



Degree project in Biotechnology
Second cycle, 30 credits

Life Cycle Assessment of Leather and Leather-Like Materials

Bovine, Polyurethane and Mycelium Leather Applied to Headphone Earpads

PILTAN GÜNDOGAN

Main supervisor: Rajib Sinha
External supervisor: Tom Fletcher
Examiner: Yves Hsieh

Abstract

The shift towards the use of more sustainable materials has promoted the technological development of leather and leather-like materials such as mycelium and polyurethane (PU) leather. This study conducted a comparative LCA to quantify and compare the environmental impact of bovine, PU and mycelium leather. Additionally, the study evaluated the material performance of mycelium leather with applications to headphone earpads. The results show that bovine leather has the highest environmental impact, mainly due to a high carbon footprint, toxicity potential and water use. PU leather was found to have an environmental burden due to reliance on non-renewable fossil-based materials and an energy-intensive production process. Mycelium leather emerged as the most sustainable alternative, with the lowest impact scores in all categories. With the right advancements and production techniques, its potential as earpad material is promising. The results of this study underline the importance of innovation of sustainable materials for consumer electronics and the need for further research to environmentally optimize a potential large-scale production of mycelium leather.

Keywords: life cycle assessment, mycelium, polyurethane, bovine leather, headphone earpads, emerging materials

Sammanfattning

Skiftet mot ett mer hållbart samhälle har uppmuntrat utvecklingen av nya läderliknande material så som polyuretan (PU) läder och myceliumläder. Denna studie genomförde därför en jämförande livscykelanalys (LCA) för att utvärdera miljöpåverkan av koläder, PU-läder och myceliumläder, med fokus på deras användning som material för öronkuddar i hörlurskomponenter. Resultaten visar att nötläder har den största miljöpåverkan med ett stort koldioxidavtryck, hög toxicitetspotential och vattenkonsumtion. PU-läder hade en generellt mindre påverkan än nötläder, men är fortfarande förknippad med ohållbara fossilbaserade råmaterial samt energikrävande produktionsprocesser. Myceliumläder framstod som det mest hållbara alternativet med lägst avtryck inom alla påverkanskategorier. Ytterligare undersökning visade att med rätt behandling och odlingsomständigheter, har myceliumläder stor potential som material för hörlurskomponenter. Resultaten av denna studie understryker även vikten av innovation av hållbara material inom elektronikindustrin, samt belyser den behovet av vidare forskning för att miljömässigt optimera en potentiell uppskalning av myceliumläderproduktion.

Table of Contents

ABSTRACT	1
SAMMANFATTNING.....	2
1. INTRODUCTION.....	5
1.1 Aims and Objectives	5
2. BACKGROUND	6
2.1 Leather and Leather-Like Materials	6
2.1.1 Bovine Leather.....	6
2.1.2 Polyurethane Leather	6
2.1.3 Mycelium Leather.....	7
2.2 Earpad Materials	7
2.2.1 Physical Properties of Bovine leather	8
2.2.2 Physical properties of PU leather	9
2.2.3 Physical properties of Mycelium leather	9
2.3 Life Cycle Assessment	9
2.3.1 Goal and Scope.....	9
2.3.2 Life Cycle Inventory Analysis	10
2.3.3 Life Cycle Impact Assessment	10
2.3.4 Life Cycle Interpretation	11
3. METHOD.....	12
3.1 Goal and Scope.....	12
3.2 Life Cycle Inventories and Modelling	13
3.2.1 Life Cycle Model of Bovine Leather.....	14
3.2.2 Life Cycle Model of PU Leather	16
3.2.3 Life Cycle Model of Mycelium Leather	17
3.3 Impact Assessment.....	18
3.4 Material Performance.....	19
4. RESULTS.....	20
4.1 Impact Assessment.....	20
5. DISCUSSION	23
5.1 Environmental Performance.....	23
5.2 Material Suitability	24
5.3 Uncertainty, Limitations and Future Work	24
6. CONCLUSIONS.....	26
7. ACKNOWLEDGEMENTS.....	27

REFERENCES	28
APPENDIX A: REFERENCE FLOWS, INVENTORIES AND PROXIES	32
Reference flow: Bovine leather	32
Reference flow: PU leather	32
Reference flow: Mycelium leather	33
Proxies and inventories for chemical production	33
APPENDIX B: ENERGY REQUIREMENTS CALCULATIONS	34

TABLES:

Table 1. Description of the important physical properties for earpad materials.	8
Table 2. Inputs and output for Beamhouse operations in bovine leather manufacturing.	15
Table 3. Inputs and output for Tanyard operations in bovine leather manufacturing.	16
Table 4. Inputs and output for manufacturing 1 m2 of waterborne PU leather.	17
Table 5. Inputs and output for scale-up fermentation process in mycelium leather manufacturing.	18
Table 6. Inputs and output for manufacturing 1 m2 of mycelium leather.	18
Table 7. Chosen impact categories for the evaluation of leather and leather-like materials.	18
Table 8. Impact scores for bovine, PU and mycelium leather production.	20

FIGURES:

Figure 1. Structure of midpoint and endpoint categories that are included in ReCiPe2016 .	11
Figure 2(a-b). Flowcharts of all three manufacturing systems.	12
Figure 3(a-f). Impact scores of all three materials and their environmentally significant activities.	21
Figure 4(a-f). Relative contribution of the process stages for the materials with highest impact scores.	22

1. Introduction

The global shift towards sustainability has significantly influenced the development of materials, pleading for the creation of more environmentally friendly alternatives across various sectors. This trend is particularly evident in the leather industry, which has faced heavy criticism for its environmentally questionable production processes [1] [2]. Known for its unique durability and versatility, cow leather, or bovine leather, is used in numerous industries, ranging from fashion to electronics [3] [4]. However, the transformation of cowhide to finished leather involves a series of environmentally intense activities, with tanning procedures being a very significant source of pollution [5] [6].

As a result, synthetic “leather-like” materials like polyurethane leather, also known as “PU leather”, is emerging as a popular alternative for traditional leather products and components. Having good mechanical properties, flexibility, corrosion resistance and processability makes PU leather a suitable alternative in many industries, including fashion, automotive and electronics [7] [8] [9]. Notably, it is a common component for headphone earpads, providing softness, flexibility and cost-effectiveness [4]. For companies such as AIAIAI, an audio company based in Denmark, PU leather is a central component of the products.

However, while being a practical and materially sufficient choice, it introduces new environmental challenges. Synthetic materials such as PU leather are made from petroleum-derived polymers, which implies environmental issues like chemical pollution and non-biodegradability [10] [9]. These serious environmental implications have caused companies to look for more sustainable leather alternatives in their components [11].

The change of focus has prompted technological innovation and development of novel materials, giving rise to a new era of product design [12] [9]. The world’s first microbe-grown headset was developed by the science collaboration *Korvaa* [13]. Bioengineered with bacterial and mycelium components, these headphones constitute the future of renewable electronics and conceptualize the use of mycelium leather as earpad materials.

Evidently, mycelium leather is gaining both scientific and commercial popularity. It is created by cultivating mycelium, the root structure of filamentous fungi, into flat sheets that hold leather-like properties [11] [14]. It holds promise for a relatively lower environmental impact compared to its synthetic and animal-based counterparts [15] [11]. However, there is a significant gap in scientific research to substantiate its environmental claims. To gain more insight into its actual impact, methodological frameworks such as Life Cycle Assessment (LCA) can be employed [16] [17]. This enables a comprehensive understanding of the environmental implications of mycelium leather in comparison to other leather and leather-like materials.

1.1 Aims and Objectives

Motivated by sustainable product development, AIAIAI are interested in evaluating the environmental impact of the current PU leather in their headphone earpads and compare it with the environmental performance of other alternatives such as bovine and mycelium leather. Therefore, the aim of this thesis is to conduct a comprehensive study that includes a comparative LCA to quantify and compare the environmental impact of bovine, PU and mycelium leather, and evaluate the material performance of mycelium leather specifically for earpad applications.

2. Background

2.1 Leather and Leather-Like Materials

2.1.1 Bovine Leather

A popular by-product of the meat industry is leather, more specifically bovine leather. Bovine leather manufacturing is the process of transforming rawhides to finished leather. The process starts at the slaughterhouse where the skin is harvested from the cow [3]. It is further processed through an elaborate operation with several steps that can vary depending on the application and preferred tanning technology [2]. However, processes share the same general elements: preparation, tanning and finishing. Preparation stages include preservation, washing, soaking, immunization, unhairing, reliming, splitting, delimiting and bating. These stages are performed in the beamhouse and are essential to prepare the rawhide for tanning [1] [3] [18].

Tanning is performed in the Tanyard, where the hide is first pickled then tanned. The main principle of tanning is to stabilize the surface of the skin by altering the proteins using a strong agent such as chromium salts [1]. There is usually a neutralizing and fatliquoring step, followed by a final finishing treatment of the leather, which entails additional softening agents and dyes [1] [3]. Modern day tanning technologies are mainly chromium-based [3], which is known to produce high concentrations of toxic effluent. The complex composition of the effluents is difficult to treat even with modern wastewater treatment technologies [5].

A literature study [19] made in 2020 on LCA and leather production found a total of 39 papers related to life cycle assessment of leather production processes, with varying functional units and system boundaries. In general, both farming and chrome tanning were acknowledged as the most environmentally impactful processes in leather manufacturing [1] [19] [2] [5]. Due to this environmental burden, development of more sustainable leather substitutes is highly important for the future of the planet [11].

2.1.2 Polyurethane Leather

Artificial PU leather is a synthetic, petroleum-based, material often used as an alternative to genuine leather. Having good mechanical properties, flexibility, corrosion resistance and processability makes it suitable for a wide range of industries [7] [8].

