles of crop rotation to meet management and business demands.

Expert farmers plan and implement rotations on an annual, seasonal, and last-minute opportunistic basis. Their annual plans are based on clear priorities, with the paramount challenge each year being to grow adequate quantities of profitable crops to keep the farm viable. At the same time, farmers consider rotational sequence on each field and how to rotate equipment and labor efficiently across the entire farm operation.

Most farms have a few key cash crops that generate significant income, and expert farmers focus on planting these key crops in the most suitable fields for those crops without compromising the soil health and long-term productivity of those fields. Field history and weather determine the suitability of a field for a particular crop, and each field's biological management is central to the long-term success of the overall farm business. Expert farmers design crop sequences to set up for future key crops, in addition to meeting the current season's production needs.

Green manures

Cotton, like other crops, requires a well-balanced composition of nutrients for healthy growth. During the first two months of growth, the cotton plant needs two-thirds (2/3) of its required nutrients, especially nitrogen. To ensure sufficient nutrient supply during this phase, it's recommended to apply a basal dose of well-decomposed compost or farmyard manure at the beginning of the growing season. Additionally, one or two head applications of compost and an organic manure rich in nitrogen (such as oil cakes or poultry manure from extensive rearing) can be applied 2-3 weeks before square bud formation. It's important to note that the nutrients from manure are not instantly available, and only get released once the manure decomposes.

In organically managed soils, cotton crops mainly depend on the nutrients supplied by minerals and organic matter in the soil. These nutrients are taken up, stored, and released through exchange, weathering, and decomposition. Soil organisms play a vital role in this process and should be supported through careful soil cultivation and regular application of organic matter. Improving overall soil fertility through measures such as increasing microbial activity, improving soil structure, and retaining moisture is more likely to result in increased yields than simply applying fertilizers.

Nitrogen, phosphorus, sulfur, zinc, and boron are the most widespread nutrient deficiencies in tropical cotton fields. However, soil tests have limitations in providing useful information on nutrient deficiencies, as they only measure the easily available nutrients. The availability of nutrients to the crop depends on various factors, including the activity of soil micro-organisms, the root system of the crop, and the water content in the soil. Excess nitrogen, phosphorus, and potassium can also disturb the uptake of other nutrients like calcium, magnesium, and micro-nutrients. In cases where a cotton crop shows deficiency symptoms, it may be more efficient to stimulate microbial activity and overcome the inhibiting factors through soil cultivation, irrigation, and incorporation of biomass rather than applying additional manure or fertilizers.

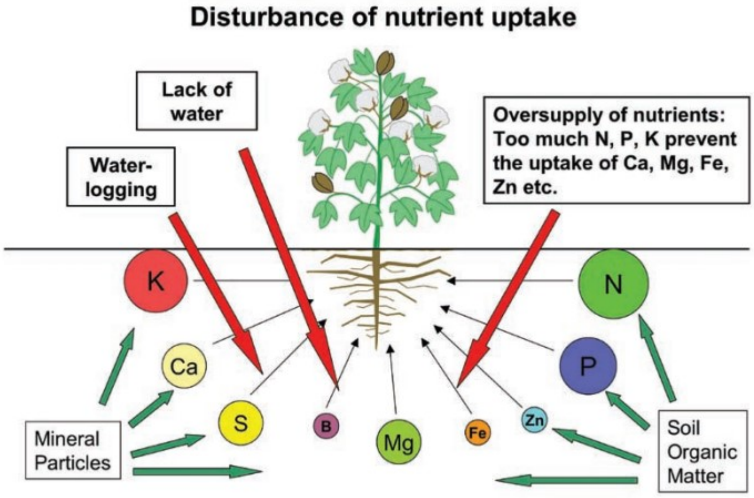


Figure 7.5: The uptake of nutrients and its disturbance [12].

The appropriate amount of nutrients needed for organic cotton depends on various factors, such as soil condition, the previous crop, and expected yield. Figure 7.6 provides a guide for the recommended nutrient quantities for organic cotton on average-fertility soil, cultivated with high-yield varieties. However, a significant amount of required nutrients can be supplied by decomposing residues of the previous crop and nitrogen fixation by leguminous crops.

Nutrient	Quantity per ha	Possible sources
Nitrogen (N)	100–120 kg/ha	Residues from previous crop, nitrogen fixation through pulses, compost, vermi-compost, FYM, DOC, liquid manures
Phosphorous (P_2O_5)	50–60 kg/ha	Residues from previous crop, compost, FYM, rock phosphate, wood ash
Potassium (K_2O)	40–50 kg/ha	Residues from previous crop, compost, FYM, muriate of potash, wood ash

Figure 7.6: Recommended nutrient doses in average organic cotton fields, to be adapted to local conditions [12].

Organic manures such as compost and cattle dung contain all the necessary nutrients, including micronutrients, in a balanced composition. Therefore, if organic manures are applied in sufficient quantities, there is usually no deficiency of micronutrients.

Farmers can ensure adequate nutrient input by following these steps in order of priority:

1. Practice crop rotational and grow leguminous crops such as pulses as inter-crops or green manures;

2. Use all the biomass available on the farm, including crop residues and cow dung, and mix wood ash into the compost heap;

3. Use any cheaply available biomass nearby, such as weeds, leaves, press mud, and agricultural processing wastes;
4. Only then complement with purchased organic manures such as oil cakes and natural mineral fertilizers such as rock phosphate, gypsum, and muriate of potash.

Natural mineral fertilizers and Bio-fertilizers

In organic farming, the use of fertilizers based on natural minerals such as rock phosphate, muriate of potash, gypsum, and lime is allowed in limited amounts. However, they should only be used when there is a deficiency of the respective nutrient in the soil, as determined by soil testing, and only in combination with organic manures.

To ensure absorption of nutrients by the organic matter, rock phosphate and ash should be added to the compost heap or pit when setting it up, rather than applied directly to the fields. Excess application of muriate of potash can be harmful to beneficial soil organisms, so it should only be used when there is a potassium deficiency in the soil. Gypsum, which contains a high amount of sulphur, can be applied to fields where there is a deficiency of this nutrient in crops like cotton, soybean, and groundnut, at a rate of 50-100 kg per ha. Lime, on the other hand, is mainly used on acidic soils, which are not commonly found in black cotton soil regions.

