A Comparative Life Cycle Assessment of Cork versus Traditional Shoe Insole Material

Alexandra Lum
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Greening Your Step:

A Comparative Life Cycle Assessment of Cork versus Traditional Shoe Insole Material

Alexandra Lum
University of Virginia
School for International Training

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Academic Director: Professor Cátia Magro, School for International Training, World Learning Inc., Brattleboro, VT 05302, USA

Advisor: Doctor Joana Almeida, NOVA School of Science and Technology, NOVA University Lisbon

Abstract
Shoes are conventionally produced from materials like plastic or rubber that have detrimental impacts on the environment such as exacerbating existing waste accumulation, increasing global amounts of greenhouse gasses, or releasing toxic chemicals into soils and groundwater. These impacts have pushed footwear companies to introduce more sustainable and ecologically-friendly materials in their products. Roughly half of all cork production occurs in Portugal. The present work employs a comparative life cycle assessment approach between traditional plastic and rubber insole material and cork insole material to investigate the environmental impact of each. Results show that during each stage of the insole life cycle, cork had less environmental impact, resource use, and emissions and thus functions as a feasible sustainable alternative to plastic and rubber.

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Relevant Vocabulary

Emission factor (EF)	"A coefficient that quantifies the emissions or removals of a gas per unit activity" (IPCC, 2019). High EF values are associated with high levels of emissions.
Insole	Part of the shoe in which the bottom of the foot touches. Can be removable, or attached to the midsole of the shoe. Also known as a footbed. Materials vary.
Plastic	"High molecular weight organic polymers composed of various elements such as carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine" (Baheti, n.d.)
Synthetic	An artificial substance or material made by chemical synthesis, usually for the purpose of imitating a natural product (Merriam-Webster, n.d.).
Quercus Suber L	Also known as a cork tree, is a medium-sized evergreen oat containing a thick kind of bark that grows over time and is often removed to produce commercial cork (Cork Information Bureau, 2015)

1. Introduction

Global climate change is no new phenomenon. The accumulation of greenhouse gasses in the atmosphere by humans has long led to global temperature increases, ocean acidification, biodiversity loss, and sea level rise (United Nations, n.d.). Following the oil and gas sector, the fashion industry is the second largest polluting industry accounting for roughly 8-10% of global emissions ("Fast fashion," n.d.). Within that industry, the footwear industry is responsible for around 1.4% of global greenhouse gas emissions. In comparison, air travel is responsible for 2.5% ("Fast fashion," n.d.).

Most shoes are produced from plastic or plastic-like materials that have detrimental impacts on the environment such as exacerbating existing waste accumulation due to inability to biodegrade or increasing global amounts of CO_2. Roughly 40 different materials are typically used in the manufacturing of a single shoe (Van Rensburg et al., 2020). This mixture of materials prevents the shoe's ability of being recycled properly and complicates the process of separating materials to be reclaimed in an economic way. Over 20 billion shoes are manufactured annually; yet, 300 million are thrown away (DiNapoli, 2022). 95% of the shoes we throw away end up in landfills (DiNapoli, 2022).

Increased knowledge on the staggering environmental impacts of the footwear industry have pushed footwear companies, citizens, scientists, and policymakers towards introducing more sustainable frameworks and materials in their business strategies and products. Ecologically-friendly material alternatives such as piñatex, organic cotton, cork, or recycled rubber have shown widespread success in both small and large footwear brands and pose hope for the future of sustainable fashion. The United Nations' Sustainable Development Goals (SDGs) also aim to mitigate the effects of climate change through more responsible production and consumption, clean energy usage, and material selection.

Life cycle assessment (LCA) is a decision making tool useful to analyze the environmental impacts of benefits of products and services. The LCA is systematic and involves four main steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. LCA could be applied to determine the environmental impacts in several categories and validate the environmental feasibility of more sustainable alternatives, namely regarding the footwear industry.

Cork is considered an 100% natural, sustainable, and biodegradable material that can be reused and repurposed to the benefit of footwear brands. The Alentejo region of Portugal is located in the mid-southern region of Portugal as shown in Figure 1 (prob need better photo than one provided). Its total area is around 31,500 km squared (Cork Information Bureau, 2015). The Alentejo region is Portugal's largest cork producer, accounting for 84% of Portugal's total cork area (Cork Information Bureau, 2015). Portugal produces over 50% of the world's total cork, which equates to about 310,000 tons of cork (Cork in Portugal, n.d.). Portugal also comprises 1/3 of the world's total cork oat area, at around 2,150,000 hectares (Cork in Portugal, n.d.). The total land area covered by cork is 2.1 million hectares (Cork Information Bureau, 2015).

Figure 1: Map of Portugal with Alentejo Region marked, adapted from EverWonderWine (Portugal, n.d.)

The Alentejo region is known as a "montado" in Portuguese. The term is "used to describe landscapes which are a specific, delicately-balanced ecosystem, consisting of mixed farming, centered around extensive oak woodlands, interspersed by areas of shrubs, grassland and cultivated fields" (Cork Information Bureau, 2015). Developed over hundreds of years, this kind of landscape has effectively allowed cork oats to thrive in harsh conditions and different climates to ensure land productivity for future generations (Cork Information Bureau, 2015). The cork tree (Quercus Suber L), is the main species that dominates the montados.

In the cork industry, a saying is applied as follows: "nothing is lost, everything is transformed" (Cork Information Bureau, 2015). The production process makes it so that "all waste arising from the production of cork stoppers is transformed into useful, high quality products" (Cork Information Bureau, 2015). These products include floor tiles, furniture, insoles, wine stoppers, insulation, shoes, yoga mats, and many more (Cave, 2023). When walking around Portugal, it is easy to find stores exclusively selling products made out of cork.

The present work aims to understand the life cycle and environmental impact differences between traditional and sustainable footwear material, specifically as it relates to shoe insoles. Research comparing the impacts of cork versus traditional insole materials are incredibly limited from a life cycle assessment framework. Traditional insoles are often made using synthetic plastic and rubber materials, leading to a plethora of issues such as increased greenhouse gas emissions, decreased recyclability, deforestation, and toxic chemical release. This work puts the production processes of both cork and plastic and rubber materials side-by-side to provide a better illustration of cork's potential in the footwear industry and relevant environmental harm.

1.1 Objectives and Research Question

The present work aims to investigate the environmental impacts of different footwear materials and their production processes, namely for shoe insoles, and propose the use of cork as a sustainable alternative. The main research question is as follows:

How can footwear companies minimize their environmental impacts by replacing rubber and synthetic insole material with natural cork?

The main objectives of this work is to:

- Conduct individual assessments on the life cycle of traditional insole material and cork insoles. This means investigating the extraction, manufacturing, and disposal processes for each.
- Identify environmental impacts of both traditional and cork insole materials.
- Propose the use of cork as a sustainable replacement material for traditional insoles.

2. Methods

This study's approach is based on a comparative analysis of different insole materials using life cycle assessment (LCA) to study the environmental effects of insole production. Information was obtained through research online rather than interviews. Thus, no verbal or written consent was required. Ethical research requirements were followed. The first part of the study provides relevant background information on traditional versus sustainable footwear materials overall. Keywords searched online included but are not limited to the following: "footwear materials," "footwear material environmental impact," "footwear material life cycle assessment," "traditional versus sustainable footwear materials," and "footwear material properties." Information on material quality, use, and chemical properties was selected and collected from scholarly articles, well-established footwear brand websites, and scientific journals. Information on environmental impacts, including quantitative data, came from similar sources, with additional information coming from footwear life cycle assessment results, and university research. Context and initial interest into the sustainable footwear industry was also fueled by educational excursions, namely to a local sustainable footwear brand, and lectures provided by the School of International Training.

The majority of this study employs a *simplified* life cycle assessment methodology for shoe insole materials. A life cycle assessment, according to the European Environment Agency, is "a process of evaluating the effects that a product has on the environment over the entire period of its life thereby increasing resource-use efficiency and decreasing liabilities" (2017). It takes into account resources consumed, emissions generated, and the environmental impact associated with each stage of the product's life cycle. Also known as a "cradle-to-grave" analysis, a LCA investigates all aspects of a product's life cycle from material extraction to disposal.

The LCA process involves four main steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (Quist, 2023). During the goal and scope definition stage, the product's boundaries, objectives, and functional unit are defined. The inventory analysis involves gathering data on the inputs and outputs of each stage of the product's life cycle. The impact assessment stage involves assessing the environmental impacts of the product or service. This work employs a simplified LCA as it omits the interpretation stage and replaces it with a comparative results/discussion section at the end of the work. It also omits a functional unit, as quantitative data was not sufficient enough to generalize to one type of insole.