In general, PU is synthesized through the reaction between isocyanate and polyols, which creates the repetitive polyurethane building units. Other additives such as surfactants, fillers, thickeners and pigments are also required [8]. After the PU is synthesized, a base fabric, woven or non-woven, is coated in the slurry of polymers, which creates the base of the PU leather [20]. When the coated sheet is dried, several treatments can be performed depending on the desired finish [20] [21].

The use of volatile organic compounds such as N,N-dimethylformamide (DMF) are common in the production process. However, the use of DMF can be avoided with waterborne PU leather production. The water-based method is recently emerging and is considered less environmentally toxic [20] [7].

2.1.3 Mycelium Leather

Mycelium is the vegetative network of filamentous fungi. These filamentous networks, known as hyphae, allow the fungi to grow and colonize extensive areas, making them one of the largest organisms in existence. Hyphae are elongated cells that are separated by internal porous walls called septa [11] [22]. They are covered by cell walls that mainly consist of natural polymers such as chitin, glucans and proteins. Cell walls largely provide protection for the hyphae and overall mechanical strength [11].

Producing mycelium through fermentation necessitates certain growth conditions [11] [23] [22]. However, it is highly efficient in generating biomass, which makes it particularly suitable for large-scale production of biomaterials [14] [22]. The choice of fungal species, substrate and production method varies depending on the intended application [11] [22]. The application in focus for this study is mycelium as a leather substitute, also called mycelium leather.

A recent review of patents [22] found a clear increase in patent publications for mycelium materials as leather substitutes, indicating an interest in commercialization and industrial expansion [11]. Despite being in a developmental phase [22]; several manufacturers have established a solid presence in the mycelium leather market. Current industry leaders, MycoWorks' Reishi™ [24] and Ecovative [25], are at the forefront of a rapidly evolving field, continuously advancing through research and innovation [22].

There are three main fermentation techniques for mycelium leather manufacturing. The two most commercially available methods are solid-state surface fermentation (SSSF) and liquid-state surface fermentation (LSSF). They are performed in a box-shaped incubator filled with substrate and the mycelium grows mainly on the surface, forming a foam-like mat structure that is harvested after incubation [22] [11].

The third method is submerged liquid fermentation (SmF). It is not as commercially available but holds promise as a large-scale continuous production method for mycelium leather [14]. Large-scale production with SmF has been mentioned in a recently patented method [26] and an experimental study by Zamani et al. [27]. The chosen fungal strain is inoculated in a bioreactor with liquid and the preferred substrate, usually a waste product of the agricultural industry [26] [27] [22]. It is then cultivated under specific conditions to effectively increase the biomass. When the desired concentration of mycelium is reached, the biomass is harvested and processed into mycelial mats [27].

The mycelium can be manipulated in various ways to achieve certain material properties. Studies show that the choice of fungal species, substrate, genetic manipulation and post-growth treatments govern the final attributes of the mycelium material [11] [23] [22]. Crosslinking with chemicals such as tannin is a common method used to elongate the hyphae by chemically linking the cell walls, which increases material strength and flexibility [22] [27].

2.2 Earpad Materials

Earpads, also known as ear cushions, are the soft components of headphones that are positioned on user's ears. They are critical components that provide comfort, noise isolation and enhance sound quality [28]. The cushioning pads are covered with a material that varies depending on the desired characteristics of the product. According to the Danish Environmental Protection Agency [4], the most common material for

earpads is polyurethane leather, followed by other customary alternatives such as polyvinyl, textiles and genuine leather.

Important characteristics of earpad materials are durability, comfort and sound isolation [4], [28]. Investigating durability requires intricate methods that involve a series of mechanical tests for technical properties such as tensile and tear strength [9]. Measuring water repellence is also important for durability [29] [9]. Other physical properties like sound isolation are best evaluated using acoustic measurements to test sound absorption [30] [31]. These categories, along with their background methodology are presented in Table 1. When developing a potential alternative material, all categories must be assessed for the material to ensure that it is sufficient for use in headphone earpads.

Table 1. Description of the important physical properties for earpad materials.

Physical properties	Description
Tensile strength	The tensile strength is measured in force per unit of area [N/mm ²], which translates to megapascals [MPa]. It represents the maximum load the material can take before breaking [21].
Tear strength	The tear strength is measured in N/mm and determines the materials resistance to tearing activities [21].
Acoustic properties	To reduce leakage and preserve sound quality, earpad materials need to isolate the sound exiting the speakers [28]. These acoustic properties are mostly determined by the materials ability to absorb sound. This can be measured through several acoustic tests, where absorbance coefficients are determined. The thickness of the material is also an important factor for sound absorption characteristics [30] [31].
Water repellence	Since earpads are used in close contact with skin, a certain level of water repellence is needed to ensure a long-lasting quality against sweat and other sources of moisture. In general, higher water absorption and permeability make it more susceptible to water induced damage [29] [27].

2.2.1 Physical Properties of Bovine leather

The tensile strength of leather varies, but the standard for chrome tanned leather for shoes is >15N/mm² [32]. The technical test performed by Meyer et al. [9], showed that the tensile strength of bovine leather with a thickness of 1,93 mm was 39,5 N/mm². They also estimated a tear strength at 82,9 N/mm [9].

The water vapor permeability of leather is around 5 mg/cm² [9] [21], which means that leather itself has mediocre water repellence and needs further treatment to achieve more hydrophobicity [29]. Furthermore, the acoustic properties of 28 mm thick bovine leather panels investigated by Barbanera et al. [31], exhibited an absorption coefficient of approximately 0,45 at 1000 Hz.

2.2.2 Physical properties of PU leather

The tensile and tear strength of PU leather has been measured to 9-13 N/mm² and 17 N/mm respectively [9], [33]. It is also proven to have low water vapor permeability, around 1-1,8 mg/cm², making it relatively water repellent [9] [21]. For an indication of the sound absorption potential of PU materials, Pelletier et al. [30] determined the absorption coefficient of 25 mm thick polyurethane foam panels to approximately 0,9 at 1000 Hz.

2.2.3 Physical properties of Mycelium leather

It is difficult to establish exact physical properties of mycelium leather because of the wide range of production methods and technologies that generate largely different material results [30] [22]. For submerged liquid fermentation, Zamani et al. [27] estimated the tensile strength of 0,153 mm thick vegetable tanned mycelium leather at 9,62 N/mm². Surface grown mycelium such as Reishi™ *Black Emboss* by MycoWorks [24] has reported tensile and tear strength values of 9,2 - 10,2 N/mm² and 9,9 N/mm respectively.

The sound absorption for mycelium materials has been investigated in various ways [23]. Acoustic tests for 25 mm thick mycelium panels showed up to 70-75 % acoustic absorption for 1000 Hz [30]. A study [23] testing the water absorption of pure mycelium found that it is naturally absorbent, but permeability depends mostly on the level of colonization and type of substrate [23]. Treatment with glycerol and hydrophobic biobased binders has been proven to increase water repellence [11].

2.3 Life Cycle Assessment

The requirements for sustainability are increasing and life cycle assessment is becoming an integral part of contemporary product development [3] [15] [17]. Standardized by ISO 14040 [34], and ISO 14044 [16], LCA serves as an efficient tool in environmental management, offering a systematic approach to evaluating the potential environmental impacts of a process, product or service. It enables insight, identifies opportunities for improvement and aids in decision-making and creating product marketing strategies [16]. Although very useful, it is crucial to acknowledge that an LCA lacks social and economic dimensions. The full network of impact is complex and requires additional analysis and research, which is important to consider when conducting an LCA [17].

The LCA framework is structured into four main phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and life cycle interpretation [16] [34]. The framework of LCA embodies a dynamic and iterative process, designed to allow flexibility, and an ability to integrate and refine data throughout the process. As more data becomes available along the phases of the LCA, it can necessitate a revising of the initial parameters until the required precision is generated [35] [17].

2.3.1 Goal and Scope

The first step of an LCA is defining the goal and scope, which should be set with careful consideration. The goal serves as the foundation on which all methodological choices in the study will be established, thereby determining the character of the LCA [17]. Some aspects that need to be addressed in the goal definition are the intended application, target audience, reasons for performing the study, limitations and influential stakeholders [35] [17]. Comparative LCA, that aims to compare the environmental impact of different

products or processes, must especially ensure that the goal and scope is uniformly configured to produce accurate results [17].

The scope describes what the LCA includes and its system boundaries, where geographical boundaries and limitations are defined. A cradle-to-grave approach covers all life phases of a product, including raw material extraction, manufacturing, transportation, utilization and waste management [17]. Another common scope for LCA is cradle-to-gate, which focuses solely on upstream processes before the finished product leaves the factory [35] [17]. Despite being a narrow approach, this scope offers valuable insight into the manufacturing process, which enables companies to find more sustainable suppliers and materials [35].

Additional study design parameters that should be defined in this phase are the product system, allocation procedures and functional unit. The series of processes that provide a specific function is the product system. Allocation is needed when there are multiple functions derived from the same process and the environmental impact of such processes need to be divided. Functional unit is the defined measure that connects the input and the output of the systems. It serves as a reference unit for comparison of the environmental impact of different product systems [17] [35].

2.3.2 Life Cycle Inventory Analysis

The required data for the study is determined based on the goal and scope, from which the product system and unit processes are created [17]. ISO 14040 [34] defines a unit process as the smallest elements of the system, each characterized by quantifiable inputs and outputs. The product system is the sum of all unit processes, which together with the elementary flows, constructs the life cycle model [17].

When data is collected to create a life cycle inventory, it is crucial to consistently align the data with the functional unit. This generates a linearly scalable system that allows further analysis. Moreover, any relevant allocation procedures are applied systematically [17] [35]. If data is unavailable, as often occurs in many LCAs, simplification, assumptions and streamlined approaches must be employed [17]. This implies the use of proxies, representative data that has similar environmental activity, for example, substituting data for paraffin when wax data is unavailable, which is a conventional input in the finishing treatment of bovine leather [3].