Liquid manures- Figure 7.7 - such as cow urine, biogas slurry, and fermented manures can provide a portion of the nutrients needed during the later growth stages of the crop. They can be applied to the soil by sprinkling, added to irrigation water, or diluted and sprayed as a foliar fertilizer. One advantage of using liquid manures is that the nutrients are quickly available to the plants, making them suitable for fine-tuning nutrient supply.

Bio-fertilizers are products that contain microorganisms that can enhance nutrient availability in the soil. In general, organic farming systems that utilize compost and other organic manures already contain beneficial microbes. However, applying bio-fertilizers can further increase the number and activity of these microbes. When transitioning a farm from chemical to organic farming, the application of bio-fertilizers can help to revitalize the soil. To determine the effectiveness of a particular bio-fertilizer in the field, farmers can conduct a simple plot trial, where one part of a field is treated with the bio-fertilizer while the other part is left untreated.

Figure 7.7: Liquid fertilizers [12].

Pest and disease management

Cotton is susceptible to a variety of pests, including caterpillars, beetles, bugs, aphids, jassids, whitefly, thrips, and mites. While healthy cotton plants have some natural defences, such as additional growth and deterrent substances like gossypol, conventional farming practices rely heavily on chemical pesticides like organophosphates and pyrethroids to control pest populations.

In organic cotton farming, the emphasis is on preventing pest problems from occurring in the first place by establishing a diverse and balanced farm ecosystem and growing less susceptible varieties where possible.

Figure 7.8 provides an overview of the preventive measures used to maintain the health of a cotton crop.

Figure 7.8: Measures used to keep a cotton crop healthy [13].

Organic cotton farming seeks to prevent pest problems from occurring in the first place by establishing a diverse and balanced ecosystem. This includes optimizing soil conditions through the use of compost and other organic manures, shallow soil cultivation, and timely irrigation. Diverse cropping systems and natural habitats also support pest control by attracting natural enemies, such as birds and beneficial insects. Intercropping with pulses and trap crops like sunflower or maize can also help to distract pests from attacking cotton plants.

It's important to avoid stressing the plants, which can make them more susceptible to pest attacks. Stress can be caused by unbalanced nutrition, water shortage, or waterlogging. Preventive measures include carefully managing manure application, avoiding dryness or waterlogging through proper irrigation, and using shallow soil cultivation to encourage soil aeration and decomposition of organic matter.

Despite these efforts, some pests may still attack cotton plants, but the damage can be managed as long as it remains below the "economic threshold" where the cost and effort to control the pest is higher than the damage it causes. Farmers can wait and see if natural enemies are able to control the pest, which can result in negligible damage to the crop.

Seed treatment and disease

In organic cotton farming, it is important to use untreated seeds that are not genetically modified, as conventionally produced cotton seeds are often treated with chemicals that are prohibited in organic farming. Organic cotton farmers can obtain untreated seeds from organic multiplication, and some organic cotton projects can also provide suitable seed materials or organize their own seed multiplication programs. Preventing damage from pests and diseases before and during germination is largely achieved by maintaining fertile soil and implementing a balanced crop rotation system. In cases where preventive measures are insufficient, alternative treatments for seeds can be used. In organic cotton farming, diseases are generally not a major issue in most semi-arid tropical regions. However, some diseases may occasionally occur and can be prevented or treated using various methods, as described below:

1. Bacterial blight: This disease can be identified by oily black spots on leaves and blackening of stems, which can result in defoliation and shedding of bolls in severe cases. Using resistant varieties can prevent this disease, while cow urine spray can be used for treatment.

2. Root rot and boll rot: These diseases are caused by various fungi and bacteria. Cow urine spray can be used for treatment.

3. Fusarium wilt: To prevent this disease, crop rotation should be practiced, cotton stalks should be removed after harvesting, infected seeds should be avoided, and well-decomposed compost should be applied.

Soil cultivation and weed management

When it comes to preparing the soil and seedbed for organic cotton farming, it is important to follow good farming practices, just as in conventional farming. Ploughing should be carried out before the summer season begins (in March and April in India), so that insect pests and weed seeds can be exposed to the sun and dry out. Soil cultivation also helps to speed up the decomposition of crop residues and compost, making nutrients available to the crop. In heavy and medium soils, it is recommended to carry out deep ploughing every few years.

After the cotton crop has germinated and the first top dressing of organic manure has been applied (such as De-oiled castor cake and compost), earthing up ridges can help to suppress weeds and reduce evaporation of soil moisture.

The spacing between organic cotton plants should be determined based on soil type and irrigation facilities. In light soils with limited irrigation water, a narrower spacing (e.g. 2x2 feet) is suitable, while in heavy soils with good irrigation, a wider spacing (e.g. 4x4 feet) is recommended. The spacing should ensure that the mature crop covers the soil completely and shades out weeds. In some places, such as Egypt, organic farmers cultivate cotton on ridges, with 20 cm distance within rows and 70 cm distance between rows. However, this system does not allow for cross-wise intercultural operations with a weeder. Cotton seeds should be sown at a depth of 3-5 cm and covered with fine soil to protect them from drying out during germination. Depending on seed quality and cost, 2 to 4 seeds can be sown per spot. If seeds do not germinate or seedlings are destroyed, cotton can be re-sown in gaps within 2 weeks after emergence of the young plants. Seeds sown later will not grow much due to shading from neighboring plants, so it’s better to fill gaps with trap crops such as sunflower, maize, or pigeon pea. After 10 to 20 days, weaker seedlings should be removed so that there are only one or two plants in each spot. Thinning too early may result in seedling death, while thinning too late may cause competition among plants and risk root damage during seedling removal.

Effective weed management in cotton requires appropriate crop rotation and timely soil cultivation. However, it is not necessary to keep cotton fields completely free of weeds throughout the season. In the early stages of crop growth, weeds absorb nutrients that would otherwise be lost through leaching. These nutrients are returned to the soil and made available to the cotton crop when the weeds are cut and decompose. Once the cotton crop has grown into a dense stand, weeds typically remain below a level where they significantly compete with the main crop.

