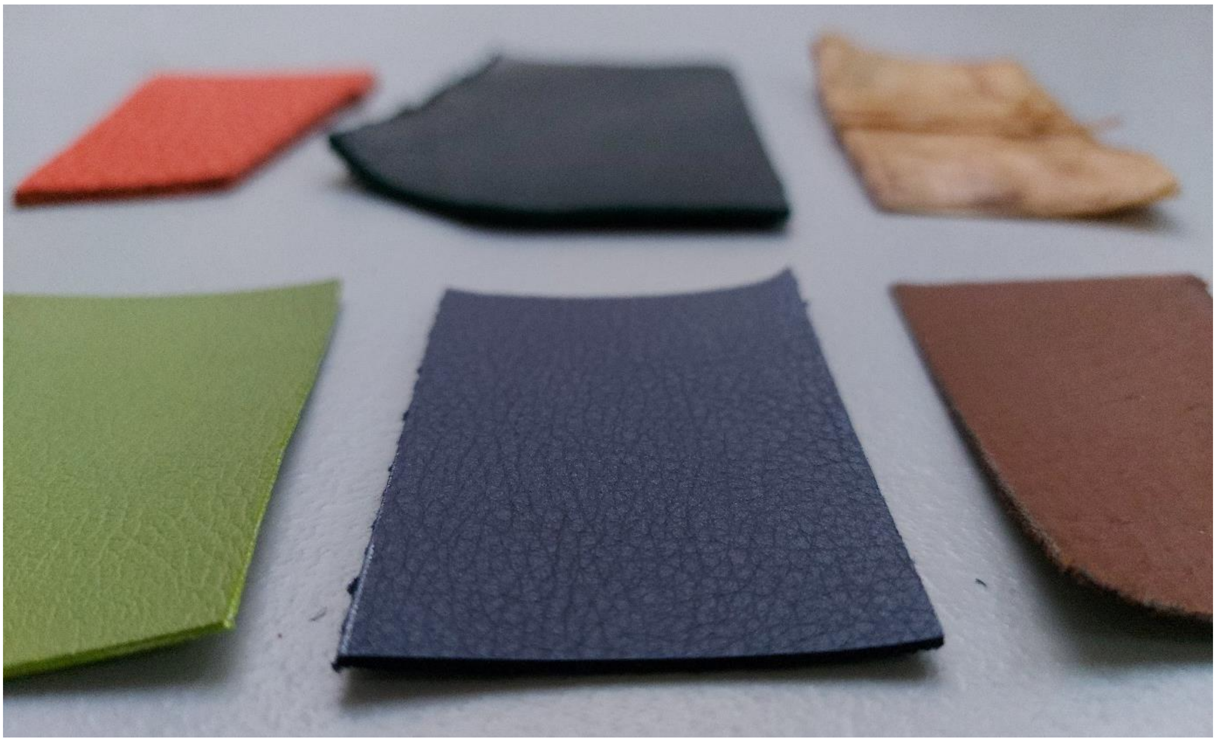
Innovative Leather Alternatives: A Short-Lived Trend or the Future of Fashion?



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Abstract

This literature review creates a clear and elaborate overview of animal and synthetic leathers used in the fashion industry and their possible innovative alternatives. The innovative alternatives discussed are plant-based, mycelium, bacterial cellulose and tissue-engineered leathers. A comparison of the mechanical properties of each of the before-mentioned materials shows that each alternative – with the exception of synthetic leather – is not yet up to par with the physical robustness of animal leather, but does meet requirements for either upholstery leather or shoe upper leather. Interviews were carried out with key players in the leather industry. All interviewees confirm the lower mechanical properties of renewable leather alternatives compared to animal leather. These innovative materials have already been used in products and consumer behaviour studies show high interest. At the moment, efforts should go into the improvement of mechanical properties of innovative materials and into the reduction of emissions from animal leather production.

Key words: plant-based leather – mycelium-based leather – bacterial cellulose – tissue-engineered leather – sustainable fashion

Lay summary

Climate change is one of the primary problems that the world currently faces and the fashion industry plays a prominent role in accelerating climate change. Within the fashion industry, the production of leather from animal skins is a large contributor to the industry's environmental impact. This environmental impact needs to be reduced to meet sustainability targets. Major brands have provided leather alternatives to customers promoted as "vegan" leather. The main resource of these vegan leathers is plastic, which is produced from fossil fuels. These plastic-based leathers are not sustainable either. Efforts have gone into the creation of innovative leather alternatives (ILAs). This research investigates properties of these ILAs such as strength and flexibility to determine how well these ILAs could replace animal or plastic leather.