Throughout the data acquisition phase, certain data quality requirements are important to consider. Temporal, geospatial and technological criteria require that the data must be collected within a close timespan of the study, sourced from a geographically relevant location and based on a common production process respectively. These requirements facilitate data validation in the LCI analysis phase. The results are then used for calculating the environmental impacts of the entire life cycle model [17] [35].

2.3.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) transforms data from the life cycle inventory into potential environmental impacts by evaluating the inputs and outputs of the product system. The methodological framework for this stage is guided by the study's design parameters that were established during the goal and scope definition [35]. They should be set to include all relevant environmental implications of the product systems. Specific impact categories, such as global warming potential or acidification, are chosen based on the relevance to the objectives. Each category is linked with an environmental indicator, which provides the quantification of

the potential environmental impact. For instance, when converting LCI results into global warming potential (GWP), the impact score is presented in kilograms of CO₂ equivalent per functional unit [17].

Impact assessment is possible at two levels: midpoint and endpoint. Midpoint impacts are the intermediate points of the cause-and-effect pathway between a direct emission and the final impact. Being closer to the actual emissions, midpoints are usually easier to quantify and are widely used in life cycle assessment. Endpoint impacts represent the final effect or damage of the emissions, which reflects the damage on human health, ecosystems and resources [17].

A model for life cycle impact assessment that employs midpoint and endpoint indicators is the ReCiPe methodology. Developed in 2008 by Goedkoop et al. [36], the method renders harmonized characterization indicators at midpoint and endpoint levels. As illustrated in Figure 1, this method enables flexibility and a holistic approach when creating environmental profiles [36]. Initially being a Eurocentric model, it has since been updated to provide globally representative characterization factors [37].

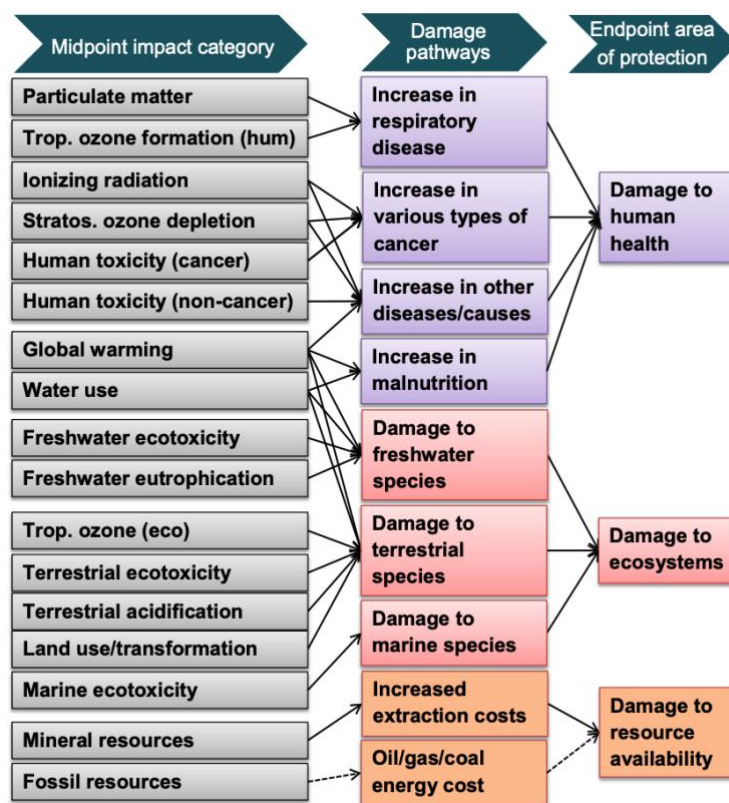


Figure 1. Structure of midpoint and endpoint categories that are included in the ReCiPe2016 methodology. Source: National Institute for Public Health and the Environment.

2.3.4 Life Cycle Interpretation

The final phase of the life cycle assessment is the life cycle interpretation [17]. The results from the life cycle impact assessment are used to derive conclusions and identify areas for development. The life cycle inventory data is reviewed to ensure accuracy and method relevancy. Any limitations, uncertainties and sensitivity of the LCA is important to include in this phase [16] [17] [34].

3. Method

3.1 Goal and Scope

The goal of this LCA is to quantify and compare the environmental impact of bovine leather, polyurethane leather and mycelium leather. The findings are intended to support product development at AIAIAI, by creating a scientific foundation for comparing the manufacturing methods of earpad materials. It also aims to identify the limitations of assessing different manufacturing methods.

To ensure accuracy, reduce complexity and facilitate comparison of the product systems, the system boundary was set to cradle-to-gate and the functional unit was defined as 1 m² of finished material. These parameters also agree with the Product Environmental Footprint Category Rules (PEFCR) for leather outlined by Rosa-Giglio et al. [3]. This report was used as a primary guide when setting the parameters of the life cycle assessment.

The system boundary entails raw material extraction and manufacturing processes. The downstream processes such as the user phase and end-of-life were not included in the life cycle assessment. Neither was waste management or the use of recycled materials. The LCA was driven towards a simplifying approach due to the unavailability of data on the production processes.

The cradle-to-gate system boundary encompassed all upstream and core processes relevant to each product system, all illustrated in Figure 2a-2c. For bovine leather, this included farming of cattle, slaughtering, beamhouse processes, tanning and any finishing procedures. The PU leather system included raw materials, polymer synthesis and processing. For mycelium leather, the system covered raw material extraction, cultivation and post-growth treatments.

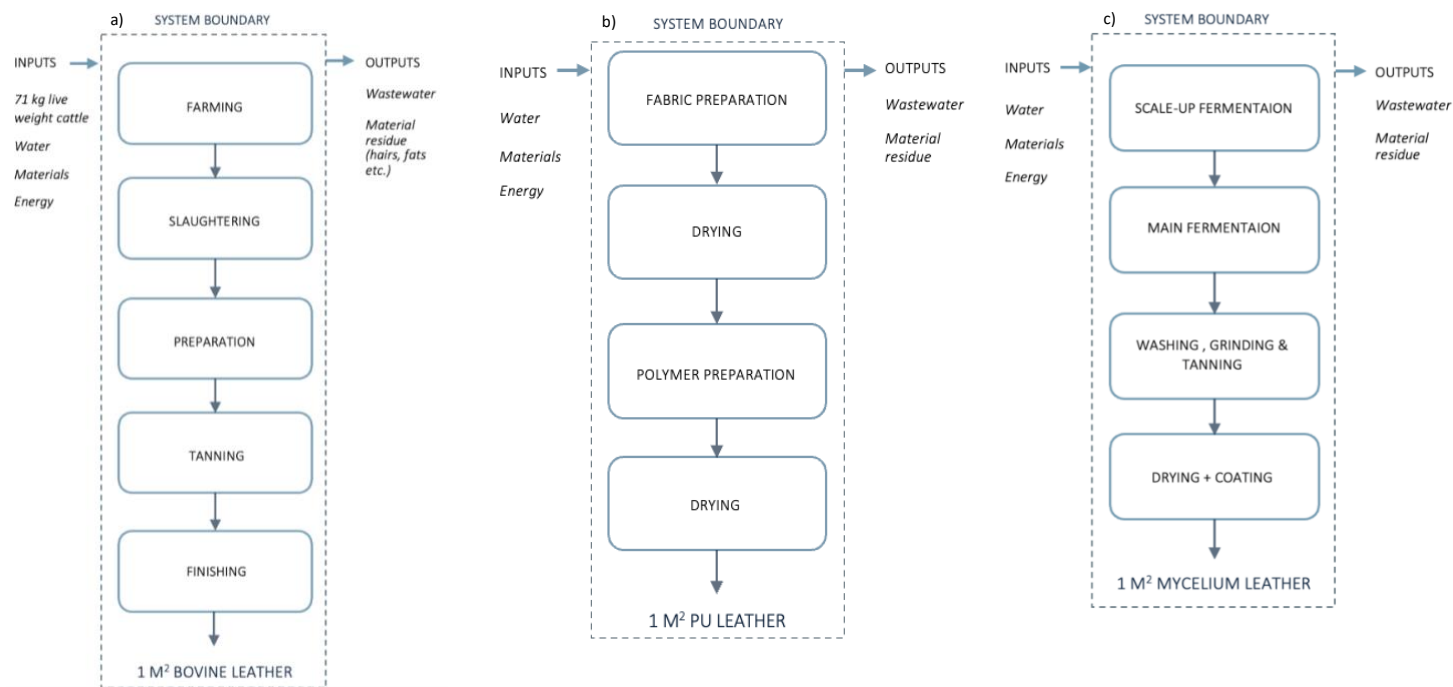


Figure 2(a-c). a) Flowchart for bovine leather production, including system boundary, functional unit, unit processes with inputs and outputs. “Preparation” entails preservation, preservation, washing, soaking, immunization, unhairing, reliming, splitting, delimiting and bating. b) Flowchart for PU leather production, including system boundary, functional unit, unit processes with inputs and outputs. c) Flowchart for mycelium leather production, including system boundary, functional unit, unit processes with inputs and outputs.

Geographical boundaries were established based on the typical manufacturing locations of each product. For bovine leather, European averages were applied, reflecting its primary production in Southern Europe [18] [3]. Swedish averages were used for mycelium leather, in line with the Swedish study that served as a reference model for stirred submerged liquid fermentation [27]. Due to PU leather being geographically independent, meaning its production is not restricted to a specific region, global averages were applied.