Some weeds serve as important hosts for beneficial insects or act as trap crops, distracting pests from the cotton plant. By carefully observing weed populations and using shallow soil cultivation methods (such as hoes and weeders) combined with selective hand weeding, experienced organic cotton farmers can usually maintain a good balance with weeds. To prevent the spread of weed seeds through compost, it is important that composts containing weed seeds go through a heat phase, which destroys the seeds .

While weed populations may increase during the conversion period, especially when transitioning from herbicides to mechanical weed management, weeds generally do not pose a major problem in organic cotton farming once proper crop rotation is established. Organic farmers in India report that weeding became even less laborious after switching to organic farming as the soil became softer, making it easier to pull out weeds.

Water management

Cotton is often grown with irrigation from groundwater or surface water in many areas. While irrigation can increase cotton yields significantly, it can also deplete freshwater resources, cause soil salinization, and waterlogging problems. Organic soil management can help improve soil structure, water infiltration, and retention, leading to better water-use efficiency in cotton cultivation.

In irrigated cotton, the application system, intensity, and timing of irrigation are critical for healthy plants and good yields. Farmers can use indicators like local plants such as "croton" to signal water stress and the need for irrigation. Irrigation during the first 6-7 weeks after sowing should be moderate to avoid heavy vegetative growth and encourage root penetration.

Waterlogging is a significant problem in cotton cultivation, as it causes increased boll shedding, general yellowing, stunted growth of plants, and nutrient reduction. Thus, in fields prone to waterlogging, improving soil structure through organic matter application is more critical than applying fertilizers. Furrow irrigation should be done quickly and not exceed four hours, which can be achieved by shortening the rows.

In areas where cotton is grown without irrigation or with limited water supply, it is important to focus on increasing the infiltration of rainwater into the soil and preserving soil moisture. The use of compost and organic manures is crucial for this purpose. Shallow soil cultivation through hoeing can break soil capillaries and reduce evaporation, while mulching can help to retain soil moisture. In some regions, black plastic mulch is used, but its ecological and economical suitability is questionable. Active rainwater harvesting through pits or trenches leading to wells can help to recharge groundwater levels and improve the availability of irrigation water.

In situations where little irrigation water is available, alternate-furrow irrigation can still be used to irrigate the crop. If there is a lack of rainfall after the seedlings have germinated, it may even be worth saving them through bucket irrigation, plant by plant.

Harvest and Post-harvest operations

The quality of the cotton harvest is determined by various factors, including the staple length, the amount of non-fibre material (such as leaves or dust) present, and the extent of pest or disease damage to the fibres. Good-quality raw material is essential for producing high-quality yarns and garments, and ultimately contributes to the market success of organic cotton projects. Cotton buyers often take the quality of the seed cotton into consideration when fixing prices, so measures to improve the harvest quality directly benefit the farmers.

To improve the quality of the cotton harvest, it is important to allow the cotton bolls to ripen fully before picking and to pick the cotton after the morning dews have dried up. It is also crucial to pick the cotton into clean cotton cloth material and to remove leaves, capsules, and damaged bolls from the harvest. Cotton of lesser quality should be kept separate using a second, smaller picking bag. Picking delays can reduce the quality of the fibres, and unripe cotton should not be picked as it will not absorb dye well enough, resulting in lower prices.

Labour costs for cotton picking are a major expense in cotton production. To increase efficiency and ensure a high-quality harvest, using a long sack that rests on the ground and keeping it permanently open with a flexible wooden ring can be helpful. Picking two rows at a time and using a separate, smaller bag for second-grade cotton are also effective measures.

To ensure the quality of the harvested cotton, farmers should take precautions when storing it before selling. Contamination from dust or chemicals such as fertilizers, pesticides, and petroleum should be avoided. It is important not to use any storage pest control, such as DDT, on the cotton. Foreign fibers, including those from clothes or human hair, should also be prevented from entering the storage area as they can affect the quality of the yarn.

The storage location should be kept clean and dry as damp conditions can lead to the growth of fungus, which can significantly decrease the quality of the cotton. In cases where organic harvest is stored in the same facility with conventional cotton, it is necessary to separate the organic, in-conversion, and non-organic produce clearly and avoid any mixing.

How to define if the cotton is organic

Once the cotton leaves the farm, it is not covered by the same legal protections. To manage the chain of custody of organic cotton from gin to finished product, private standard-setting organizations have developed voluntary standards such as the Organic Content Standard (OCS) and the Global Organic Textile Standard (GOTS).

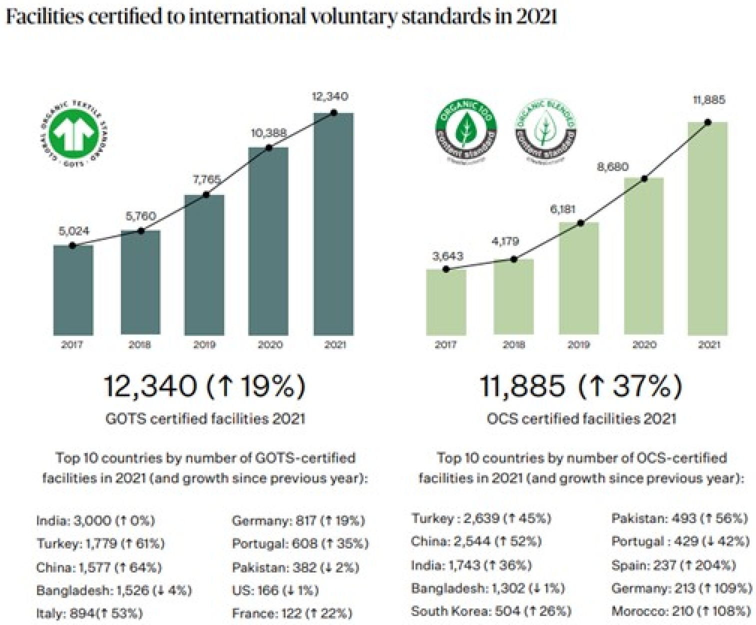


Figure 7.9: Trends of top 10 countries GOTS and OCS certified[12].