Plant-based, yeast-based, lab-grown and bacterial leather are examined through a literature review. Values in literature reveal that one yeast-based leather called Reishi™ meets the requirements of leather for shoes. Piñatex®, a leather made from pineapple leaves, and Desserto®, a leather made from cactus leaves, were not strong enough to be used in shoes according to requirements, but could be used for applications in furniture.

Interviews with stakeholders in the leather industry were conducted to retrieve more information on the qualitative side of these materials, such as their look and feel. These interviewees include two designers, the co-founder of an ILA producing company and the head of R&D at a leather-finishing company. All four interviewees confirmed the lower physical properties of ILAs compared to animal leather.

Despite these lower properties, major brands have created prototype products containing yeast-based leather. Plant-based leathers are already used to create shoes and bags. These products have received positive reviews so far. A brief analysis shows that consumers are interested in these ILAs because of their lower environmental impact and their cruelty-free nature. Some consumers are also willing to pay more for these ILAs than for animal leather.

Even though these ILAs will not replace animal leather in the fashion industry soon, they provide an alternative for conscious consumers and have the potential to grow larger once their properties are improved.

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Introduction

Everyone I know owns at least one - and often more - clothing items containing traditional leather. This is not a surprise, considering the fact that in 2014 alone, around 24 billion pairs of shoes were produced (The Good Shopping Guide, 2022) and 41% of all leather from tanneries in Europe is used in footwear (European Commission, 2022). A total of 68% of leather is used in the fashion industry as a whole.

Traditional leather is made from raw animal hides, which are supplied by the meat industry. This makes it seem like leather is a by-product that has the potential to last for a lifetime depending on the use. However, the meat industry emitted 14.5% of all greenhouse gas emissions globally in 2013 (FAO, 2013). Additionally, most leather produced worldwide comes from raw bovine hides (Joseph & Nithya, 2009) and cattle accounted for 65% of all livestock emissions (FAO, 2013), resulting in a greenhouse gas emission profile of approximately 9.5% worldwide. Further, the production of leather from raw hides is very polluting, mainly due to the use of toxic chemicals in the tanning procedure (Chan, 2021).

Based on these emissions and the fact that the leather market represents a value of around 400 billion dollars per year (Grand View Research, 2021), the impact of leather cannot be disregarded on the grounds that it is a by-product.

Because of the large environmental impact of animal leather, efforts have gone into the development of leather alternatives. One group of alternatives that emerged is plastic-based leather, which is usually produced from polyvinyl chloride (PVC) or polyurethane (PU) (Jones et al., 2021). The production of these synthetic leathers contributes less to global warming and water scarcity than the production of bovine leathers, but the impact of the chemicals and fossil fuels used for their production are similar (Jones et al., 2021). Additionally, these synthetic alternatives are not biodegradable and can shed microplastics.

In the meantime, new leather alternatives are being invented that are biodegradable and not based on fossil fuels. My research focuses on the identification of this new group of leather alternatives and their characteristics compared to traditional leather. From here on, this new group is coined innovative leather alternatives (ILAs) for the sake of clarity. The main goal of this review is to identify how likely it is that these innovative materials replace animal leather. After an introductory part on the production of traditional leather, this research will delve deeper into the chemical and mechanical properties of a variety of these ILAs found in literature. These properties are compared to the requirements of certain leather products, as well as the properties of traditional leather. This comparison will identify the state of these ILAs and their competitiveness.

The fashion industry is not only interested in quantitative aspects of leather, such as mechanical and chemical properties. The feel and look, as well as the marketability of the material is just as important to create an interesting and successful product. These more qualitative characteristics cannot be identified as easily through literature. For this reason, I decided to interview experts at different stages of the production process to ask for their opinions on these materials. The experts I have interviewed are; two designers working with ILAs, the co-founder of a company producing an ILA and the head of R&D of a leather finishing company that focuses on sustainability.

Based on the combination of quantitative and qualitative characteristics of ILAs, I aim to clarify the state of these ILAs compared to traditional leather and synthetic alternatives.