3.2 Life Cycle Inventories and Modelling

The life cycle inventory was created by collecting data through literature studies. Data availability determined how the production systems were modeled, which is further explained in the following section. When literature was unavailable, simplified approaches were taken and the streamlined models were constructed to be as accurate as possible. The activities for each process were modeled using Ecoinvent version 3.9.1 with cut-off allocation.

Proxies, or representative substances, were utilized when certain activities were unavailable in the database. All proxies used in the life cycle inventory analysis are listed in Appendix A. When proxies were insufficient, additional inventories for the manufacturing of the chemicals was modeled.

Calculations for energy requirements for PU leather and mycelium leather were derived from scale-up frameworks for chemical processes formulated by Harding [38] and Piccinno et al. [39]. These values and calculation methods are available in Appendix B

3.2.1 Life Cycle Model of Bovine Leather

In their study about the environmental footprints of leather manufacturing technologies, Laurenti et al. concluded that even with primary data, the environmental performance of different leather processing systems varies considerably [2]. To produce justifiable results, data collection for bovine leather was strategically focused on fewer sources to ensure the extraction of consistent data.

The inventory structure for bovine leather was derived from the paper on the framework for sustainable leather manufacture published by UNIDO [1]. The reference flow for bovine leather was based on values from the Italian and Spanish production system described by Notarnicola et al. [18], and the conversion factors described in the PEFCR guide [3], all of which are presented in detail in Appendix A. Accordingly, the weight of 1 m² of finished leather was assumed to be 1,076 kg, representing 20% of the original weight of the raw hide. Therefore, a total of 5,38 kg raw hide was assumed to be needed per m² of finished leather, which corresponds to 71,7 kg of live weight [3], [18].

Following the allocation guidelines of Rosa-Giglio et al. [3], 12% of the cattle in bovine leather production was assumed to proceed to be slaughtered, the rest is used for milk products. Derived from fundamental data provided by Notarnicola et al. [18], the hide was calculated to represent 7,5% of the live weight. As a result, 0,9% of the environmental load was allocated by mass to farming. Furthermore, 3,5% of all the slaughterhouse activities were economically allocated to hides, and 60% of the Tanyard activities were allocated by mass to the hides [3].

The inputs for the agricultural phase were covered by the market activity “market for cattle for slaughtering, live weight” as provided by the Ecoinvent v3.9.1 database [40]. This dataset assumes a system where cattle is farmed for 1-2 years, covering the life stages of the living animal up until the slaughterhouse process. It did not include transportation from the farm to the slaughterhouse.

The slaughterhouse inputs were derived from Notarnicola et al. [18], which included transportation to the slaughterhouse. This study was selected for its geographical relevance and comprehensive dataset, which included primary data and disclosed all inputs, including energy consumption for each unit process. However, due to the publication date of the study, a more recent source, such as the report from UNIDO [1], was utilized to construct the core processes of leather manufacturing. This report provided detailed information on the material inputs for all beamhouse operations, including preservation, washing, soaking, immunization, unhairing, reliming, splitting, delimiting and bating, which are compiled in Table 2. Since UNIDO [1] did not provide useful data on energy, Notarnicola [18] was used as a model for electricity and thermal energy for the Beamhouse operations.

Table 2. Input and output for Beamhouse operations in bovine leather manufacturing.

Input	Process	Activity	Amount	Unit	Source
	Farming	Live weight	72	kg	[3] [18]
	Slaughterhouse	Water	141,8	kg	[18]
		Fuel oil	4,17	MJ	[18]
		Diesel	4,17	MJ	[18]
		Thermal energy	9,56	MJ	[18]
		Electricity	0,09	kWh	[18]
	Preservation	Sodium chloride (12,6 % w/w)	0,68	kg	[1]
		Water (43% w/w)	2,31	kg	[1]
		p-dichlorobenzene (0.3 % w/w)	0,02	kg	[1]
	Washing	Water (100 %)	5,38	kg	[1]
		Surfactant (2g/l)	0,01	kg	[1]
	Soaking	Water (400% w/w)	21,53	kg	[1]
		Sodium hydroxide (2g/l)	0,043	kg	[1]
		p-dichlorobenzene (0.1% w/w)	0,005	kg	[1]
		Thermal energy	1,35	MJ	[1] [18]
		Electricity	0,02	kWh	[1] [18]
	Immunization	Water (80% w/w)	4,31	kg	[1]
		Lime (1,5% w/w)	0,08	kg	[1]
		Electricity	0,07	kWh	[1] [18]
		Thermal energy	1,80	MJ	[1] [18]
	Unhairing	Sodium sulfide (1,5 w/w %)	0,08	kg	[1]
	Reliming	Water (100 % w/w)	5,38	kg	[1]
		Lime (1% w/w)	0,05	kg	[1]
		Sodium sulfide (0,2 w/w %)	0,01	kg	[1]
	Washing 2	Water (300% w/w)	16,15	kg	[1]
	Splitting	Electricity	0,05	kWh	[1] [18]
	Deliming	Ammonium Sulphate (3% w/w)	0,29	kg	[1]
		Electricity	0,03	kWh	[1] [18]
		Thermal energy	1,66	MJ	[1] [18]
	Bating	Proteases (enzymes 0.15% w/w)	0,008	kg	[1]
Output	3,22 kg Pelt for tanning				

According to the allocation rules, the weight of the pelt that exits the beamhouse is 60% of the original hide weight [3]. The following Tanyard operations were modeled using the available inventories of Yu et al. [6]. This elaborate life cycle assessment of tanning methods ensured a more accurate representation of the most environmentally intense processes in leather manufacturing [1], [5]. Due to data on chemicals for chrome tanning not being available in *Ecoinvent*, sodium dichromate production was also modeled by following the inventory created by Yu et al. [6]. The dataset also included thermal and electric energy used in the Tanyard.

Finishing activities such as coating and waxing the leather were based on the Spanish leather manufacturing data provided by Notarnicola et al. [18]. The inventories for Tanyard operations and finishing activities are presented in Table 3. Inventory for chrome powder production is available in Appendix A.

Table 3. Input and output for Tanyard operations in bovine leather manufacturing.

Input	Process	Activity	Amount	Unit	Source
	Pickling	Pelt	3,23	kg	[6] [3]
		Water	6,46	kg	[6]
		Sodium chloride	0,45	kg	[6]
	Tanning	Water	12,92	kg	[6]
		Chrome powder	0,45	kg	[6]
		Sodium formate	0,06	kg	[6]
		Sodium bicarbonate	0,07	kg	[6]
		Electricity	1,48	kWh	[6]
		Thermal energy	2,95	MJ	[6]
	Rewetting	Water	10,33	kg	[6]
	Neutralizing	Water	15,50	kg	[6]
		Sodium formate	0,03	kg	[6]
		Sodium bicarbonate	0,03	kg	[6]
	Retanning	Water	2,58	kg	[6]
		Acrylic resin	0,08	kg	[6]
		Dicyandiamide resin	0,05	kg	[6]
		Vegetable tannin	0,10	kg	[6]
		Dyestuff	0,05	kg	[6]
	Fatliquoring	Water	9,04	kg	[6]
		Fatliquor	0,36	kg	[6]
	Finishing	Aniline	0,007	kg	[18]
		Casein	0,007	kg	[18]
		Wax	0,005	kg	[18]
		Acrylic polymer	0,036	kg	[18]
		Dye	0,004	kg	[18]
		Lacquer	0,005	kg	[18]
		Electricity	0,453	kWh	[18]
		Thermal energy	1,690	MJ	[18]
Output	1 m ² of bovine leather				

3.2.2 Life Cycle Model of PU Leather

A limited range of production methods were found to be sufficient for constructing the life cycle inventory of waterborne PU leather alternative. Eventually, a patented method for making waterborne PU without the use of DMF by Xiaomin et al. [20], was used to model the inventory. This patent provided a moderately detailed description of the polymer preparation, ratios and drying methods. The base fabric was assumed to be coated twice, once with an adhesive solution and once with the waterborne PU polymer mixture. Mixing time for the preparation of the polymer slurry was assumed to be 1,5 h, based on the methods of Wang et

al. [7]. The patented method [20] was employed and used as a base for the inventory, which is demonstrated in Table 4. All assumptions and calculations for stirring and drying are presented in Appendix B.

Table 4. Inputs and output for manufacturing 1 m² of waterborne PU leather.

Input	Process	Activity	Amount	Unit	Source
	Fabric preparation	Fabric	0,23	kg	[7]
		Carboxymethyl cellulose	0,014	kg	[7]
		Silicone oil	0,014	kg	[7]
		Water	0,47	kg	[7]
	Drying	Electricity	3,33	kWh	[7]
	Polymer preparation	PU resin	0,58	kg	[7]
		Water	0,17	kg	[7]
		Cellulose	0,023	kg	[7]
		Carboxymethyl cellulose	0,006	kg	[7]
		Pigment	0,006	kg	[7]
		Isocyanate	0,017	kg	[7]
		Electricity	0,021	kWh	[7] [20] [38]
	Drying	Electricity	3,33	kWh	[7]
Output	1 m ² of waterborne PU leather				

3.2.3 Life Cycle Model of Mycelium Leather

Mycelium leather production was modeled as a submerged liquid fermentation based on the study by Zamani et al. [27]. This method was chosen due to the available detail of the production process. The process was divided into two parts: scale-up and main fermentation. Both were assumed to have a sterilization step and a stirred fermentation process, where calculations and values were scaled-up using the chemical process formulas by Harding [38] and Piccinno et al. [39]. Only the most energy consuming processes such as sterilization, heating and stirring were accounted for. These values and calculation methods are available in Appendix B.

The biomass calculations for the reference flow were derived from Zamani et al. [27], where the desired thickness was adjusted using their formula for density of the mycelium leather. Coating chemicals were also obtained through this method.