Information on the simplified rubber and plastic insole material LCA came from a variety of scientific articles, journals, already-existing life cycle assessments, and industry websites. Extraction information and preprocessing information was often collected from general life cycle assessments for plastic and rubber globally. Manufacturing and production information came from insole or footwear-specific life cycle assessments and other well-established footwear industry websites. Quantitative data in terms of functional units varied and could be both global or country-specific. Broader studies on polymer processing, greenhouse gas emissions in the footwear industry, and marine life impact were used to complement the simplified LCA and fuel the impact assessment section.

Information for the simplified cork insole LCA was collected using similar methods. Context regarding cork in Portugal, specifically in the Alentejo region, derived from APCOR, which is the Portugueses cork association that "promotes, divulges, and carries out research in the Portuguese cork industry" (Cork Information Bureau, 2015). Information on the production steps of cork came from previous life cycle assessments and well-established cork industry websites, such as Amorim Cork and Supra Cork. Relevant vocabulary and chemical processes were clarified from scholarly articles. Example production processes and sustainable strategies from current cork footwear and insole brands were used to complement the simplified LCA and impact assessment section. Relevant keywords searched included "cork extraction process," "cork environmental impact," "cork insole manufacturing process," and "cork insole material." Improved personal understanding on manufacturing processes for cork insoles in particular was obtained through an informal phone call with Muki Shoes' founder.

This work used canva, a free online graphic design tool, to generate the flow diagrams that appear in the LCA throughout the study. Other figures included in the study were adapted or screenshotted from existing scientific articles. Tables included in the study included information from literature used.

3. Overview of traditional and sustainable materials used in footwear

3.1 Traditional materials for shoe production

A single shoe can be made up of a variety of materials. A study done by Van Rensburg et al. as part of the Waste Management & Research journal completed a life cycle assessment of the footwear industry and provides crucial insight into different material impacts and production processes. The most common and predominantly used materials, according to Van Rensburg et al. (2020), include rubber, synthetics, textiles, and leather. These materials and their average percentage composition in a typical shoe from a 2007 study are shown in Figure 2. Materials used in shoes are critical in determining not only the life cycle of a shoe, but also how they can be disposed of or recycled, and what their environmental impact looks like.

Figure 3 shows a diagram highlighting the main parts of the shoe for reference.

3.1.1 Rubber

Rubber, in this case, refers to both natural rubber and synthetic rubber. Natural rubber, a polymer, is a natural product obtained from latex which comes from certain tropical plants. Not all latex-producing plants produce rubber, but around 2,500 species currently do (Arias & Van Dijk, 2019). Rubber materials expand after production processes to include crepe, tire, and virgin synthetic rubber (Van Rensburg et al., 2020). However, the properties of synthetic rubber, mentioned in section 3.1.2, differ from natural rubber.

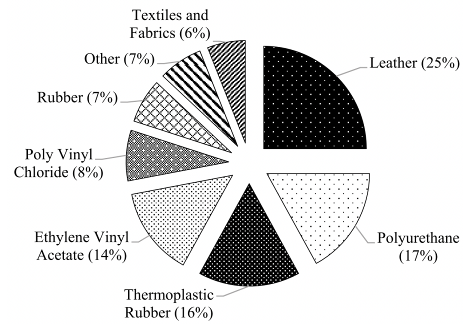

Figure 2: "The material composition of an average shoe," adapted from Waste Management & Research (Van Rensburg et al., 2020).

Rubber is normally found in the outsoles and insoles of shoes because of its properties (Van Rensburg et al., 2020). Rubber is stretchable, flexible and durable. It easily resists changes in temperature, lasts long, and has high abrasion resistance (Arias & Van Dijk, 2019). Rubber is also waterproof. This work will focus on rubber more in depth in later sections.

3.1.2 Synthetics

A synthetic, by definition, is something created by chemical synthesis used to imitate a natural material or product. Plastic is a common synthetic. Synthetics can exist in the upper and lower parts of the shoe and often make up a shoe insole. These synthetics include polyvinyl chloride (PVC), ethylene vinyl acetate (EVA), thermoplastic rubber (TPR), and/or polyurethane (TPU/PU). PVC is a plastic polymer with high insulation properties and tends to be more cost-effective than leather (Scott, 2021). EVA is a rubber-like substance additionally used as foam. EVA soles have the strongest shock-absorbing properties, are flexible, lightweight, and elastic (Scott, 2021). Most shoe brands use EVA for insoles, especially sport shoe brands. Thermoplastic rubber (TPR) is another polymer class that is newer and has excellent slip resistance. Polyurethane soles are similar to EVA insoles in their properties but also are durable and slip-resistant (Scott, 2021).

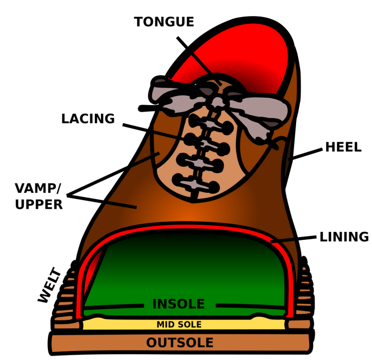

Figure 3: Different parts of a shoe, labeled and adapted from Wikimedia Commons (File:shoe-parts-en.svg, n.d.).

Foam is "any plastic or rubber compound with air bubbles or cells inside," and provides foot cushioning in insoles (Krahenbuhl, 2022). Some insoles use memory foam insoles which allow the insole to adapt to the user's foot structure, and are typically made out of polyurethane. Though many users enjoy the extra cushioning, memory foam insoles generally have low heel stability and break down faster (Memory foam, n.d.). This work will focus on synthetics more in depth in later sections.

3.1.3 Textiles

Textile materials are mainly used in the upper parts of shoes, such as the vamp. They include "cotton, nylon, viscose, polyester, and wool" (Van Rensburg et al., 2020). Cotton is typically thread into yarn. Wool comes from sheep and is extracted by shearing, combing, and cleaning the sheep (Van Rensburg et al., 2020). This work will not focus on textiles, as they are not commonly used to produce shoe insoles.

3.1.4 Leather

Leather is used in many different parts of a shoe, making it an exceptionally popular and crucial material for the footwear industry. It can be found in the upper parts, lower parts, and lining of the shoe (Van Rensburg et al., 2020). It can even be found in shoe soles. Leather comes from animal skins, the most common being cows. However, many industries use leather from sheep, dogs, cats, or even more exotic animals like certain reptiles. According to Rensburg et al., leather "can be sewn, formed and made waterproof without losing its breathability and durability" (2020). Thus, leather is a vital material for shoe production. Many scholars have dedicated their studies towards finding suitable substitutes for leather, given their high importance. This work will not focus on leather.

3.2 Sustainable alternatives for shoe production

Traditional materials used in shoes often have extensive environmental impacts, which this work will outline in section 3.3. Several materials are increasingly being used as sustainable alternatives in shoe products to reduce waste accumulation, minimize pollution, and advance environmental efforts. These materials include, but are not limited to pinatex, cork, recycled plastic and rubber, and organic cotton.

Table 1 lists the main traditional materials used in shoes and their sustainable alternatives.

3.2.1 Piñatex

Piñatex is a natural fiber derived from pineapple leaves. Piñatex can be woven together to generate the thread that holds shoe materials together. It is a crucial alternative to animal leather and textiles, and is often used in the upper parts of the shoe. Piñatex is water resistant, versatile, and has many of the same properties as leather (Nguyen, n.d.). This work will not focus on piñatex as it is not often used in the production of insoles.

3.2.2 Cork

Cork is a natural material that is found on the outer bark of a cork oak tree. Cork can be used in the upper and lower parts of a shoe, but is often found in the insoles of shoes due to several unique properties it holds. According to the Lifelong Learning Programme which provides an online course on sustainable materials in footwear, cork is a good shock absorber, thermal insulator, is lightweight, has good slip resistance, resists wear, and both allows the foot to breathe while preventing moisture (2016). It is also microbial. Cork can also provide ideal arc support and is "proven to reduce and prevent foot illnesses" (Amorim Cork Composites, 2020). Cork insoles, similar to memory foam, can conform to a user's feet and arch within 10 hours of wear; however, they will not flatten out because of their rigid structure (Memory foam, n.d.). Some have referred to cork as "nature's foam" (Amorim Cork Composites, 2020). This quality makes cork ideal for all sorts of footwear, from orthopedic to stylish. The present work centers around cork and will expand on cork in later sections.