Farmers can only sell their cotton crops as organic if they meet certain requirements around soil health and the prohibition of artificial fertilizers, hazardous synthetic pesticides, and genetically modified organisms (GMOs).

These standards require certification recognized by the International Federation of Organic Agriculture Movements (IFOAM) and involve a system of monitoring and certification.

To summarize, there are two types of certifications for organic cotton: farm-level certification and supply chain certification.

Farm-level certification involves third-party certification bodies verifying that organic farmers meet strict national organic laws and regulations, while supply chain certification ensures that any claims made about products containing organic content are true by managing the chain of custody of organic fibers as they make their way along the supply chain.

There are three key parties involved in the assurance process: the standard-setting body, certification bodies, and accreditation bodies.

The standard-setting body creates standards for the segregation, identification, and volume reconciliation of organically grown content at each stage of the supply chain, which are then enforced by certification bodies.

Accreditation bodies monitor and assess the certification bodies to ensure that they are operating as intended.

The OCS In-Conversion Public Exemption V0.1 is a new version that encourages all supply chain participants to signal demand for in-conversion cotton with their suppliers and certification bodies to increase the availability of organic cotton fiber in the future.

Chapter 8

LCA applied to a sport tape made by organic cotton

8.1 Life Cycle Inventory

The main difference between organic and conventional cotton production is the use of chemicals. Traditional cotton farming often involves the use of pesticides and synthetic fertilizers, which can contaminate the soil, groundwater, and nearby crops.

Organic cotton farming, on the other hand, relies on practices that promote soil health, water conservation, and biodiversity.

Sterkur's traditional cotton production takes place in China and the idea is to start sourcing organic cotton from the same country.

China produced 33,687 tonnes of organic cotton fiber on 15,727 hectares of certified organic land in 2020/2021, a 10% increase from the previous year. Additionally, 225 tonnes of in-conversion fiber were grown on 178 hectares of in-conversion land during the same period [12].

To find farmers who grow organic cotton, Sterkur could look for those who follow strict requirements around soil health and prohibit the use of artificial fertilizers, hazardous synthetic pesticides, and genetically modified organisms (GMOs).

To assess the environmental impacts of Sterkur's sport tape made from organic cotton, a custom LCA analysis was conducted.

The processes involved were the same as for conventional cotton used in the previous analysis, except for the data set of organic cotton.

As the Ecoinvent database only provides information on fiber, the subsequent steps involved in transforming the fiber into yarn and then into textile cotton were based on the processes used for conventional cotton.

To figure out this issue, the Sankee diagram of traditional cotton – Figure **??** - was the base to carry out the flow chart related to the organic cotton. Regarding the first one, all the electricity of different powers and various countries reported in the Sankee, was summed up, as well as for the transportation and the heat.

As shown in the Figure 8.1, the fiber undergoes various processes involving electricity and transportation to be transformed into yarn, which is then processed with additional energy inputs to create the finished textile cotton product.

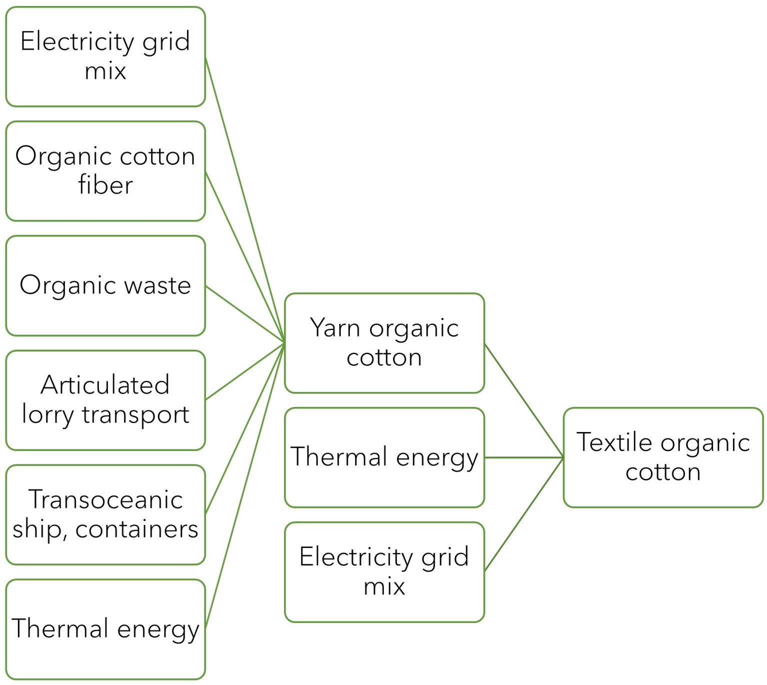


Figure 8.1: Flow chart to obtain the textile organic cotton.

To clarify, the Life Cycle Assessment of the sport tape made by organic cotton does not differ significantly from that of the traditional cotton sport tape. The only additional assessment conducted for the organic cotton product is that of the organic cotton cycle itself.

So, in the Table 8.1 is reported the data to obtain the yarn and in the Table 8.2 the data for the textile organic cotton.

The last step to obtain the woven that takes part of the sport tape is in the Table 8.3.

Output flow	Quantity	Unit of measure	Reference Dataset
Yarn organic cotton	1.05	kg	
Input flows			
Electricity	7.68	MJ	Electricity grid mix, CN (EF)
Organic cotton fibre	1.24	kg	Market for fibre organic cotton (GLO) (Ecoinvent)
Thermal energy	3.92	MJ	Thermal energy from natural gas, CN (EF)
Transport	1.54	t*km	Articulated lorry transport (EF)
Transporting capacity	4.39	t*kg * km	Transoceanic ship, containers, consumption mix (GLO) (EF)

Table 8.1: Inventory of yarn organic cotton.

Output flow	Quantity	Unit of measure	Reference Dataset
Fabric organic cotton	1	kg	
Input flows			
Yarn organic cotton	1.05	kg	See the Table 8.1
Electricity	6.84	MJ	Electricity grid mix, CN (EF)
Thermal energy	2.23	MJ	Thermal energy from natural gas, CN (EF)

Table 8.2: Inventory of textile organic cotton.