The scale-up process involved a 20 L bioreactor that was used for cultivation of the inoculum for the main fermentation. It was assumed that the mycelium was cultivated in a stirred 1000 L bioreactor for 48h, followed by harvesting, washing, grinding, vegetable tanning, drying and coating with glycerol. The biomass tanning process was assumed to be performed in a tank under stirring in room temperature for 24h. The drying step was added according to a patented method for continuous large-scale submerged liquid fermentation of mycelium leather [26]. It was assumed to be dried using the same oven as PU leather.

Vegetable tannin production was modeled with the inventory from the life cycle assessment of tannin extraction from spruce bark by Ding et al. [41]. This inventory involved bark preparation and hot water extraction. For vegetable tannin production, 1,2% of the environmental loads of debarking were

economically allocated to bark chips according to available life cycle inventories for vegetable tannin production [41].

Table 5. Inputs and output for scale-up fermentation process in mycelium leather manufacturing.

Input	Process	Activity	Amount	Unit	Source
	Sterilization	Energy	0,00091	kWh	[27] [38]
	Fermentation	Substrate	0,037	kg	[27]
		Water	0,93	kg	[27]
		Agitation	0,078	kWh	[27] [39]
Output	Inoculum for main fermentation				

Table 6. Inputs and output for manufacturing 1 m² of mycelium leather.

Input	Process	Activity	Amount	Unit	Source
	Sterilization	Energy	1,17	MJ	[27] [38]
	Fermentation	Biomass	0,93	L	[27]
		Energy (reaction)	0,85	kWh	[27] [39]
		Energy (agitation)	8	kWh	[27] [38]
		Water	46,65	kg	[27]
		Substrate	1,87	kg	[27]
	Washing	Water	0,84	kg	[27]
	Grinding	Energy	0,0034	kWh	[27] [39]
	Tanning	Vegetable tannin	0,118	kg	[27]
		Water	7,85	kg	[27]
		Energy (stirring)	1,51	kWh	[27] [38]
	Washing	Water	0,84	kg	[27]
	Drying	Energy	3,33	kWh	[27] [7]
	Glycerol bath	Glycerol	0,02	kg	[27]
		Water	10	kg	[27]
Output	1 m ² of mycelium leather				

3.3 Impact Assessment

In this study, ReCiPe 2016 v.1.03. midpoint methodology was used for impact assessment. All impact scores were modeled and generated by the open source LCA software Activity Browser. The results were transferred to MS Excel, where they could be further analyzed and cross-validated with the life cycle inventories. Table 7. shows the impact categories were chosen based on the relevant categories for leather [3].

Table 7. Chosen impact categories for the evaluation of leather and leather-like materials.

Impact category	Abbreviation	Unit
Global warming potential	GWP	kg CO ₂ eq
Terrestrial acidification potential	TAP	kg SO ₂ eq

Freshwater ecotoxicity potential	FETP	kg 1,4-DCB eq
Freshwater eutrophication potential	FEP	kg P eq
Human toxicity potential: carcinogenic	HTPc	kg 1,4-DCB eq
Human toxicity potential: non-carcinogenic	HTPnc	kg 1,4-DCB eq
Water consumption potential	WCP	m ³
Particulate matter formation potential	PMFP	kg PM2,55 eq
Fossil fuel potential: non-renewable resources	FFP	kg oil eq

3.4 Material Performance

The material performance of mycelium, PU and bovine leather was researched and compared through collection of data from relevant literature. The physical property requirements for earpads described in Chapter 2.2 were a guideline to assess the applicability of mycelium leather as earpad material. The literature values mentioned for tensile strength, tear strength, acoustic properties and water repellence were used to further discuss the suitability of mycelium leather as earpad material.

4. Results

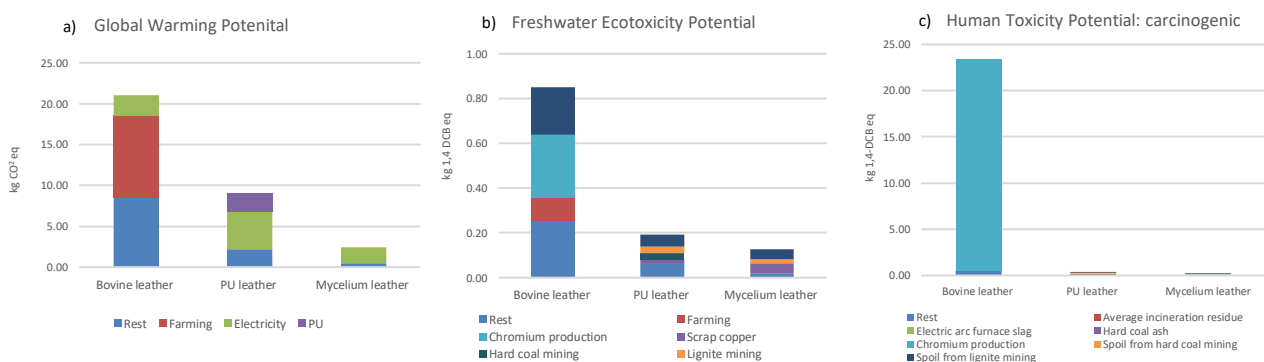
4.1 Impact Assessment

The environmental impact assessment was conducted using the ReCiPe 2016 midpoint methodology. Table 8 presents the final impact scores for each material in all impact categories. Categories with the highest and most noteworthy impact scores include global warming, freshwater ecotoxicity, human toxicity, fossil fuels and water consumption potential.

Table 8. Impact scores of bovine, PU and mycelium leather production.

Impact category	Unit	Bovine leather	PU leather	Mycelium leather
Global warming potential	kg CO ₂ eq	21,0	9,0	2,4
Acidification: Terrestrial	kg SO ₂ eq	0,074	0,028	0,0055
Ecotoxicity: Freshwater	kg 1,4-DCB eq	0,85	0,19	0,13
Eutrophication: freshwater	kg P eq	0,0039	0,0029	0,0011
Human toxicity: carcinogenic	kg 1,4-DCB eq	23,4	0,41	0,16
Human toxicity: non-carcinogenic	kg 1,4-DCB eq	1239,3	5,3	2,7
Water use	m ³ water	0,19	0,12	0,08
Particulate matter formation	kg PM _{2,55} eq	0,017	0,015	0,002
Fossil fuel potential: non-renewable resources	kg oil eq	2,0	2,8	0,4

The most significant impact categories from the assessment were global warming potential, freshwater ecotoxicity, human toxicity, fossil fuels and water consumption potential. These were further analyzed to map out the most contributing activities within each manufacturing system. This dissection is demonstrated in Figures 3(a-f).



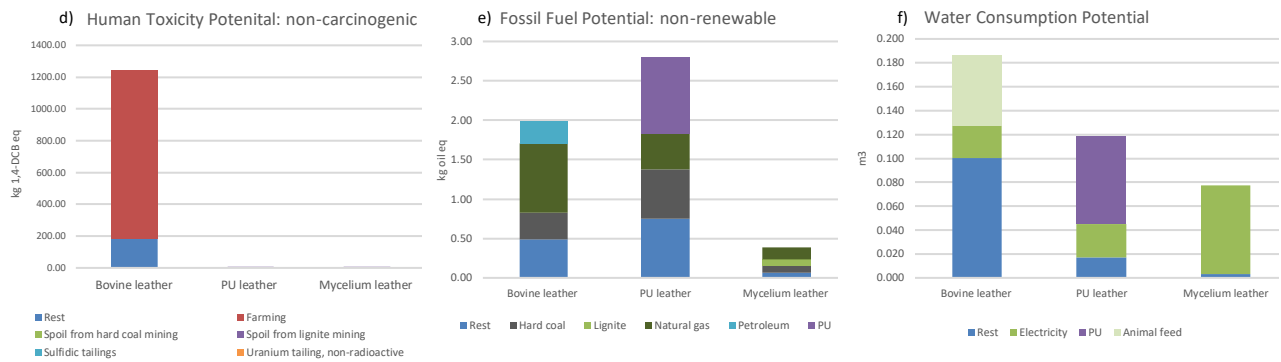


Figure 3(a-f). Impact scores of all three materials and their environmentally significant activities for the categories identified as having the highest impact. Activities below 10% contribution are categorized as “Rest”.

Bovine leather had the highest impact score for all impact categories except FFP. Its largest contributors were found to be farming and tanning related activities.

Farming was found to be the biggest contributing activity for GWP, HTPnc and WCP. This is outlined in Figure 3a and 3d where “Farming” is directly attributed the major contribution for GWP and HTPnc, adding up to a total of 21,0 kg CO₂ and 1239,3 kg 1,4-DCB respectively. As demonstrated in Figure 3f, WCP is estimated to 0,19 m³ where “Animal feed” is assigned the biggest impact, which is also an activity associated with the farming process. For HTPnc, bovine leather exhibited a vastly different impact at 1239,3 kg 1,4-DCB eq. This differed greatly from the values for PU and mycelium leather at 5,3 and 2,72 kg 1,4-DCB respectively. Aside from farming, activities related to electricity showed a significant contribution to the GWP and WCP of bovine leather, which is outlined in Figures 3a and 3f as the second most contributing activity.

Figure 3b and 3c highlight “Chromium production”, an activity related to the tanning process, as the most significant activity within the FETP and HTPc, where the total potential was estimated to 0,85 and 23,4 kg 1,4-DCB each. Similar to the results in HTPnc, the impact of bovine leather is much higher than PU and mycelium. The second significant contributor to the FETP was “hard coal mining”, followed by “Farming”.

PU leather had generally lower impact scores than bovine leather, but higher than mycelium in all categories. As illustrated in Figure 3a, 3e and 3f, the raw material “PU” had a significant impact on GWP, WCP and FFP. Similar to bovine leather, the use of electricity was also a contributor for GWP, and WCP where the total emission was 9,0 kg CO₂ and the water consumption was estimated to 0,12 m³. FFP was calculated to 2,8 kg oil, which was the highest among all materials.