3.2.3 Recycled plastic and rubber

Many sustainable footwear companies use recycled plastic and rubber for footwear materials to avoid exacerbating already-existing waste accumulation. For example, several sustainable shoe brands in Portugal, such as Zouri, have gathered trash and plastic bottles from beaches and repurposed them into footwear materials. In doing so, these companies view waste as raw material that can be transformed into a product, rather than simply waste. Recycled rubber can be reclaimed from remnants of used tires, for example. These recycled materials are often used in shoe soles to replace raw rubber or synthetic plastic and have the same properties as regular rubber and plastic.

3.2.4 Organic cotton

Organic cotton has the same properties as regular cotton with different production processes. More information on these processes is located in section 3.4.4.

Table 1. List of traditional materials used and their respective sustainable alternatives

Traditional footwear material	**Used mainly in x part of shoe**	**Sustainable alternative**
Rubber	Lower parts, outsole and insole	Cork, recycled rubber
Synthetics	Lower and upper parts, but mainly in outsole and insoles	Cork, piñatex, recycled plastic and rubber
Textiles	Upper parts	Piñatex, organic cotton
Leather	Upper and lower parts, including insole	Piñatex, cork

3.3 The environmental impacts of traditional materials

A life cycle assessment on shoe consumption in Sweden done by Gottfridsson and Zhang as part of a masters thesis in industrial ecology at the Chalmers University of Technology provides crucial insight into different environmental impacts of traditional shoe materials. This source, in addition to several other scientific and scholarly articles are used in section 3.3 and sections 4 and 6.

3.3.1 Rubber

The main environmental impacts deriving from rubber production include the emission of greenhouse gasses, deforestation, and the replacement of natural agricultural land to latex plantations (Gottfridsson & Zhang, 2015). Rubber production emits volatile organic compounds (VOC) and carbon dioxide into the atmosphere exacerbating air pollution and ozone depletion (Gottfridsson & Zhang, 2015). Additionally, wide-spread latex plantations can have negative impacts on species habitats and biodiversity. According to Van Rensburg et al., "conversion of land use zones from natural forests to rubber plantations disrupts the natural habitat and causes a subsequent loss of biodiversity as ecosystem changes occur" (2020). Overall, using rubber crops in a large-scale economic way can be detrimental to the environment.

Rubber is a thermoset material. According to Martin's Rubber, an expert company in rubber engineering, this means that "the curing process (as opposed to the melting and cooling process used in thermoplastics) called vulcanisation results in a permanent change in the molecular structure of the rubber" (Clarke, 2013). This feature gives rubber its elastic properties, making it so that "once a part is cured, it cannot be melted down and recycled into a new part in the same way as plastics can be" (Clarke, 2013). Similarly, rubber can be made into foam. Foam itself consists of multiple different types of plastics, which, when combined, are unable to be recycled (Krahenbuhl, 2022). Thus, when left in landfills, foam releases toxic particles.

3.3.2 Synthetics

The environmental impacts of synthetics, or plastic, are numerous. Firstly, plastic is made from fossil fuel materials such as coal, oil, and natural gas. The production process, similar to rubber, releases VOCs into the environment, and because plastic derives from fossil fuels, it is considered a non-renewable resource (Van Rensburg et al., 2020). Other harmful pollutants and toxic wastes are released during the manufacturing process. Plastic and synthetic materials are also not biodegradable. They can take up to 1000 years to decompose (DiNapoli, 2022). Even with recycling efforts, the vast majority of plastic (91%) ends up in landfills (Van Rensburg et al., 2020). The accumulation of synthetics in landfills further releases pollutants such as "polyaromatic hydrocarbons, dioxins and furans" into the atmosphere and negatively impacts the environment long-term (Van Rensburg et al., 2020). Pollutants can seep into soils and water and harm nearby drinking water.

3.3.3 Textiles

When cotton is not produced organically, it uses excessive amounts of pesticides and is incredibly water-intensive, meaning it intakes a lot of water. As a result, the cultivation of cotton can "severely degrade natural ecosystems" (Van Rensburg et al., 2020). Roughly 10% of global pesticide usage and 25% of insecticide uses derived from cotton production. Additionally, environmental impacts also arise from chemicals used in cotton blends. Nylon is a synthetic fiber produced from using fossil fuels and emits large amounts of nitrous oxide, which is 300 times the potency of CO_2 (Uren, 2020). Polyester is another synthetic fiber that is often used in cotton blends and has negative environmental impacts. Wool, on the other hand, increases environmental degradation through animal farming, transformation, waste, and resource use (Gottfridsson & Zhang, 2015).

3.3.4 Leather

The leather production process involves several steps beginning with the slaughtering of an animal. Several differing environmental impacts emerge in each production step. According to Van Rensburg et al., "extrapolation of data for over 776 million pairs of leather footwear estimates that over 2.25 million tonnes of chemicals are used to treat leather and the majority of it is released into the environment" (2020). Cattle production, a large leather industry, is a large methane emitter and uses vast amounts of land. Food and water consumption, as well as feedlot operations can produce large amounts of pollution and waste that often are not treated (Van Rensburg et al., 2020). This waste often exists in the form of waste water "containing chemicals and biological material as well as solid waste such as contaminated sludge" (Gottfridsson & Zhang, 2015). When left untreated, the hazardous chemicals in wastewater can range from chromium, strong acids, and pesticides (Gottfridsson & Zhang, 2015). The use of chromium in particular releases large amounts of emissions and harmful pollutants such as VOCs (Van Rensburg et al., 2020). Many of these chemicals are used in the tanning process in leather production. One Life Cycle Assessment (LCA) of leather shoes from the Universitat Autònoma de Barcelona found that "nearly 50% of the non-renewable prime materials and 70% of the water consumed" were used during the tanning stage (Milà, et al., 1998).

Leather, when left in landfills, also has several environmental impacts. Many of the chemicals used in leather production leak out into the soils and into groundwater, which negatively impacts human and environmental health.

3.4 The environmental benefits of sustainable materials

3.4.1 Pinatex

Pinatex has a very minimal environmental impact. Pineapple leaves are a bi-product of a pineapple harvest that is already taking place; thus, the extraction of the leaves does no harm to the plant nor the harvest. Obtaining pinatex also does not require any additional pineapple production or land use. According to an online learning platform on sustainable materials, "264 tons of CO_2 emissions were saved in making Piñatex by using 825 tons of waste leaves from the pineapple harvest, which are otherwise discarded" (Craft, 2022). Extraction does not involve toxic chemicals, generate waste, and is not water intensive. From an animal welfare standpoint, pinatex is also cruelty-free, as it avoids the slaughtering of animals for consumer purpose.

Some stages of the pinatex manufacturing processes use energy which may derive from fossil fuels. Pinatex is not fully biodegradable; however, 80% of it is, making it much more sustainable than other materials (Nguyen, n.d.).

3.4.2 Cork

Cork is a natural environmentally-friendly material and is 100% biodegradable. Harvesting cark does no harm to the cork tree, and additionally absorbs CO_2 which mitigates the effects of climate change. It is a carbon negative material, promotes biodiversity, and can be reused. Further environmental benefits and expanded quantitative data are not mentioned in this section, as they are outlined more in depth in section 5 and 6.

3.4.3 Recycled plastic and rubber

A large portion of the environmental impact and pollution that comes from plastic and rubber occurs over time, after production processes, when they sit in landfills. Using recycled plastic and rubber reduces the pollution that would otherwise exist in these waste zones. Additionally, using recycled rubber minimizes the need for increased deforestation and conversion of agricultural land for the purpose of expanding latex plantations (Gottfridsson &

Zhang, 2015). This helps preserve biodiversity and prevent habitat loss. Ultimately, using recycled plastic and rubber excludes any of the pollution and harm that results from initial production and manufacturing.

However, there are differences between how and to what extent recycled rubber versus plastic can be used. As mentioned earlier, the initial curing process of rubber is permanent and makes it so that it cannot be melted down again and recycled like plastics (Clarke, 2013). Therefore, it is more difficult to use recycled rubber exactly how a company may want to.

On the other hand, plastic can be melted into a new product (Clarke, 2013). This process does use energy and emit pollution; however, it is a much more sustainable and circular process than generating plastic from scratch.