Output flow	Quantity	Unit of measure	Reference Dataset
Organic cotton	37.5	g	
Input flows			
Fabric organic cotton	37.5	g	See the Table 8.2

Table 8.3: Inventory of the woven organic cotton for one sport tape.

Summarizing, the process to achieve the data related to organic cotton was more complex than for the traditional one that was already presented as woven in the database.

However, the next steps of production phase, use and disposal phase, instead, are exactly the same as the previous case, for this reason they are not reported again in this chapter .

8.2 Life Cycle Impact assessment

8.2.1 *Production phase*

The impact assessment method used, as well as in the sport tape made by traditional cotton, is the Environmental Footprint and the results of the indicators are reported in the Table 8.4.

Indicator	**Impact result**	**Unit**
Climate change	0.33925	kg CO2 equivalent
Climate change- Land use and land use change	0.01773	kg CO2 equivalent
Acidification	0.00367	mol H+ eq
Eutrophication, freshwater	0.00056	kg P eq
Eutrophication, marine	0.00442	kg N eq
Eutrophication, terrestrial	0.01212	mol N eq
Water use	0.08038	m3 deprivation

Table 8.4: LCIA of one sport tape made by organic cotton.

To gain a better understanding of the impact categories and which process has the greatest impact, the Figure 8.2 reports the impacts for the production of a sport tape made by organic cotton.

The analysis of all the impact categories indicates that the production of cotton and adhesive with the coating process has the greatest environmental impact.

The transport with transoceanic ship has impact mainly on the *climate change* (8.2% of the total impact), on *acidification and terrestrial eutrophication* (27.6% and 22.3% respectively) and a limited impact on *marine eutrophication* (about 5% of the total impact), while the packaging and the transport by lorry result having negligible impacts for all the analyzed impact categories.

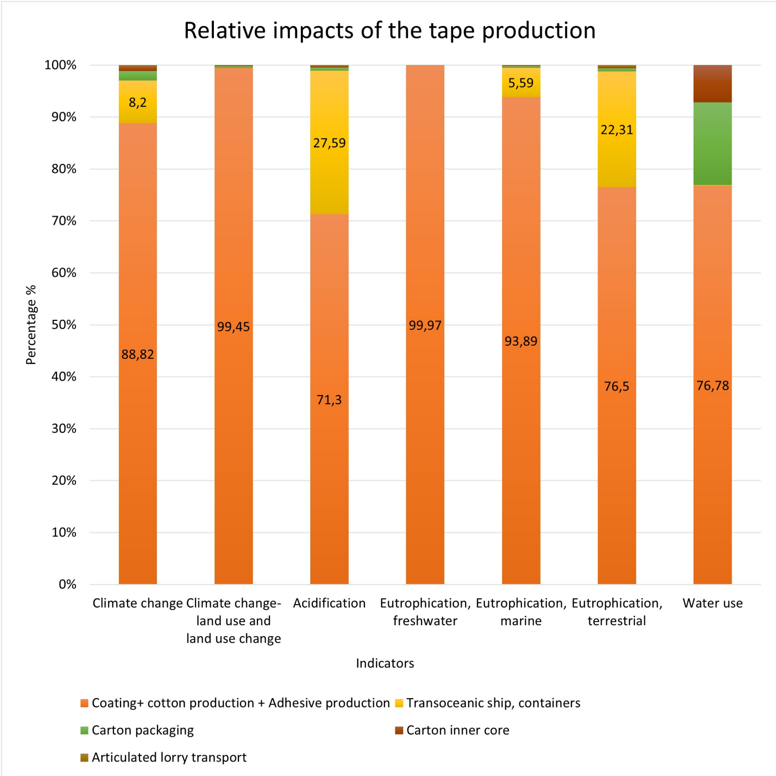


Figure 8.2: Impacts for the production of a sport tape made by organic cotton.

The coated cotton with adhesive has been further analyzed - Figure 8.3 - to determine which material and corresponding process has the most significant impact.

The results show that cotton has the greatest impact on categories compared to all other materials used in the sport tape, except for *Climate change-land use and land use change*, where Rosin resin accounts for 98% of the total impact.

This finding is noteworthy because the resin has the same value in both conventional and organic tapes, but what differs is the impact value of organic cotton of *Climate change-land use and land use change* , which has decreased.

As in the case of conventional cotton, the categories identified as the most robust and medium were considered, and therefore, the analysis focused on *climate change* (as a robustness type I, see Figure A.3), *acidification*, and the three categories of *eutrophication* (as robustness type II, see Figure A.2), for the same reasons mentioned in the conventional cotton.

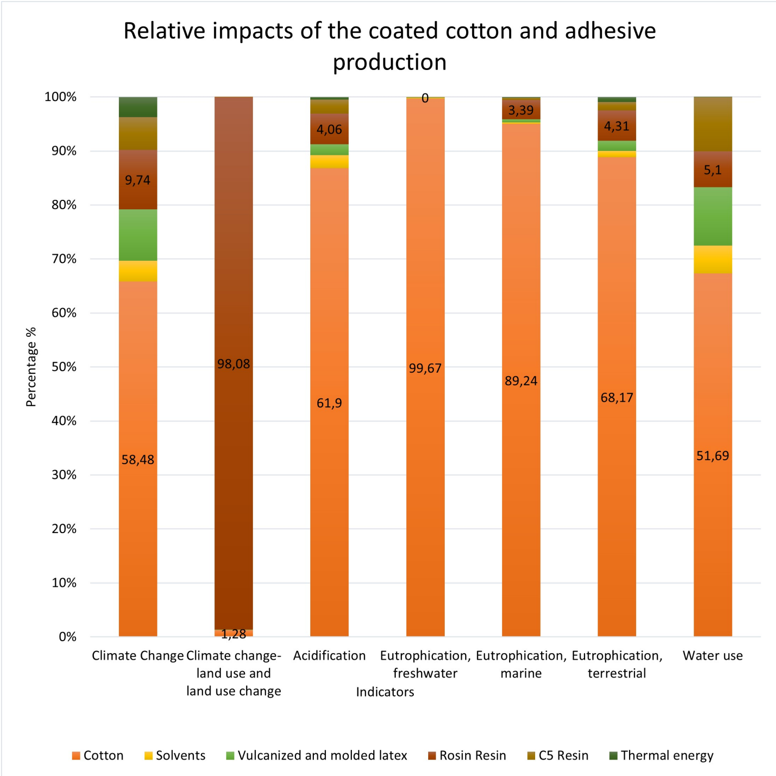


Figure 8.3: Impacts of the production of the coated cotton and adhesive.