Mycelium leather scored lowest in all impact categories. As seen in Figure 3a and 3f, electricity was the most significant contributor to GWP and WCP. Figure 3e shows a total of 0,4 kg oil for the FFP of mycelium, which was mostly caused by the use of “hard coal” and “natural gas”, which are similar contributing activities for both bovine and PU leather.

For further investigation and validation, the product system of the most impactful material was dissected for the relative contribution of its unit processes. These results are illustrated in Figures 4(a-f).

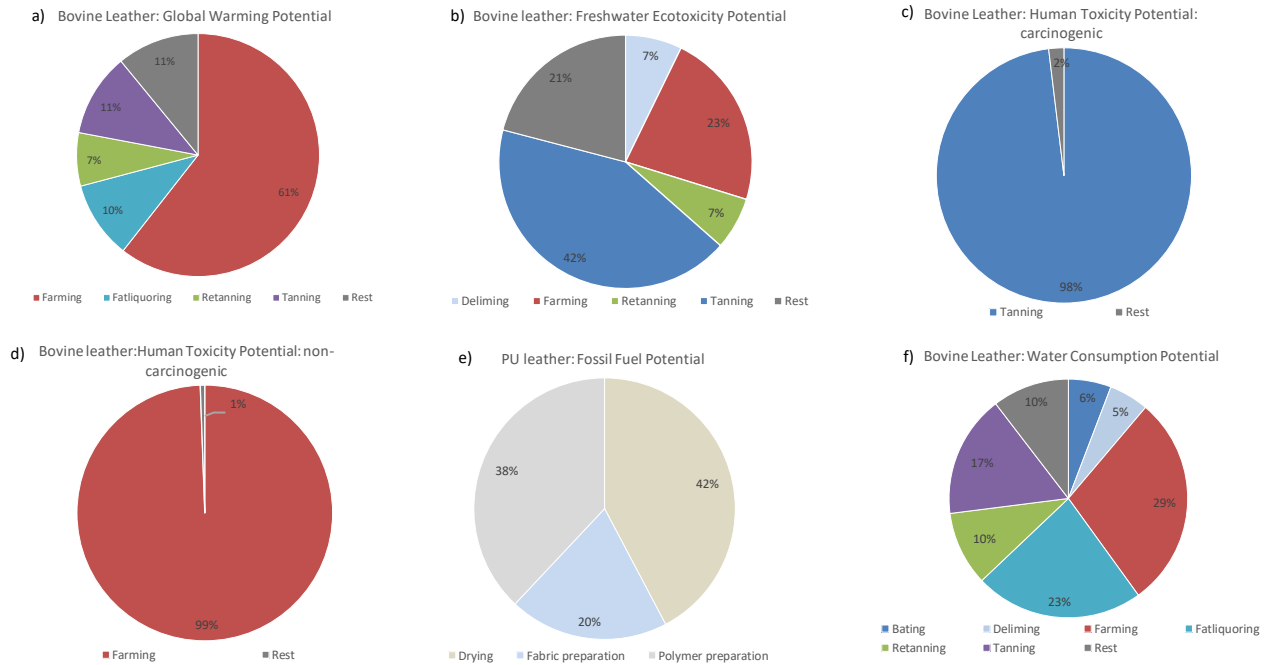


Figure 4(a-f). Relative contribution of the unit processes for the manufacturing systems with highest impact scores. Activities below 5% contribution are categorized as “Rest”.

The results from Figure 3a, 3d and 3f align with the relative unit process contributions demonstrated in Figure 4a, 4d and 4f. 61% of the GWP for bovine leather was estimated to be due to farming. Moreover, tanning processes had the second greatest impact to the carbon footprint with 11% contribution. Furthermore, 99% of the HTPnc and 29% of the WCP was attributed to farming processes.

For the impacts of chromium on FETP and HTPc, Figures 4b and 4c highlight the tanning process as most significant at 42% and 98% respectively. These ratios correspond to the results in Figure 4b and 3c. Tanning was also evident in the WCP, where 17% was attributed to tanning. However, this represents tanning activities excluding chromium, since chromium was not identified as a significant activity in Figure 3f.

The relative unit process contributions for PU leather showed that “polymer preparation”, which entails the preparation of the PU, had the biggest contribution at 42%, followed by “drying” at 38%. This correlates to Figure 3f, where PU and electricity are identified as the biggest contributors.

5. Discussion

5.1 Environmental Performance

Bovine leather production scored highest in all impact categories except for non-renewable fossil-fuel consumption, where PU leather production was in the lead. These results confirm the environmental discussions around bovine leather and call for an evaluation of its life cycle. The carbon footprint of leather was estimated at 21,0 kg CO₂ eq, which is fairly aligned with literature values [12] [18] [42] [12], although they vary depending on the system boundaries, allocation principals and the dataset of the study. For instance, a study by Schäfer et al. [12] with similar system boundaries and functional unit estimated 31,35 - 45,26 kg CO₂, which is most likely diverging due to different allocation procedures. Another comparison can be made with Laurenti et al. [2], whose highest carbon footprints was calculated to be 12 kg CO₂ eq for chrome-tanned leather, excluding farming and slaughterhouse operations. For this LCA, Beamhouse, Tanyard and finishing processes represent approximately 40% of the total GWP score for bovine leather, which corresponds to 8,2 kg CO₂. These values are close but require further methodological investigation.

Farming and Tanyard operations were identified as the most environmentally heavy processes in bovine leather production, which aligns well with literature claims [1] [18] [5] [43]. Farming, which is frequently left out of the system boundaries [3] [19], has proven to be highly impactful in most of the impact categories. Tanning processes were the primary cause of ecotoxicity and carcinogenic human toxicity, which aligns with the findings of Notarnicola et al. [18]. However, for non-carcinogenic toxicity, bovine leather scored extraordinarily high in comparison with the alternative materials, almost all because of agricultural practices. No literature could be found, from the research conducted during this study, to support this level of non-carcinogenic toxicity caused from farming corresponding to the framework of this study.

The biggest contribution factor for PU leather was identified as the use of fossil-based polymers. It also had a high impact on the toxicity potential and water consumption, which was expected even with the exclusion of DMF [10]. The carbon footprint was estimated at 9,0 kg CO₂, which is higher than literature values for PU leather production with DMF by Wool et al. [44], who reports approximately 5,6 kg CO₂ / kg of PU produced. This difference is most likely due to the geographical boundary and the drying method of the chosen reference study for waterborne PU, which is reflected in the use of electricity in Figure 6f.

Studies were found for “artificial leather”, where the exact material composition were not disclosed. 4,7 kg CO₂ was estimated from a cradle-to-gate analysis of artificial leather by Schäfer et al. [12]. Another value for the full life cycle of artificial leather suggests an emission rate of 15,8 kg CO₂/m² [43], positioning 9,0 kg CO₂ as a viable value for the manufacturing process. Comparisons should be done with caution since the sources do not specify the exact type of plastic, even though most have similar carbon emissions [12].

Overall, mycelium leather has shown the least environmental impact in all categories. With a carbon footprint of 2,4 kg CO₂, it holds great promise as an emerging material. Being a relatively new technology, environmental impact values for SmF are unattainable. Even though the results are similar to the 2,76 kg CO₂ carbon footprint of MycoWorks' Resishi™ [15], they have different production methods, and a comparison would not be completely justified.

Evidently, electricity was a major contributor for all impact categories, which indicates that the choice of energy source is a determining factor for the overall environmental impact of mycelium leather. Another reason behind the low environmental impact the assumption that mycelium is cultivated using waste products as substrate, which alleviates the total environmental burden [22] [11]. This could be a determining factor to the sustainability of mycelium leather. In the case of a potentially higher level of commercialization and production scale, raw material acquisition might have a higher environmental impact, which would require a reevaluation of the material.

5.2 Material Suitability

High mechanical stability is determined through high tensile and tear strength, which is evident for bovine leather. It is a highly durable material, with medium water repellence and good sound absorption properties [21] [9] [31]. The average lifespan for headphones is 3,3 years [45]. With the right coatings and regular maintenance, the material could potentially outlive the rest of the headphone components. However, in the context of headphones where the life span is shorter, leather remains to be an unsustainable alternative that is not suitable as earpad material.

Since PU leather is a primary choice for earpads [4], it is assumed that the material has sufficient mechanical properties. Therefore, mycelium leather properties could be evaluated from that standard. Based on that assumption, tension strength of both submerged liquid fermentation and surface fermentation match earpad requirements, but it might lack potential in terms of tear strength [27] [24].

Mycelium has a naturally high permeability for water. However, when tailored with coatings, treatments and cultivation techniques, it can become a material with better water repellence [27]. Furthermore, acoustic properties of mycelium have shown great promise. Even if the values are lower than traditional PU materials, mycelium managed to reach high levels of sound absorption [30]. This is an indication that mycelium leather can provide good sound isolation when applied to earpads.

The available literature values for the physical properties of mycelium leather show that the material is becoming more durable and applicable to a wider range of sectors. However, it is still in an experimental phase and does not live up to the standard of PU leather in some respects. This indicates that further investigation and tests must be performed to specifically determine its suitability for earpads.

Having some undetermined material properties impacts the overall sustainability of mycelium leather. If the material is too brittle and needs to be renewed more often, this could lead to an undesired effect on the overall environmental impact. Therefore, it is crucial to thoroughly evaluate any potential prototypes.

5.3 Uncertainty, Limitations and Future Work

This LCA does not account for post-production processes, which are essential when evaluating the entire life cycle impact of a product. Additional research for post manufacturing phases such as transportation, utilization and disposal are crucial to comprehend the full environmental impact of the materials.