3.4.4 Organic cotton

Organic cotton is different from conventional cotton as it does not use genetically modified seeds, entirely avoids pesticides, and doesn't use harmful chemicals or fertilizers. A well-established cotton underwear company highlights that "organic cotton is responsible for 46% less greenhouse gasses than conventional cotton" (Rigg, 2021). Regular cotton is also less water-intensive compared to organic cotton. As a reference, it takes 2,700 liters of water to produce cotton for one t-shirt whereas organic cotton uses only 243 liters (Rigg, 2021). There is also significantly less water pollution from organic cotton because there are no pesticides running into water sources that communities rely on (Rigg, 2021).

The end-of-life capacities for the footwear materials mentioned are shown below in Table 2.

Table 2: End-of-life capacity for footwear materials, sourced mainly from DiNapoli (2022)

Organic cotton	Traditional cotton	Cork	Piñatex	Leather materials	Natural Rubber	Synthetic materials
1-5 months to biodegrade	5+ months to biodegrade	3-10 years to biodegrade	Not fully biodegradable; easy to decompose	25-40 years to biodegrade	50-80 years to decompose	Not biodegradable; up to 1000 years to decompose

4. Results for Simplified Life Cycle Assessment of Rubber and Plastic Insoles

4.1 Goal and scope definition

The goal of this LCA study is to show and compare the environmental impacts of different traditional materials and their production processes used to make shoe insoles. The scope includes the entire life cycle of the insoles, from raw material extraction to end-of-life disposal (i.e. cradle to cradle).

System boundaries: In analyzing life cycles associated with insole production, various complications arise including:

- Several different types of materials are used in the production of a single insole including raw materials and/or synthetic materials including PVC, EVA, TPR, TPU, and more.

- Each material, whether chemically made or naturally extracted, generally has its own unique production process. Thus, the production processes mentioned in this paper will often be generalized to account for all types of materials and their relative processes. For example, a single insole may incorporate many different types of materials and thus processes for someone with a foot condition.
- The scientific LCAs evaluated used different FU; therefore, this LCA does not use a specific FU. Calculations to try to convert different FU into one were not possible with the time allocated to complete this study.

4.2 Inventory analysis

Many shoe insoles are made from a variety of rubber or synthetics including plastic, foam, and synthetic rubber. Others may come from leather or gel. Material selection determines the comfortability of an insole, its durability, its lifetime, and its environmental impact. In recent years, there has also been an increase in rubber and plastic shoe consumption by 36%, whereas other material shoes have mainly held constant or even decreased (Gottfridsson & Zhang, 2015). As such, this LCA will be investigating the use of plastic and rubber as materials for insole production. A flow diagram listing inputs and outputs of each process is shown in Figure 5.

4.2.1 Extraction of raw materials and refining

Rubber. As for rubber, latex is extracted from a latex tree by making a cut into the bark through a process called tapping that collects the liquid sap. Tapping can begin about 5-6 years after planting, and then occurs every two days resulting in about 50 grams of solid rubber each tapping instance (Encyclopedia Britannica, inc.). At a density of 375 trees/ha, ~2,500 kg of rubber can be produced per hectare annually (Encyclopedia Britannica, inc.). Then, the latex is coagulated with formic acid and ammonia to form rubber (Encyclopedia Britannica, inc.). This latex is placed into three categories, concentrated latex, block rubber, and ribbed smoked sheet (RSS). Block rubber is used for shoe insoles.

Thailand is a crucial rubber-producing country, producing around 35% of global latex in 2009 (Jawjit et al., 2009). A study done by W. Jawjit et al. as part of the Journal of Cleaner Production investigated the impacts of Thailand's rubber industry. The study found that, assuming a yield of 5.64 tons of fresh latex per ha/year, the diesel use in tillage was 0.78 liter/ha/year, in transportation was 5 liter/trip, and in block rubber mills was 1000 MJ/ton (Jawjit et al., 2009). The electricity use for block rubber mills was 220 kWh/ton and the liquified petroleum gas use was 1252 MJ/ton (Jawjit et al., 2009). Emission factors further illustrated greenhouse gas emissions. The emission factor of carbon dioxide in diesel use in tractors for tillage was 73 g/MJ and in latex transportation was 74,000 kg/MJ (Jawjit et al., 2009). Synthetic fertilizers used in rubber plantations are also a source of greenhouse gas emissions from their energy-intensive production process.

Plastic. As for plastic, the raw materials that exist come from a variety of sources, largely crude oil and natural gas. The process of fossil fuel extraction uses up a large amount of energy and fossil fuels are not a renewable resource. Once extracted, fossil fuel materials need to be refined, for example, crude oil needs to be transformed into different petroleum products (Baheti, n.d.). This process involves heating the crude oil and then sending it to a distillation unit where heavy oil "separates into lighter components called fractions" (Baheti, n.d.). These fractions consist of compounds crucial to plastic creation (Baheti, n.d.). The crude oil refining process overall uses large amounts of energy, accounting for 6-8% of all global industrial energy consumption (Crude Oil Refineries).

4.2.2 Polymerization and copolymerization

Polymerisation is the next step in the production process. Polymerization is the linking of monomers to form a polymer through chemical bonding. One way to achieve this linkage is through addition polymerisation, in which a catalyst is introduced. PVC and polyethylene are examples of additional polymers. Copolymerisation, is another technique that combines "two or more different monomers in differing proportions" into a copolymer (Lifelong Learning Programme, 2016). PVC and EVA are copolymers, mainly used in shoe insoles in their thermoplastic form.

Polymer processing is incredibly energy intensive as it "requires a high volume of electric power for thermal energy" (Khripko, et al., 2016). Most of this electricity comes from fossil fuel energy, namely petroleum. A study done by Halina Marczak at the Lublin University of Technology found that 70 MJ of energy was consumed to produce ~1 kg of polyethylene in 2016 (Marczak, 2022). 52 MJ of energy were consumed to produce ~1 kg of PVC (Marczak, 2022). The study also found that the production of plastic in primary forms in the EU in 2020 amounted to 55,000 in 2020 (Marczak, 2022). Additionally, the polymerization process is expensive. Energy use from processing accounts for "5-10% of total production costs" (Khripko, et al., 2016).

Table 3 places the previous quantitative data into an organized fashion.

Table 3: Inputs and outputs for the extraction and processing of rubber or plastic

PROCESS	INPUT	OUTPUT	SOURCE
Rubber tillage	0.78 liter/ha/year of diesel tillage (assuming a yield of 5.64 tons of fresh latex per ha/year)	Greenhouse gasses; Emission factor of carbon dioxide: 73 g/MJ	Jawjit, 2009
Rubber transportation	5 liter per trip of diesel	Greenhouse gasses; Emission factor of carbon dioxide: 74,000 kg/MJ	Jawjit, 2009
Block rubber mills	1000 MJ/ton of diesel; 220 kWh/ton of electricity; 1252 MJ/ton of petroleum gas	Greenhouse gasses, pollution	Jawjit, 2009
Polymerization	Energy; 70 MJ/kg of polyethylene; 52 MJ/kg of PVC	Greenhouse gasses, toxic chemicals, pollution	Marczak, 2022

4.2.3 Shaping/molding

The next step in the manufacturing process is shaping. In this process, a combination of melted materials are mixed together (Baheti, n.d.). These materials include polymers, reinforcing fillers, plasticizers, and/or protective agents and, once melted, create a compound. To melt them, the compound is placed in a mold and heated to around 150 to 170 degrees celsius (Lifelong Learning Programme, 2016). For rubber materials, this process is known as vulcanization and takes about 6-12 minutes so that the chemical reaction can occur between the polymers molecules (Lifelong Learning Programme, 2016). For thermoplastics, the compound is heated to 140 to 190 degrees celsius and injected into a mold and then cooled for 2-6 minutes (Lifelong Learning Programme, 2016). Prior to injection, compounds such as PVC and EVA "may be incorporated with expansion agents that release gasses when heated" (Lifelong Learning Programme, 2016). This generates air bubbles in insoles that reduce their weight. Heating is incredibly energy-intensive and releases greenhouse gasses. Burning PVC also releases harmful pollutants like hydrochloric acid and carcinogen dioxins.

The Journal of Ecological Engineering found that injection molding consumed around 12 MJ of energy per kg of plastic. Another study done by Khripko et al. from the International Journal of Energy and Environmental Engineering comparing the energy demand and efficiency measures in polymer processing in Germany versus Australia found that molding demanded 5.3 GWh of electricity per year and 13,000 liters of heating oil (Khripko et al., 2016).

The Khripko et al. study also found that the "the injection moulding plant in Germany can save 56 % of its primary energy" and Australia would save 52% of its primary energy if larger energy efficiency initiatives were put in place (Khripko, et al., 2016). The study also found that the thermal oil system has extensive environmental impact and is associated with major energy losses. This is because fossil fuels, for example coal, are first converted to thermal energy, then electricity, then the electricity is transported and transformed rather than having one singular conversion occur (Khripko, 2016).