8.2.2 *Comparison between production and end-of-life*

Tables have been generated to provide further analysis of the impact of cotton throughout the entire lifespan of the sport tape.

The Tables 8.5 and 8.6 , that follow, list the entire life cycle of the sport tape, which encompasses the previously reported production stage and the end-of-life phase (incineration of the sport tape).

Finally, they display the overall result of sport tape that incorporates all of the aforementioned components.

Indicator	Cotton production	Sport tape (cotton+ coating+ adhesive + packaging	Unit of measure
Climate change	0.1984	0.33925	kgCO2 eq.
Climate change - Land use and land use change	0.00023	0.01773	kgCO2 eq.
Acidification	0.00227	0.00367	mol H+ eq.
Eutrophication, freshwater	0.00056	0.00056	kg P eq.
Eutrophication, marine	0.00394	0.00442	kg N eq.
Eutrophication, terrestrial	0.00826	0.01212	kg N eq.

Table 8.5: Environmental impacts of a sport tape made by organic cotton during the production phase of its life cycle. The contribution of cotton production is highlighted in the first column.

Indicator	Incineration	Sport tape Life cycle (from cradle-to-grave)	Unit of measure
Climate change	0.1782	0.51779	kgCO2 eq.
Climate change - Land use and land use change	-4.6775	0.01772	kgCO2 eq.
Acidification	-0.00022	0.00345	mol H+ eq.
Eutrophication, freshwater	-7.5165E-8	0.00056	kg P eq.
Eutrophication, marine	-4.40749E-5	0.00438	kg N eq.
Eutrophication, terrestrial	-0.00038	0.01174	kg N eq.

Table 8.6: Environmental impacts of a sport tape made by organic cotton during the entire life, from cradle-to-grave. The contribution of incineration is highlighted in the first column.

The impact of waste incineration on the environment is evident in the case of climate change, with a contribution of 34.42% in relation to the entire life of the sport tape.

This means that waste incineration during the end-of-life phase contributes to the impact of the sport tape on *climate change*.

However, it is worth noting that this impact is specific to the *climate change* impact category and may not necessarily be reflected in other impact categories.

As well as in the case of traditional cotton, the negative results of incineration, in particular considering the other indicators, are due to the benefits that it has on environment.

Since in the Netherlands, all waste incinerators are referred to as Waste-to-Energy (WtE) plants, the facilities generate electricity and heat by burning waste. Compared to alternative energy sources, which are often based on fossil fuels, WtE plants can prevent externalities associated with such energy sources.

This has been a significant selling point for waste incinerators that incorporate energy recovery, as opposed to relying on landfills.

Chapter 9

Conventional VS Organic cotton

In order to understand the distinction between conventional cotton sport tape and organic cotton sport tape, it is important to assess the impact categories across the entire life cycle of the sport tapes. The following Figures demonstrate a significant difference between the two types of sport tape.

Conventional cotton has a notably higher contribution to all impact categories except for *eutrophication of freshwater* - Figure 9.4.

The impacts of *eutrophication freshwater* indicator are dependent on the production of cotton seeds. Analyzing both conventional and organic seeds in the Ecoinvent database, it is found that the conventional seed has a higher yield of 1750 kg/ha compared to the 1430 kg/ha of a certified organic farm which produces organic cotton. The water emissions involve the same materials but with different quantities, with some materials having higher values for organic cotton.

To clarify this point, it is necessary to consider research by the Textile Exchange, which shows that cultivation of rotation crops and inter-cropping can reduce nutrient losses due to leaching, resulting in a 26% lower eutrophication potential for organic cotton fiber [14]. Additionally, the report "*Life Cycle Assessment of Organic, BCI and Conventional Cotton: A Comparative Study of Cotton Cultivation Practices in India*" [15] confirms that the eutrophication potential of conventional cotton is much higher than that of organic cotton. This can be attributed to the fact that the conventional system is dominated by soil erosion, and soil erosion data is influenced by area and not production yield. This means that lower yield per hectare can result in higher soil erosion per kg of final product.

This last sentence can explain why organic cotton may have a higher eutrophication freshwater indicator score, as it has a lower yield according to the Ecoinvent dataset, which could result in higher soil erosion. However, this is in contrast with the aforementioned researchers. Therefore, the result can be explained in different ways, such as the creation of different seed datasets or a mistake in the dataset which can be examined more deeply in future analyses.

To clarify instead the other impacts, the use of organic cotton results in a 46% reduction in *climate change* - Figure 9.1 - impact compared to conventional cotton, with the subcategory of *climate change-land use and land use change* showing a 82% decrease - Figure 9.2.

Additionally, *acidification* decreases by 43% - Figure 9.3 - when organic cotton is used instead of conventional cotton. Furthermore, the *marine and terrestrial eutrophication* would decrease by 53% - Figure 9.5 - and 40% - Figure 9.6 - respectively, if organic cotton was used instead of conventional cotton.

These results present a significant opportunity for improvement in environmental sustainability, making the use of organic cotton a worthwhile consideration.

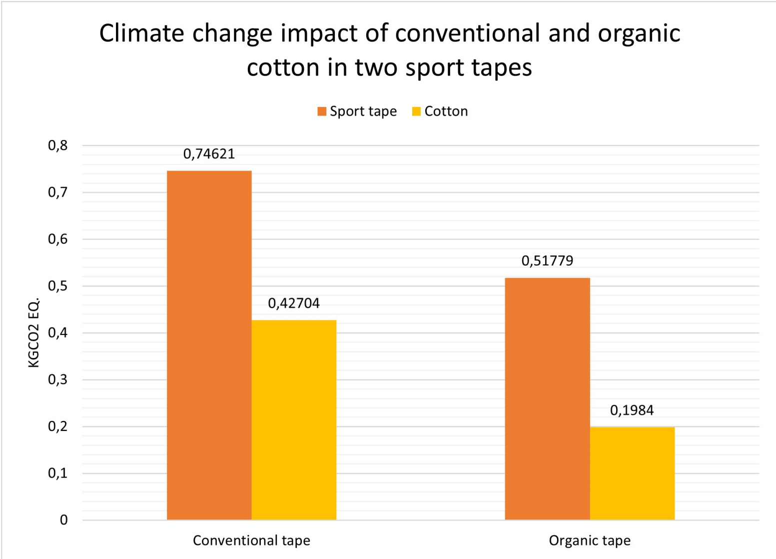


Figure 9.1: Examining the impact of conventional and organic cotton production on the *climate change* indicator with respect to the entire tape.