Furthermore, the data availability and the use of only secondary data influence the final accuracy and quality of the LCA, which must be accounted for when analyzing the results.

New emerging technologies rarely have accessible data. This is why the dataset for PU leather was primarily taken from a patent [20], and the mycelium model was based on a single study [27]. This was limiting and led to a series of assumptions that could have affected the accuracy of the results. An example is the wet-laying process for mycelium leather that was not accounted for due to the complexity of scaling the operation. Additional limitations concerning novel technologies emerged when searching for comparative literature values. Due to the lack of available environmental data, fair comparisons are difficult to make, and the evaluation phase is heavily affected by this uncertainty. It is also important to consider that the materials are deeply impacted by their varying stages of technological maturity.

Additional limiting factors are the study design parameters, such as system and geographical boundaries, that affect the precision and representativeness of the results. Electricity usage varies greatly depending on the energy mix of the location, which could be why PU has a higher carbon footprint than corresponding literature.

Lastly, this study uses a very generalized method to assess the material suitability. It must be noted that these guidelines do not cover all aspects of the functional properties of earpads. They are meant to create a framework of reference when starting to assess the potential applicability.

6. Conclusions

Based on the results of this comparative LCA, bovine leather has the overall highest environmental impact, mainly in terms of a high carbon footprint, toxicity potential and water use. It is followed by PU leather, relying on non-renewable raw materials and an energy intensive manufacturing process. The least environmental impact was shown by mycelium leather, making it the most sustainable leather-like material of the three alternatives. It is notable that factors such as data collection and geographical boundaries have a significant impact on the results.

The prospectives of mycelium leather as earpad material are promising. With the right advancements and production techniques, it could meet the mechanical and acoustic requirements for durable earpads. However, any potential prototypes should be thoroughly evaluated to ensure durability. Overall, mycelium leather is a progressive solution that highlights the importance of research and innovation of sustainable materials for the future of electronics.

7. Acknowledgements

This thesis has been an enlightening adventure that would not have been possible without some serious support. I want to express my deepest gratitude for those who have helped me throughout these turbulent couple of months. To my main supervisor Rajib Sinha, thank you for your continuous support and valuable expertise. Your insightful questions and guidance through the complex jungle of life cycle assessment have been invaluable. Your passion and knowledge for the subject has significantly shaped this work.

I want to extend my heartfelt appreciation to my external supervisor, Tom Fletcher. Not only have you been an exceptionally kind and supportive supervisor, but you have also been a true inspiration. Thank you for believing in me. I look forward to following your future endeavors.

A special thank you AIAIAI, whose values and ideals as a company give me hope for the future. Thank you for giving me this wonderful opportunity. A shout out to the amazing AIAIAI crew who welcomed and helped me through my time in Copenhagen. Tusind tak!

I want to thank my family and friends who have been immensely supportive. To my mother and father, who patiently never stopped encouraging me. Lastly, I want to express my deepest apologies to Klättestugan for my absence in the climbing gym these couple of months.

Thank you all for your support and belief in me.

References

- [1] J. Buljan and I. Kral, " The Framework for Sustainable Leather Manufacture, 2nd ed. United Nations Industrial Development Organization, 2019. [Online]. Available: https://leatherpanel.org/sites/default/files/publications-attachments/the_framework_for_sustainable_leather_manufacturing_2nd_edition_2019_f.pdf.
- [2] R. Laurenti, M. Redwood, R. Puig and B. Frostell, "Measuring the Environmental Footprint of Leather Processing Technologies," *Journal of Industrial Ecology* 21: 1180-1187. Available: <https://doi.org/10.1111/jiec.12504>
- [3] P. De Rosa-Giglio, A. Fontanella, G. Gonzalez-Quijano, I. Ioannidis, B. Nucci, and F. Brugnoli, "Product Environmental Footprint Category Rules - Leather," on behalf of the Leather Pilot Technical Secretariat, Unione Nazionale Industria Conciaria (UNIC), Confederation of National Associations of Tanners and Dressers of the European Community (COTANCE), Scuola Superiore Sant'Anna (SSSUP), Spin 360, 25 Apr. 2018, valid until 31 Dec. 2020.
- [4] A. Schmidt, E. Bjarnov and T. Brandt Nielsen, "Survey of chemical substances in headphones and hearing protection aids," Danish Ministry of The Environment, 2008.
- [5] P. Senthil Kumar and G. Janet Joshiba, "Environmental and Chemical Issues in Tanneries and Their Mitigation Measures," *Leather and Footwear Sustainability*, 2020. In: Muthu, S. (eds) *Leather and Footwear Sustainability. Textile Science and Clothing Technology*. Springer, Singapore. Available: https://doi.org/10.1007/978-981-15-6296-9_1
- [6] Y. Yu, Y. Lin, Y. Zeng, Y. Wang, W. Zhang, J. Zhou, and B. Shi, "Life Cycle Assessment for Chrome Tanning, Chrome-Free Metal Tanning, and Metal-Free Tanning Systems," *ACS Sustainable Chemistry & Engineering*, vol. 9, no. 18, pp. 6720-6731, Apr. 2021.
- [7] Y. Wang and L. Jin, "Preparation and Characterization of Self-Colored Waterborne Polyurethane and Its Application in Eco-Friendly Manufacturing of Microfiber Synthetic Leather Base," *Polymers*, vol. 10, no. 3, p. 289, 2018. Available: <https://doi.org/10.3390/polym10030289>
- [8] S. Tian, "Recent Advances in Functional Polyurethane and Its Application in Leather Manufacture: A Review," *Polymers*, vol. 12, no. 9, p. 1996, 2020. Available: <https://doi.org/10.3390/polym12091996>
- [9] M. Meyer, S. Dietrich, H. Schulz, and A. Mondschein, "Comparison of the Technical Performance of Leather, Artificial Leather, and Trendy Alternatives," *Coatings*, vol. 11, no. 2, p. 226, 2021. Available: <https://doi.org/10.3390/coatings11020226>
- [10] A. Kemono and M. Piotrowska, "Polyurethane Recycling and Disposal: Methods and Prospects," *Polymers*, vol. 12, no. 8, p. 1752, 2020. Available: <https://doi.org/10.3390/polym12081752>
- [11] A. Amobonye, J. Lalung, M. K. Awasthi, and S. Pillai, "Fungal mycelium as leather alternative: A sustainable biogenic material for the fashion industry," *Sustainable Materials and Technologies*, vol. 38, p. e00724, 2023. Available: <https://doi.org/10.1016/j.susmat.2023.e00724>
- [12] M. Schäfer, M. Gottschling, F. Cerdas, and C. Herrmann, "Methodology for Assessing the Environmental Impact of Emerging Materials," in *Technologies for Economic and Functional*

- Lightweight Design, K. Dröder and T. Vietor, Eds. Berlin, Heidelberg: Springer Vieweg, 2021. Available: https://doi.org/10.1007/978-3-662-62924-6_8
- [13] Avian, "avian.fi," [Online]. Available: <https://aivan.fi/case/korvaa-the-worlds-first-microbe-grown-headset/>.
- [14] VTT, "VTT," 07 2021. [Online]. Available: <https://www.vttresearch.com/en/news-and-ideas/alternative-leather-and-synthetic-leather-vtt-succeeded-demonstrating-continuous>.
- [15] E. Williams, K. Cenian, L. Golsteijn, et al., "Life cycle assessment of MycoWorks' Reishi™: the first low-carbon and biodegradable alternative leather," *Environmental Sciences Europe*, vol. 34, no. 120, 2022. Available: <https://doi.org/10.1186/s12302-022-00689-x>
- [16] International Organization for Standardization, "ISO 14044:2006, Environmental management -- Life cycle assessment -- Requirements and Guidelines," 2006. [Online]. [Accessed 2024].
- [17] H. S. Matthews, C. T. Hendrickson, and D. H. Matthews, *Life Cycle Assessment: Quantitative Approaches for Decisions That Matter*, 2014.
- [18] B. Notarnicola, R. Puig, A. Raggi, P. Fullana, G. Tassielli, C. De Camillis, and A. Rius, "Life Cycle Assessment of Italian and Spanish Bovine Leather Production Systems," *Afinidad*, vol. LXVIII, no. 553, pp. 167-176, May-June 2011.
- [19] D. Navarro, J. Wu, P. Fullana-i-Palmer and R. Puig, "Life Cycle Assessment and Leather Production," *Journal of Leather Science and Engineering*. Available: <https://doi.org/10.1186/s42825-020-00035-y>, 2020.
- [20] L. Xiaomin, F. Jianyan, Q. Jianbo and L. Pengni, "Preparation method of waterborne polyurethane synthetic leather base". China Patent CN102080332B, 2010.
- [21] T. B. Sudha, P. Thanikaivelan, K. P. Aaron, K. Krishnaraj, and B. Chandrasekaran, "Comfort, chemical, mechanical, and structural properties of natural and synthetic leathers used for apparel," *Journal of Applied Polymer Science*, vol. 114, no. 3, pp. 1761-176
- [22] E. Elsacker, S. Vandelook, and E. Peeters, "Recent technological innovations in mycelium materials as leather substitutes: a patent review," *Frontiers in Bioengineering and Biotechnology*, vol. 11, p. 1204861, Aug. 2023. doi: 10.3389/fbioe.2023.1204861. PMID: 37609120; PMCID: PMC10441217.
- [23] F. Appels, S. Camere, M. Montalti, E. Karana, K. M. Jansen, J. Dijksterhuis, P. Krijgsheld and H. A. Wösten, "Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites," *Materials and Design*, vol. 161, pp. 64-71, 2019.
- [24] MycoWorks, "madewithreishi.com," Jan 2020. [Online]. Available: <https://www.madewithreishi.com/stories/performance-results-q120>.
- [25] Ecovative, "ecovative.com," [Online]. Available: <https://www.ecovative.com/leather/>. [Accessed 2024].
- [26] G. Szilvay, "Methods of making non-woven materials from mycelium". Patent WO2021136883A1.
- [27] E. R. K. B. Wijayarathna, G. Mohammadkhani, A. M. Soufiani, K. H. Adolfsson, J. A. Ferreira, M. Hakkarainen, L. Berglund, I. Heinmaa, A. Root, and A. Zamani, "Fungal textile alternatives from bread waste with leather-like properties," *Resources, Conservation and Recycling*, vol. 179, p. 106041, 2022. doi: 10.1016/j.resconrec.2021.106041.