Production processes in insoles can vary depending on material or desired end product. Ideastep, a well-established insole manufacturer, provides more information about different potential insole shaping processes in addition to injection molding. These processes are listed below in Table 4.

Table 4: Processes involved on insoles production

	Typical insole materials used in the process	Technical description	Process characteristics
Perfusion production	PU, GEL	Mixture of two materials is injected into a mold.	High efficiency Output rate around 70-100 molds/day
Cold forming	EVA, foam	Pre-cut sheet is baked in an oven causing material to soften and be able to be placed into the mold. Water is used to cool the mold.	Used with simple products. Materials that cool fast have higher yields.
Hotpress forming	"Used in products with higher technical content or product requirements" (Insoles Production, 2021)	Sheet is hotpressed then placed on a cold-pressing device.	High cost, low output Used for complex products
Injection	Thermoplastic polyurethane (TPU), TPR (thermoplastic rubber)	Material is heated in high temperatures and then injected into a mold. Can be removed after cooling.	Used in high-end products (i.e. orthopedic insoles)
Open mold casting	GEL, other elastomeric liquid materials	Use a nozzle to inject GEL into a mold. The mold is heated to speed up formation.	Mostly used for front and back palm pads. High efficiency High output

4.2.4 Manufacturing

The manufacturing process of insoles involves a variety of processes that include gluing, packaging, printing patterns, and polishing.

Firstly, the insole is inspected for air bubbles, which can form during the production process. Though some air bubbles are intentional, such as in foam materials, other times they are not and can compromise not only the appearance of the insole, but its quality and end life. Air bubbles can be detected visually if the insole is transparent; otherwise, pressing down on the product can determine the location of bubbles (Insoles Production, 2021). In terms of end life, the existence of air bubbles can make it so that scraps generated by the product after its use are not able to be repaired and thus reused properly.

Lack of material is another issue outlined by Ideastep. Some insoles, post-production, are uneven or cave inwards in harmful areas. This unevenness impacts the quality of the product and minimizes market value. Poor material measuring or mold design can come from human error, mechanical equipment issues, or a general shortage of materials (Insoles Production, 2021).

Special insoles, such as orthopedic insoles, require extra polishing during the manufacturing process. Polishing involves polishing the edges, heels, or arches of insoles (Insoles Production, 2021). According to Ideastep, "some products or materials may also require secondary processing, such as EVA laminated layer[…] to roughen the surface to ensure reliability and convenience of reprocessing" (Insoles Production, 2021).

Some insoles have fabric covers on them. In the manufacturing process, they are stitched or glued onto the plastic or rubber.

Gluing is a crucial step in insole production, and is used in both the "front and back stages of insoles production" (Insoles Production, 2021). Glue is a type of plastic, and thus has harmful end-of-life environmental impacts in landfills when seeped into soil and groundwater. Laminating treatments are an example of gluing. More specifically, materials like leather or fabric are glued into the shoe and then "molded with EVA/PU/GEL/TPR" (Insoles Production, 2021). Many insoles also benefit from gaskets, which are "reinforced shells to enhance comfort and function such as PORON pads on the heel Film, [or] heel and foot arch TPU support film" (Insoles Production, 2021). Figure 4, derived from an Amazon insole diagram, shows the placement of these gaskets in relation to the insole as a whole. Complications and customer complaints arise when gluing is not done properly and can result in short insole lifespan or delamination. Additionally, glue overflow negatively impacts the appearance of the product and market value.

Figure 4: "High Elastic GEL Insole," adapted from Amazon (Feet insoles comfort, n.d.)

4.2.5 Packaging and transportation

Transportation involves the transportation of materials from one place to another. In the case of shoe insoles, this takes into account the transportation of rubber from trees, for example, to processing plants. Rubber can be imported from all around the world, increasing transportation emissions and environmental impact. After processing, materials may or may not need to be transported to a manufacturing plant for further inspection. Once packaged, some insoles will be transported to a shoe company that then inserts it into a variety of shoes and some insoles are directly transported to the consumer. Consumer shipping can also occur internationally, increasing greenhouse gas emissions.

Packaging can vary from PVC boxes to simple paper bags, depending on the insole production company. Some insoles will be transported to a shoe company that then inserts it into a variety of shoes and some insoles are directly transported to the consumer.

4.2.6 Use phase

The duration an insole can be used before breaking or reaching its end of life depends on how often the user wears the shoe and the physical activity being exerted on the insole. When made with foam of soft plastic, insoles may need to be replaced after 6 months to a year when worn regularly (How often, 2023). Higher quality and often more expensive insoles may be used for around 3 years when properly taken care of. This includes specially made orthotic insoles.

4.2.7 End-of-life:

When insoles are worn out and have reached their end-of-life, they are mainly thrown away and then taken to the landfill or incinerator. 95% of the 300 million pairs of shoes we throw away annually will end up in landfills. In the UK, over 30 tons of insoles reach landfills annually, which is "equivalent to 18 cars" (How recycling your insoles, 2021). Many insoles are also burned, and when burned, chemicals such as phthalates, are released even faster and are harmful to human reproductive systems (Hesperian Health Guides, n.d.). Other chemicals include lead, mercury, cadmium, and aromatic hydrocarbons (Hesperian Health Guides, n.d.).

During manufacturing and processing, companies mix several plastics and other materials together which make recycling efforts extremely difficult for insoles. Foam, for example, is not able to be recycled because it is made up of multiple finds of plastics (Krahenbuhl, 2022).

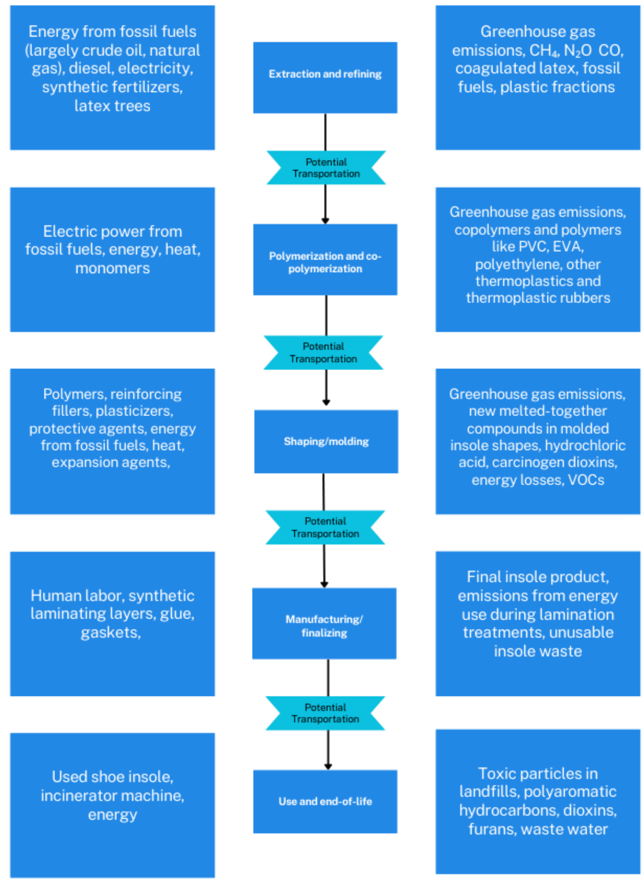

Figure 5: Flow diagram of the inputs (left) and outputs (right) of each stage of the simplified rubber and plastic shoe insole life cycles

A select few users may decide to recycle their insoles or send them to organizations that attempt to repurpose them. Nike, for example, has used waste materials from old shoes to make playground floorings (Hesperian Health Guides, n.d.). However rubber, being a thermoset material, cannot be recycled in the same way pure plastic can because of vulcanization. Put differently, rubber cannot be reheated and molded into a new product once it has already gone through the manufacturing process. This limits rubber's ability to be reused in certain ways.

However, when recycled, traditional and pure-polymer insole materials can be granulated and used again to make new insoles (Marczak, 2022).

4.3 Impact assessment

The expansion of rubber forests for the purpose of generating materials such as insoles has detrimental impacts on biodiversity loss, soil degradation, and deforestation. The Thailand study found that replacing and converting tropical forests with rubber plantations resulted in a "net loss of carbon to the atmosphere" (Jawjit et al., 2009). One staggering statistic from the study showed that, in this case, "carbon loss from [forested] ecosystems account for 97% of the total greenhouse gas emissions from rubber plantations" (Jawjit et al., 2009). This data coincides with carbon losses resulting from palm oil plantations, which are widely known for their greenhouse house emissions and deforestation. Deforestation in both plantations additionally releases CH_4, N_2O and CO (Jawjit et al., 2009). Synthetic fertilizers used in rubber plantations are also a large source of greenhouse gas emissions.