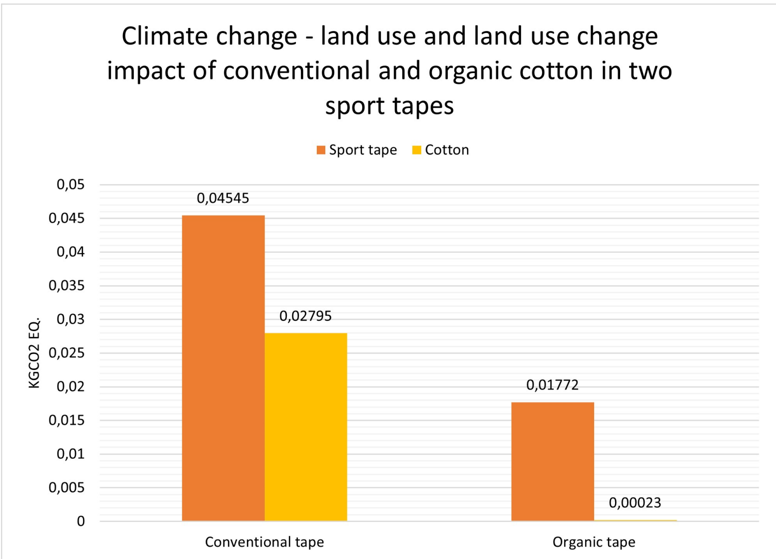


Figure 9.2: Examining the impact of conventional and organic cotton production on the *climate change- land use and land use change* indicator with respect to the entire tape.

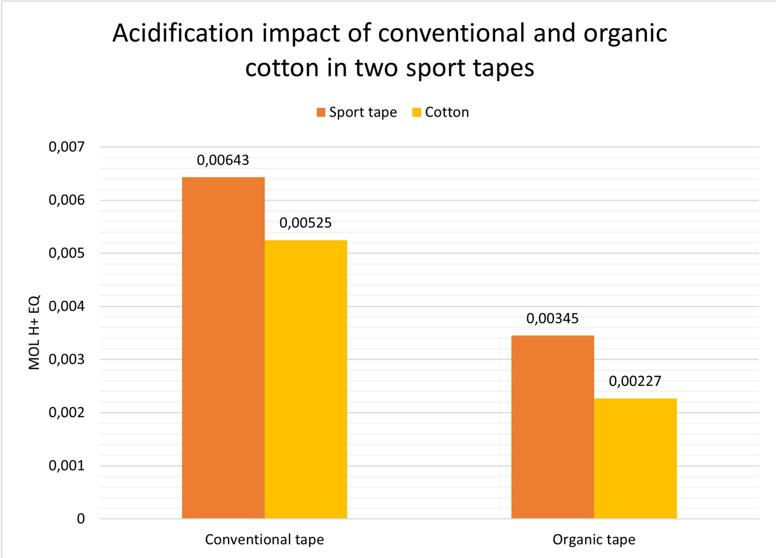


Figure 9.3: Examining the impact of conventional and organic cotton production on the *acidification* indicator with respect to the entire tape.

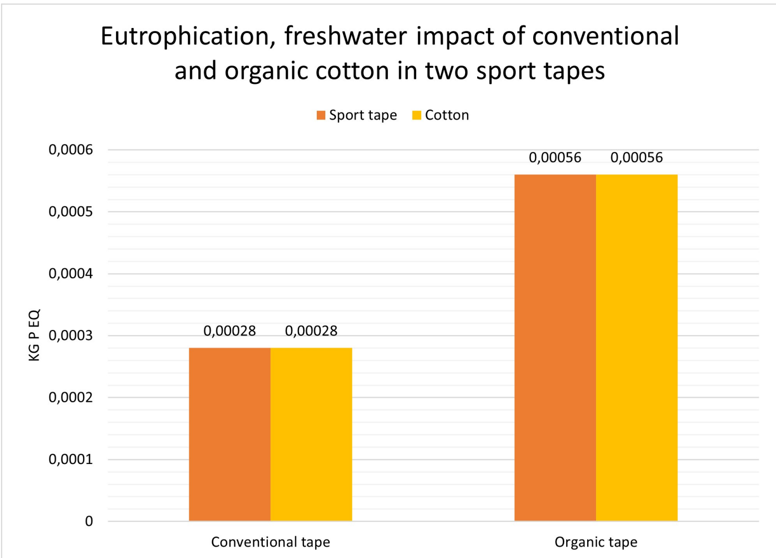


Figure 9.4: Examining the impact of conventional and organic cotton production on the *eutrophication, freshwater* indicator with respect to the entire tape.

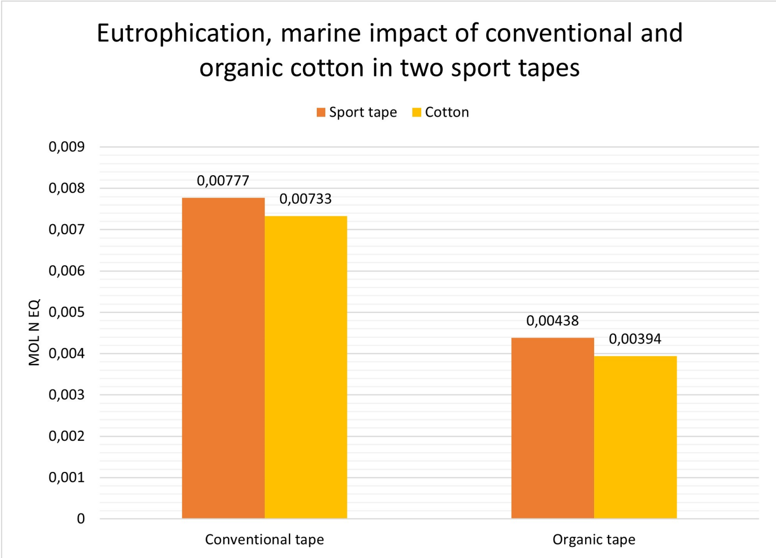


Figure 9.5: Examining the impact of conventional and organic cotton production on the *eutrophication, marine* indicator with respect to the entire tape.