- [28] A. Celestinos, E. McMullin, R. Banka, and P. Brunet, "Audio Engineering Solutions in Consumer Electronics," presented at the 147th AES Convention, Valencia, CA, USA, Oct. 2019. Available: <https://www.aes.org/e-lib/browse.cfm?elib=20605>
- [29] V. Jankauskaite, I. Jiyembetova, A. Gulbiniene, J. Širvaitytė, K. Beleška, and V. Urbelis, "Comparable Evaluation of Leather Waterproofing Behaviour upon Hide Quality. I. Influence of Retanning and Fatliquoring Agents on Leather Structure and Properties," *Materials Science*, vol. 18, no. 2, 2012. doi: 10.5755/j01.ms.18.2.1918.
- [30] M. G. Pelletier, G. A. Holt, J. D. Wanjura, E. Bayer, and G. McIntyre, "An evaluation study of mycelium based acoustic absorbers grown on agricultural by-product substrates," *Industrial Crops and Products*, vol. 51, pp. 480-485, 2013. doi: 10.1016/j.indcrop.2013.09.008.
- [31] M. Barbanera, E. Belloni, C. Buratti, G. Calabrò, M. Marconi, F. Merli and I. Armentano, "Recycled leather cutting waste-based boards: thermal, acoustic, hygrothermal and ignitability properties," *Journal of Material Cycles and Waste Management*, 2020.
- [32] ISO, "ISO.org," 2019. [Online]. Available: <https://www.iso.org/standard/69524.html>.
- [33] F. Harnagea and C. Secan, "Researches upon the Tensile Strength and Elongation at Break of the Leather Substitutes," *Annals of the Oradea University. Fascicle of Management and Technological Engineering*, vol. XIX, no. IX, 2010, doi: 10.15660/AUOFMTE.2010-2.1865.
- [34] International Organization for Standardization, "ISO 14040:2006, "Environmental management — Life cycle assessment — Principles and framework,"" 2006. [Online]. Available: <https://www.iso.org/standard/37456.html>. [Accessed 2024].
- [35] European Commission - Joint Research Centre - Institute for Environment and Sustainability, *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*, vol. First Edition, Luxembourg: European Commission, 2010.
- [36] M. Goedkoop, R. Heijungs, M. Huijbregts, A. Schryver, J. Struijs, and R. van Zelm, "ReCiPE 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level," 2008.
- [37] M. A. J. Huijbregts et al., "ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization," RIVM Report 2016-0104, National Institute for Public Health and the Environment, 2016.
- [38] K. Harding, "A Generic Approach to Environmental Assessment of Microbial Bioprocesses through Life Cycle Assessment (LCA)," Ph.D. dissertation, Dept. Chem. Eng., Univ. of Cape Town, Cape Town, South Africa, 2008.
- [39] F. Piccinno, R. Hischer, S. Seeger, and C. Som, "From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies," *Journal of Cleaner Production*, vol. 135, pp. 1085-1097, 2016. doi: 10.1016/j.jclepro.2016.06.164.
- [40] Ecoinvent, "Ecoinvent," 2018. [Online]. Available: <https://ecoquery.ecoinvent.org/3.9.1/cutoff/dataset/20433/documentation>. [Accessed 2024].
- [41] T. Ding, S. Bianchi, C. Ganne-Chedeville, P. Kilpeläinen, A. Haapala and T. Rätty, "Life cycle assessment of tannin extraction from spruce bark," September 2017. [Online]. Available: <https://iforest.sisef.org/contents/?id=ifor2342-010>.

- [42] L. M. i Canals, X. Domènèch, J. Rieradevall, et al., "Use of Life Cycle Assessment in the procedure for the establishment of environmental criteria in the Catalan ECO-label of leather," *International Journal of Life Cycle Assessment*, vol. 7, pp. 39-46, 2002. doi: 10.1007/BF02978908.
- [43] UNIDO, "Leather Carbon Footprint," United Nations, 2017.
- [44] R. Wool, "COMPOSITES HAVING LEATHER-LIKE CHARACTERISTICS". Patent US 2013/0337711 A1, 2013.
- [45] T. Herrmann, A. Zimmerer, C. Lang-Koetz, and J. Woidasky, "The Climate Impact of the Usage of Headphones and Headsets," in *Progress in Life Cycle Assessment 2021. Sustainable Production, Life Cycle Engineering and Management*, F. Hesser et al., Eds. Cham: Springer, 2023. doi: 10.1007/978-3-031-29294-1_2.

Appendix A: Reference flows, Inventories and Proxies

Reference flow: Bovine leather

In the Spanish system, one head of cattle with the live weight of 425 kg generates 31,9 kg of raw hide, which corresponds to 7,5 % of the live weight. The weight for 1 m² of finished leather is 1,076 kg, representing 20% of the original weight of the raw hide. Therefore, a total of 5,38 kg raw hide is needed, which represents 71,7 kg of live weight.

Table A1. Conversion describing the relationship between the live weight and raw cowhide for 1 m² of finished leather.

Process	Live weight [kg]	Conversion factor	Raw hide [kg]	Source
Total live weight to raw hide	425	0,075058824	31,9	[18]
Live weight to raw hide [1m ²]	71,70551137	0,075058824	5,382131324	[18]

Table A2. Conversion factor describing the relationship between 1 m² of raw hide and delimed/bated leather.

Process	Raw hide [kg]	Conversion factor	Delimed/bated [kg]	Source
Raw hide to delimed/bated leather	5,382131324	0,6	3,229278794	[35], [18]

Table A3. Conversion factor describing the relationship between raw hide and 1 m² of finished leather.

Process	Weight [kg]	Area [m ²]	Thickness [mm]	Source
Finished Leather	200	185,8	1,3	[18]
Finished leather [1m ²]	1,076426265	1	1,3	[18]
Raw hide	5,382131324	1		[35], [18]

Reference flow: PU leather

Table A4. Base fabric inventory for the model.

Fabric preparation	Amount [%]	Area [m ²]	Thickness [mm]
Fabric	0,23	1	1

Table A5. Creation of inventory for PU leather slurry components with stated ratios and final amounts needed for 1 m² of finished PU leather.

Primary coating components, slurry 0,6 [kg/L] 0,5 [kg/m ²]		Ratio	Final amount [kg]
PVC		3	0,014150943
Silicone oil		3	0,014150943
Water		100	0,471698113
Second polymer coating components, slurry 0,7 [kg/L] and 0,8 [kg/m ²]			
PU resin		100	0,575539568
Water		30	0,172661871
Thickener: cellulose		4	0,023021583
Physique filler: lignocellulose		1	0,005755396

Pigment	1	0,005755396
Crosslinking agent: isocyanate	3	0,017266187

Reference flow: Mycelium leather

Table A6. Reference flow calculations for Mycelium leather based on the study on submerged liquid fermentation.

Type of treatment	Thickness (m)	Density (kg/m3)	Area (m2)	Weight (kg)	Weight (kg/m2)
RD-T	0,000153	654	0,0001	1,00062E-05	0,100062
RD-TG	0,000163	717	0,0001	1,16871E-05	0,116871
RD-TGB	0,000192	824	0,0001	1,58208E-05	0,158208
Desired thickness (derived from RD-T)	0,0004	654	0,0001	0,00002616	0,2616

Proxies and inventories for chemical production

Table A7. Proximate activities used for unavailable substances in Ecoinvent.

	Original substance	Proximate activity	Source
Bovine leather	Surfactant	Non-ionic surfactant	
	Acrylic resin, Casein, Lacquer	Market for acrylic binder, with water in 54% solution sate	
	Dicyandiamide resin	Market for anionic resin	
	Dyestuff	Market for aniline	
	Fatliquoring	Market for fatty acid	
	Wax	Market for paraffin	
PU leather	Silicone oil	Market for silicone product	
	PU resin	Market for polyol	
	Pigment	Market for aniline	
	Isocyanate	Market for methylene diphenyl diisocyanate	

Table A8. Inputs and output for chrome powder production in bovine leather manufacturing.

Input	Process	Activity	Amount	Unit	Source
	Production	Sodium dichromate	0,5	kg	
		Caproic acid	0,15	kg	
		Sulfuric acid	0,45	kg	
		Water	1	kg	
		Electricity	0,2039	kWh	
		Thermal energy	5,292	MJ	
Output	Chromium powder 1 kg				

Appendix B: Energy Requirement Calculations

Table B1. Parameters for energy calculation in mycelium leather manufacturing.

Parameters	Amount	Unit	Source
Stirring energy (cultivation)	3,7	kW/ m ³	[38]
Volume (main cultivation)	1	m ³	[27]
Time (main cultivation)	48	h	[27]
Energy (total main cultivation)	18,2	kWh	[39]
Volume (scale-up cultivation)	0,02	m ³	[27]
Time (scale-up cultivation)	24	h	[27]
Stirring energy (tanning, viscous)	8	kW/m ³	[38]
Grinding energy	12	kWh/ton	[39]
Sterilization energy	25	MJ/m ³	[38]