The polymerization process has clear environmental impacts due to its high energy intensity requirements from fossil fuels, pollution, and waste generation. According to Khripko et al., the plastic industry contributed both directly and indirectly to over one third of global greenhouse gas emissions (2016). A single pair of sneakers made with traditional materials typically generates 30 lbs of CO_2 emissions which equates to "keeping a 100-watt light bulb on for a week" (DiNapoli, 2022). The processing of polymers also often involves the use of various chemicals, such as solvents, additives, and dyes. These chemicals can be hazardous to human health and the environment if not handled and disposed of properly.

Entirely rubber-made insoles can take 50-80 years to break down (DiNapoli, 2022). Synthetic materials can take up to 1000 years to decompose (DiNapoli, 2022). The chemicals used in insole processing, when left in landfills, become released into the environment and contaminate soil and groundwater (Hesperian Health Guides, n.d.). When burned, the harmful chemicals are released into the environment and impact human health. Most traditional insoles end up in landfills or are burned due to their inability to be recycled.

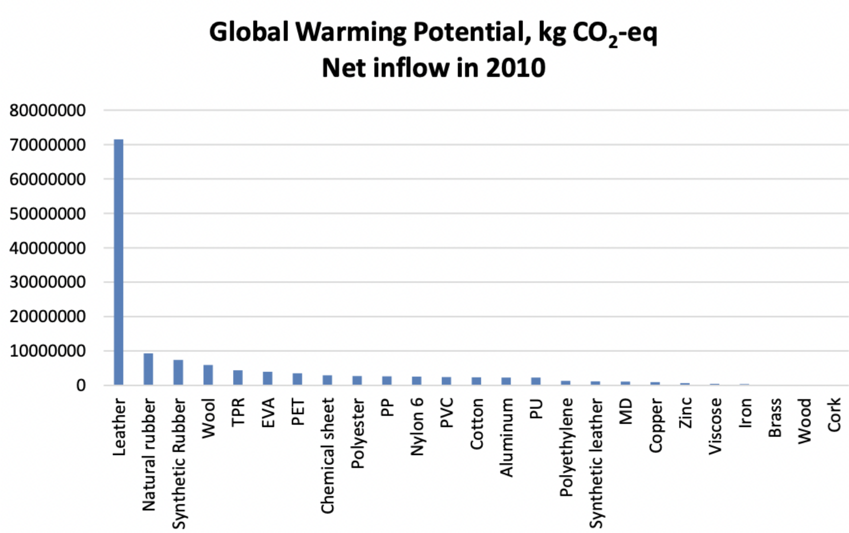

Figure 6. Global warming potential (GWP) of different shoe materials, adapted from Gottfridsson & Zhang (2015)

Another study published in the Journal of Hazardous Materials investigated the impact of microplastics (MP) on aquatic environments from shoe soles using tadpoles as a subject. It found that traditional shoe soles release chemicals like benzothiazole, para-xylene, and zinc which "inhibit growth and induce abnormalities in aquatic-living organisms and cause water and oxidation stress" (Araújo et al., 2022). Tadpoles often mistaken microplastics as food and their ingestion resulted in harmful intestinal conditions. However, the impacts expanded beyond just ingestion, as tadpoles were found to function as "potential vectors for [microplastic] dispersal" (Araújo et al., 2022). Once ingested, the microplastic fragments are reduced in size and emitted through the feces, resulting in "much greater amounts of MPs than the number was ingested" (Araújo et al., 2022).

One Life Cycle Assessment for shoe consumption in Sweden found that the global warming potential (GWP) for net inflow in 2010 for consuming different shoe materials was highest among leather, natural rubber (~9,000,000 kg CO_2-eq), and synthetic materials (~25,000,000 kg CO_2-eq) as shown in Figure 6 (Gottfridsson & Zhang, 2015). The lowest GWP was in cork (Gottfridsson & Zhang, 2015). Eutrophication potential was also high among synthetic and rubber materials, at ~6,000 kg PO_4-eq and ~ 13,000 kg PO_4 -eq, respectively (Gottfridsson & Zhang, 2015).

For more impacts, see section 3.3.1 and section 3.3.2.

5. Environmental, economic, and social benefits of cork

Cork trees play an important role in mitigating global warming as they both capture CO_2 and release oxygen into the air. According to the School of Agronomy in Lisbon, "the montado has the capacity to retain around 6 tons of CO_2 per hectare each year, which in Portugal corresponds to over 4 million tons of CO_2 per year" (Cork Information Bureau, 2015). For each ton of cork produced, the forest can "sequester up to 73 tons of CO_2" (Amorim Cork Composites, 2020). This has implications for cork forests around the world as they act as carbon sinks. According to ApCor, the annual emissions from driving an average car are compensated by "less than 1.5 hectares of montado" (Cork Information Bureau, 2015). A single cork stopper additionally retains ~8 grams of CO_2, which is 200x its weight (Cork Information Bureau, 2015). This compares to a vehicle, which on average releases 150 grams of CO_2 per kilogram. It is clear that the consumption of cork, even a single cork wine stopper, holds incredible power in mitigating the effects of climate change. One study by a researcher at the Portuguese National Institute for Engineering and Industrial Technology (INETI), Luis Gil, further pointed out the impact of consuming cork stoppers on pollution trends. Those who drink an average of two glasses of wine a day will ultimately purchase 122 cork stoppers annually, which retains "1.183,40 grams of CO_2 from the atmosphere - the equivalent to a 7 km vehicle mileage/year" (Cork Information Bureau, 2015).

Cork trees also help to maximize soil conservation and hinder desertification. Soil erosion largely results from the flow of excessive amounts of water from rain or other sources. Cork trees are able to retain 26.7% of total precipitation (Cork Information Bureau, 2015). The size of cork trees also provide a barrier against wind which functions to protect soils from blowing away. Perhaps even more importantly, cork trees play a huge role in preventing desertification. They extract and return crucial nutrients into the soil, improving soil organic matter which additionally increases soil water retention. Cork trees also promote biodiversity, another mechanism against desertification. Montados and the Mediterranean in general have been qualified as one of the 36 biodiversity hotspots in the entire world. This means that they have at least 1,500 vascular plants as endemics, which are plant species found nowhere else in the world. In the Alentejo region, plant diversity "can reach a level of 135 species per 1000 square meters" (Cork Information Bureau, 2015). These plants have a variety of bentifs in the medical field and culinary field. According to ApCor, "no other substitute product of cork can be this sustainable from the environmental perspective, taking into account the poor soil and harsh climate" (Cork Information Bureau, 2015).

However, perhaps the most important quality of a cork tree lies in its uniqueness compared to other trees. Most other trees cannot survive with extensive removal of bark. Bark provides a crucial outer layering that protects the inner part of the tree from over-moisture and additionally helps regulate its temperatures during hot or cold seasons.

Cork is economically sustainable – it has a high market value. Currently, cork exports result in a balance of trade of 935 million euros in Portugal (Cork Harvesting, n.d.). It is a huge contributor to the country's GDP, as has been for decades. Additionally, the cork industry employs almost 8000 direct manufacturing jobs (Cork Harvesting, n.d.). That number becomes significantly higher with indirect jobs. Aside from production and consumption benefits, the montados provide a home for hunting and fishing activities, cattle breeding, food cultivation, and also furnish a perfect environment for ecotourism. The financial benefits derived from tourism visits are distributed among rural populations nearby. Cultural attachments to cork in Portugal have also been historically important.

6. Results for Simplified Life Cycle Assessment of Cork Insoles

6.1 Goal/scope definition

The goal of this simplified LCA intends to provide a relevant comparison from the simplified LCA of rubber and plastic insole materials provided above with production processes associated with cork insoles. The life cycle of a cork insole looks significantly different than that of a rubber or plastic insole. However, current research on the life cycle of cork insoles appear to be lacking, or not publicly distributed online. Thus, this simplified LCA gathers information from cork extraction industries, manufacturing plants, and sustainable shoe websites to illustrate more holistically how cork insoles are currently being processed and disposed of.

The cork insole production process consists of extraction/stripping, processing (drying, decontaminating), manufacturing, transportation/packaging, use, and end-of-life.