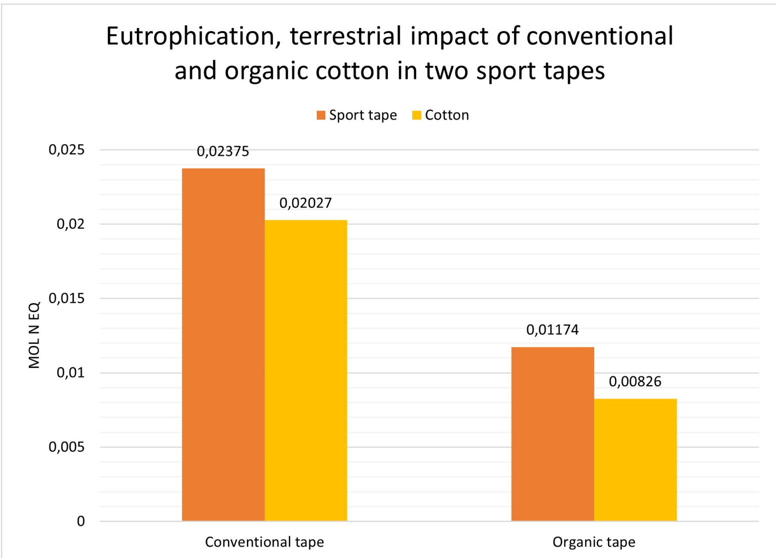


Figure 9.6: Examining the impact of conventional and organic cotton production on the *eutrophication, terrestrial* indicator with respect to the entire tape.

Chapter 10

Conclusion

The Life Cycle Assessment of sport tape has yielded results that demonstrate the possibility of improvement. The thesis outlines the processes involved in producing sport tape and evaluates them using the Environmental Footprint method and its indicators, which include *climate change*, its sub-category *climate change-land use and land use change, acidification, water use* and the three *eutrophications: freshwater, marine and terrestrial.*

The analysis reveals that the main impacts are due to the production of coated cotton with the adhesive, while they are not so much influenced by factors such as transport by lorry, transoceanic ship and the production of cartons. However, one of the originally chosen indicators, specifically the *water use*, was excluded from the analysis because, according to the *Suggestion for updating the PEF method* [7], it is not deemed a robust indicator (see A.1), so the remaining ones are used for the purpose of this thesis.

Indeed, they demonstrate that the production of cotton has the highest impact on the environment during the entire life cycle of the sport tape.

As regards the last phase of tape's life, it must be said that it cannot be recycled or reused, so it must be incinerated. In the case of *climate change-land use and land use change, terrestrial and marine eutrophications* and *acidification*, the waste contributes positively, thanks to the credit that electricity generates. Waste-to-energy incinerators generate electricity and heat by burning waste. Instead, the impact of waste incineration on the environment, in the case of *climate change* has a contribution major than 23% with respect to the entire life of the sport tape. This means that the incineration contributes to the impact of the sport tape on climate change.

Therefore, the analysis focused on cotton, which gives significant impact, mainly because of its important water consumption, use of pesticides and petroleum-based fertilizers, land clearing, soil erosion, and contamination.

To tackle the environmental concerns related to traditional cotton, organic cotton has been suggested as a viable alternative. In order to assess its impact, a new Life Cycle Assessment was conducted.

Additionally, the study revealed that the use of organic cotton for the tape led to a 46% reduction in *climate change* impact when compared to the tape made by conventional cotton. Moreover, there was a substantial reduction of approximately 82% in the sub-category of *climate change-land use and land use change.* The study also found that the use of organic cotton resulted in a 43% decrease in *acidification.* Furthermore, the *eutrophication* of both *marine and terrestrial* showed a significant reduction, with the *marine* environment showing a 53% decrease and the *terrestrial* environment showing a 40% decrease if organic cotton was used instead of conventional cotton.

It is important to keep in mind that these results are based on the production of tape in China and that certain data was not available. However, the inventory data were provided by the company and supplemented with information from literature.

Although some approximations were made, the overall results support the validity of the study's findings.

Appendix A

EF impact categories and their robustness

Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world $_{eq}$	Available WAter REmaining (AWARE) as recommended by UNEP, 2016	III
Resource use[25], minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb $_{eq}$	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.	III
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)[26]	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002	III

Figure A.1: Impact categories of III degree of robustness

Acidification	Accumulated Exceedance (AE)	mol H+ $_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N $_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P $_{eq}$	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N $_{eq}$	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	II
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	USEtox model 2.1 (Fankte et al, 2017)	III
Land use	• Soil quality index[24] • Biotic production • Erosion resistance • Mechanical filtration • Groundwater replenishment	• Dimensionless (pt) • kg biotic production • kg soil • m^3 water • m^3 groundwater	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	III

Figure A.2: Impact categories of II and III degree of robustness

EF Impact category	Impact category Indicator	Unit	Characteri-zation model	Robust -ness
Climate change, total[23]	Radiative forcing as global warming potential (GWP100)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 $_{eq}$	Steady-state ODPs as in (WMO 2014 + integrations)	I
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model 2.1 (Fankte et al, 2017)	III
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model 2.1 (Fankte et al, 2017)	III
Particulate matter	Impact on human health	disease incidence	PM method recomended by UNEP (UNEP 2016)	I
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq $U^{235}{}_{eq}$	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	II
Photochemical ozone	Tropospheric ozone concentration increase	kg NMVOC $_{eq}$	LOTOS-EUROS model (Van	II

Figure A.3: Impact categories of I and II degree of robustness

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