6.2 Inventory Analysis

6.2.1 Extraction/stripping

The first step in a cork insole life cycle is extraction of natural cork from the cork tree during summer harvesting season. This process is known as "stripping" (Manufacturing process, 2021). Stripping is carried out manually by a harvester with a specially designed hatchet, avoiding potential harm to the trunk (Manufacturing process, 2021). Stripping occurs every 9 years, with the first (virgin) and second (secondary) stripping producing low quality waste cork, and reproduction cork occurring after the 3rd stripping. The average yield for each type of cork is as follows: 2-5 kg/tree of virgin cork, 10 kg/tree of secondary cork, 15 kg/tree of reproduction cork in the third stripping, and then all other reproduction cork harvests are around 30 kg/tree

(Tártaro et al., 2017). Cork insoles often consist of granulated virgin and secondary cork, which is also known as "waste cork." The process of stripping is shown in Figure 7.

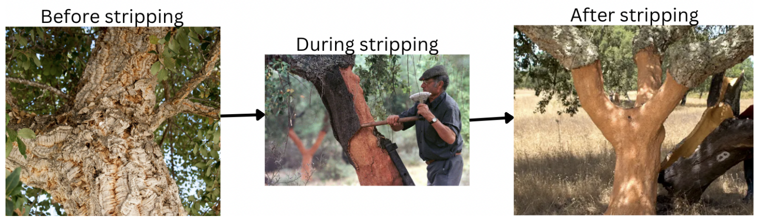

Figure 7. Cork extraction process

Tree and land management also fall under extraction. Every 2-4 years in a cork tree plantation, a disc harrow cleans up "spontaneous vegetation" and then spreads it out to enhance soils (Tártaro et al., 2017). The disc harrow typically uses about 110-180 horsepower in each cleaning (Tártaro et al., 2017). In the 5-7th year, pruning occurs by hand or by machine. Cleaning and pruning steps are repeated after stripping processes.

6.2.2 Processing

The first step in cork processing involves curing. The cork slabs extracted during harvest are stacked outside and left to dry for anywhere from a few weeks to several months (Manufacturing process, 2021).

The dried cork slabs are then taken to a cork processing plant, where they are lowered into "large copper vats filled with boiling water containing a fungicide" (Manufacturing process, 2021). Here, the cork is "treated with heat and water to remove dirt and water-soluble components like tannin" (Manufacturing process, 2021). The cork remains submerged for around 30-75 minutes (Manufacturing process, 2021). This process not only removes any contaminants from the cork, but also makes the cork more flexible and softer for manufacturing processes (Manufacturing process, 2021).

Following the heat treatment, the cork slabs are "heaped and stabilized to straighten" for roughly 14-21 days, and then after removing the poor-quality outer layers of the slab by knife, are placed in a dark cellar where they dry out for a few more weeks (Manufacturing process, 2021). Lower quality (waste) cork is typically granulated with a machine (Manufacturing process, 2021). This ground cork is used for shoe insoles. Higher quality cork may be used as a substitute for leather on the upper parts of a shoe.

A study done by Tártato et al. at the University of Porto completed a life cycle analysis of insulation cork boards (ICB) which have an almost-identical material composition of cork insoles. The study found that the decontamination and granulation processes consumed around 6.434 kWh of electricity per cubic meter of IBC (Tártato et al., 2017). A single cubic meter, assuming average shoe volume, could fit 200 pairs of shoes inside it, thus, for just an insole, electricity consumption could be calculated around ~0.008 kWh per insole. Emissions from electricity for an ICB board are 1.038 kg CO_2 eq. per cubic meter, approximately equating to ~0.001 kg CO_2 eq. per shoe insole (Tártato et al., 2017).

Comparisons made between cork industries and traditional insole material companies' environmental impact in terms of energy consumption, carbon footprint, greenhouse gas emissions, and more are shown in Table 5.

6.2.3 Manufacturing

To generate pure agglomerated cork, the cork particles are placed into a mold, covered, and either quickly steamed at 315 degrees celsius or heated at 260 degrees celsius for 4-6 hours (Manufacturing process, 2021). Heat activates the cork's natural resins and binds the cork into a solid block (Manufacturing process, 2021). This block can then be transported to an insole plant that cuts or further heats the mold into the insole shape. Other times, the granulated cork itself is transported to an insole plant that performs mold heating directly to the shape of the insole. The end product for a pure agglomerated cork is 100% natural.

Agglomerated cork that is not pure is combined with other materials. Many orthopedic insoles use thermoforming to combine cork and EVA (Amorim Cork Composites, 2020). Another insole company, Footcork Evolution, developed by Amorim Cork Composites, which is the largest cork producer in the world, blends the granulated cork with other "by-products from other industries" (Amorim Cork Composites, 2020). This process is called industrial symbiosis, defined as "the process by which wastes or by products of an industry or industrial process become the raw materials for another" (Internal Market, n.d.). This process is incredibly sustainable and allows for by-product materials to gain a new life. Composition cork is made by "uniformly coating the cork granules with a thin layer of an additional adhesive agent" (Manufacturing process, 2021). The adhesive agent placed on the granulates can vary from glue to EVA to natural resins. Eldacorcho, a spanish cork brand, uses glue as an adhesive agent for their insole products (Eldacorcho. 2022). Once coated, the granulates are put into a mold and heated slowly at temperatures depending on the adhesive used (Manufacturing process, 2021). Then, the blocks are removed and cooled from the mold (Manufacturing process, 2021). Similar to pure agglomerated cork, insole companies can perform this process themselves and mold the cork and adhesive agent to their insole shapes initially, or obtain the composition cork block from companies and then re-heat to mold into a desired shape.

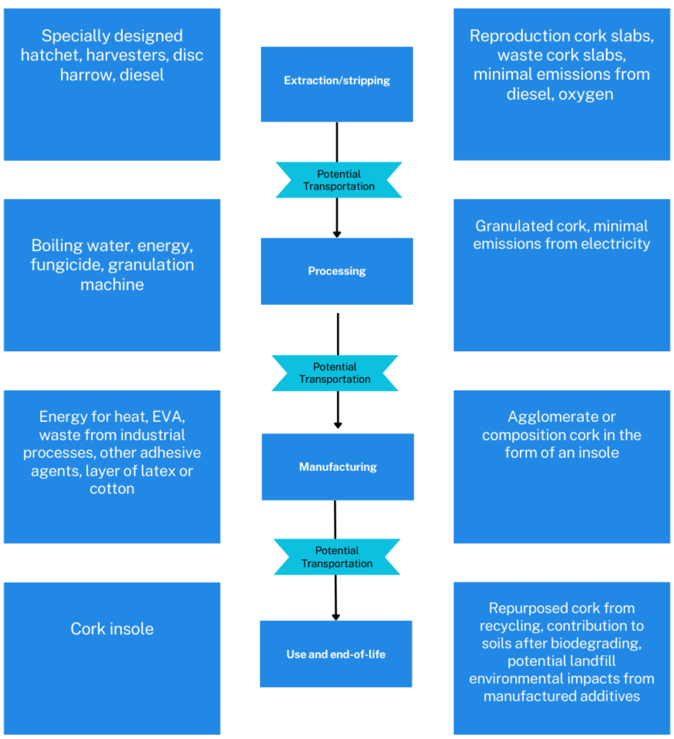

Figure 8. Flow diagram of the inputs (left) and outputs (right) of production for a cork insole

After either of these processes, the cork insole is trimmed and cut to ensure proper shaping.

The final material composition of a cork insole and its manufacturing process depends on the footwear brand and its intended use. Cork insoles may contain a latex layer or cotton layer on top, or may be manufactured and melted with rubber or plastic to maximize certain desired properties as in composition cork. Thus, many cork insoles are not composed entirely of only cork.

6.2.4 Packaging and transportation

Transportation for cork may vary. Cork produced in Portugal and transported to companies in Portugal use much less diesel and energy than other forms of transportation such as shipment or air travel. Shipments made from companies to international customers would also use more energy and produce more pollution. Exact numbers for travel in the transportation phase are unclear; however, it is clear that local Portuguese insole industries would produce less emissions than international industries with less access to cork.

PRIMAL Soles, considered to be the world's "first 100% recyclable, circular and sustainable shoe insole" ships its cork from Amorim composites to their own manufacturing plant in the Netherlands. While a significant amount of cork usually remains in Portugal and thus prevents large transportation emissions, PRIMAL Soles sends packages via regular mail in extremely light packages to limit CO_2 emissions (Bansal, 2023). By using an app called Shopify, all consumers are also required to financially offset their calculated transportation emissions (Bansal, 2023).

6.2.5 Use phase

Cork shoe insoles have a long lifespan and can be reused in multiple pairs of shoes. They are biodegradable and can be composted at the end of their life cycle. During the use phase, cork insoles have a low environmental impact as they are a sustainable and natural material that does not release harmful chemicals.

6.2.6 End-of-Life

At the end of their useful life, cork shoe insoles can be disposed of through composting or recycling. Cork is a biodegradable material that can decompose naturally and does not harm the environment. Alternatively, the insoles can be recycled to create new products such as insulation or flooring. Therefore, the end-of-life phase of cork shoe insoles has a low environmental impact.

Many cork shoe brands provide a business mechanism for users to give back their used insoles so that they don't end up in landfills. PRIMAL Soles reintroduces these used insoles back into the production process, for example. Other brands, such as Zouri, give recycled footwear to a local furniture company that uses the materials in their products.

6.3 Impact Assessment

Cork production is CO_2 negative (Bansal, 2023). The stripping process does no harm to the tree. In fact, "By stripping the cork bark from the cork oak tree, it helps the tree to regenerate itself and in the process absorb more CO_2 out of the atmosphere" (Bansal, 2023). A harvested cork tree captures 5 times the amount of CO_2 than a non-harvested tree (Amorim Cork Composites, 2020). Extraction is also manual, thus it emits no greenhouse gasses. The global warming potential of cork is close to 0, as shown in Figure 6.

Footcork Evolution, as an example, has a "negative carbon balance of -8.2 kg CO_2/m^2" when taking in account the carbon intake of cork forests and the carbon emission from industrial processes (Amorim Cork Composites, 2020).

Table 5. Cork insole environmental impact compared to traditional materials

		Source
Greenhouse Gas Emissions	6x less than average PU foams	(Amorim Cork Composites, 2020)
Energy consumption	3x less than average PVC materials	(Amorim Cork Composites, 2020)
Resource consumption	8x less than average EVA foams	(Amorim Cork Composites, 2020)
Carbon footprint	-116.23 kg CO2 eq. per cubic meter of IBC compared to 127.70 kg CO2 eq. per cubic meter of PU	(Tártato et al., 2017)

As the vast majority of wine stoppers require reproduction cork for their product, cork insoles do not. Cork insoles are naturally using "waste" materials in their products. Additionally, the waste from industrial processes are "100% reusable," as in Amorim Cork (Amorim Cork Composites, 2020). Powder coming from industrial processes and biomass can be used for energy that is re-entered into the production process in a circular way. Granulates and "waste" cork are completely recyclable and reusable for cork insoles.

The main emissions that derive from cork production take place in the processing and manufacturing steps, where thermal energy and electricity are used to heat and mold the cork into a proper insole shape. Other emissions, though minimal, come from diesel used in land management.

7. Discussion

Based on the information provided in both LCAs, cork functions as a feasible and relevant sustainable alternative material to plastic and rubber materials in shoe insoles.

Rubber extraction requires the replacement of natural agricultural land to latex plantations which involves deforestation, habitat degradation, and biodiversity loss. Diesel use, electricity use, and transportation from rubber tillage and mills are large greenhouse gas emitters and involve larger raw material use and energy consumption than cork. The emission factors mentioned in section 4.2.1 were exceptionally high. Rubber also typically uses synthetic fertilizers which similarly have a pollutive production process and can decrease soil fertility and ecosystem health. Plastic requires the extraction of solid fossil fuels, a nonrenewable resource, which is an incredibly invasive, pollutive, and dangerous procedure. Crude oil refining processes also account for 6-8% of all global industrial energy consumption after extraction (Crude Oil

Refineries). Cork, on the other hand, has a much more sustainable extraction and land-management process. Cork forests, or montados, maintain high biodiversity, soil conservation systems, and carbon sequestration without needing to clear land. The stripping process of cork even increases the amount of carbon sequestered, whereas this does not happen in rubber trees. The disc harrow, one of the only machines used in cork land-management, does not dispose of spontaneous vegetation, but rather reuses it to enhance cork soils. Oftentimes, direct extraction is not even required for cork insole production since most of the cork used to make the insole is existing waste from cork stoppers.

Plastic and rubber require extensive processing and shaping procedures that have detrimental environmental impacts compared to cork. Data gathered from Marczak's study showed that polymerization and polymer processing requires high amounts of electricity for thermal heat. Just one kilogram of a synthetic material like PVC or polyethylene often consumes 70 MJ of energy for production, or 19.44 kWh (Tártato et al., 2017). Not only does this process release VOCs into the environment and other toxic chemicals, but it is incredibly expensive. On the other hand, cork is often left to dry naturally to prepare it for production processes. The energy consumption from cork decontamination and granulation is incredibly minimal, using ~0.001 kg CO_2 eq. per shoe insole. Assuming a shoe insole is 2 oz, for example, just the polymer processing stage of an insole would exceed energy consumed compared to cork.

Injection molding, the next step, was one of the most energy intensive processes in plastic and rubber insoles. Here, further chemicals, plasticizers, and expansive agents were melted together to create a compound under high temperature, releasing more greenhouse gasses from fossil fuels and harmful chemicals like hydrochloric acid and carcinogen dioxins. The Khripko et al. study provided important insight into how Germany and Australia can minimize their primary energy use by over half through energy efficiency measures, demonstrating how polymer processing plants typically over-use energy to the planet's detriment. In contrast, the production of cork insole materials is less resource-intensive and energy-intensive than rubber and synthetic materials, as shown in Table 5. Cork heating and shaping can use cork as a sole material, or incorporate other synthetic or natural additives. As shown through Amorim Cork, industrial symbiosis uses waste or by-products from plastic or rubber industries as raw materials for cork insole additives, making it an incredibly sustainable process that doesn't require additional material extraction. Once heated into an agglomerated or composition cork, the cork can be reused in later processes.

Packaging and transportation impacts appeared higher in plastic and rubber insoles as they required more processing steps, shipment fuel, and less environmental packaging strategies. Rubber and plastic insoles are also often shipped internationally. On the other hand, cork produced in Portugal tends to remain locally sold, reducing transportation emissions.

The end of life options for plastic and rubber versus cork are drastically different. Most shoe insoles are thrown away. If taken to an incinerator, chemicals from plastic and rubber insoles can be harmful to human health and release toxic particles. When left in landfills, chemicals from these insoles can seep into soils and groundwater. Recycling is also not possible, as several plastics and other materials are mixed together, such as in form, and unable to be separated in an economic way. Only pure-polymer insoles can be granulated and used again. Cork is an 100% biodegradable product whereas synthetic materials can take 1000 years to decompose. Cork is also able to be recycled and repurposed.

8. Research limitations

The research presented has several gaps that are important to mention. LCAs used for this study were limited in terms of their focus on insoles in particular. Thus, the work often generalized quantitative data from general footwear material LCAs and applied them to insoles. This hindered the work's ability to provide exact quantitative data relevant to insole production. The lack of functional units due to the variety of LCAs used also made quantitative comparison on environmental impacts between cork and transitional materials difficult to illustrate. LCAs on cork insoles in particular were also unable to be found. Thus, the extraction and processing portions of the simplified cork insole LCA contained more quantitative data as research already existed in that realm from general cork industries. When it came to manufacturing data, numbers were much more difficult to find. Thus, comparing energy or resource use between the two simplified LCAs in manufacturing and processing was limited. Future research should aim to fill this gap.

9. Conclusion

The footwear industry has a significant impact on the environment, primarily due to the use of non-renewable materials such as plastic and rubber insoles. However, the incorporation of cork as a sustainable alternative has the potential to significantly reduce this impact. Cork is a renewable and biodegradable material that offers several advantages over synthetic materials. By reducing the amount of non-renewable resources used and decreasing the amount of waste generated through the use of cork, footwear brands can become more sustainable and contribute to a healthier planet.

The natural antimicrobial properties of cork make it an ideal material for use in footwear, reducing the need for chemical treatments. Additionally, cork is highly durable and lightweight, making it an excellent choice for insoles. Furthermore, the use of sustainable materials such as cork can also have a positive impact on consumer behavior. Consumers are becoming increasingly aware of the environmental impact of the products they use, and the adoption of sustainable materials can be a selling point for companies.

In conclusion, the incorporation of cork as a sustainable alternative to plastic and rubber insoles is a step towards a more sustainable and environmentally friendly footwear industry. The benefits of cork are numerous, and its adoption, namely in Portugal, could help the industry reduce its environmental impact while also appealing to environmentally conscious consumers.

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