Literature review

In this research, the following leathers and alternatives are examined:

- Cowhide leather
- Synthetic leather
- Mycelium leather
- Plant-based leathers, based on the following resources:
    - Pineapple leaves
    - Cactus leaves
    - Mangos
    - Apples
- Kombucha leather
- Tissue-engineered leather

The production process and sustainability of all alternatives are discussed. Next, the quantitative analysis will be discussed with regards to technical properties and durability character of these materials.

For every topic, search engines Google and Google Scholar were used first to gain general knowledge. Web of Science™ was successively used to find sources that could be included in this literature review. Since this review discusses innovative materials, it was not always possible to find academic sources for certain topics. In this case, company websites were used to gain information. If the amount of reliable information found on a certain material was insufficient, it was not included in this review. The scope of this research has been narrowed down to materials that are focused on use in the fashion industry. Finally, the state of sustainability of every material will be discussed briefly, but a Life Cycle Assessment (LCA) will not be carried out.

To investigate characteristics not readily found in literature – such as qualitative characteristics and industry opinions of these materials – stakeholders in the field of leather (alternatives) were interviewed.

Before these innovative alternatives are investigated, a brief overview of traditional leather will be given. This is relevant because traditional leather will serve as a benchmark to the alternatives – both in terms of material properties and marketability. While proponents of leather alternates may argue that novel material development should be judged according to more tailored standards, any technology seeking to disrupt an incumbent will likely face a significant degree of scrutiny based on traditional requirements. Indeed, companies and manufacturers have repeatedly stated that alternate materials must not fall short of existing properties traditional leather, especially in terms of durability. These concerns reflect the centrality of end-user acceptance to brands seeking sustainable replacements for leather.

After the qualitative and quantitative analyses, the current applications of ILAs and consumer behaviour regarding these innovative materials will be discussed. Finally, I will add my own observations, which I gained during this research process. Based on these beforementioned sections, a conclusion will be drawn, possible future research avenues will be presented and I will give my personal outlook on the state of the leather industry.

Different types of leathers

Traditional leather

Leather is made from the skins of animals, which are often retrieved from the meat industry. Bovine skins represent 7 wt% of the total weight of bovine cattle and approximately 16 wt% of all co-products from bovine cattle (Lynch et al., 2021). These skins are a collagenous matrix. The structure of cow leather can be seen in Figure 1A, compared to the structure of a synthetic leather (Figure 1B).

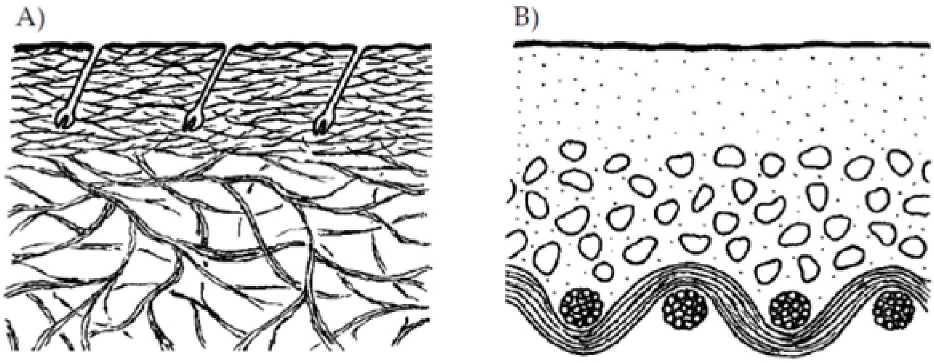

Figure 1: Cross-sectional drawings of A) cow's leather and B) synthetic leather. Cow's leather shows the structure of a skin, whereas synthetic leather is built up by applying layers to a woven or non-woven support layer. Retrieved from Meyer et al. (2021).

Short history

The use of animal skins stems from the Palaeolithic age, which started around 3.3 million years ago and ended approximately 11,650 years ago. It was noted that when these skins remained wet, rotting would set in quickly. Leaving these skins to dry was also not ideal, as this resulted in a very hard and rough material (Muthukrishnan, 2021). Through experimentation, it was found that greasy materials could be rubbed into the leather to keep it more flexible, and slowly the field of leather tanning developed to the processes that are commonly used today.

The tanning process

After cattle is slaughtered, the animal is flayed and the skin is cured. This curing phase is needed to prevent putrefaction due to microbial activity of the skin (Muthukrishnan, 2021). The most common method of curing is by applying salts to the flayed side of the skin. When the skins reach the factory, they are soaked in water to remove the salts added during the curing phase. Subsequently, strong alkaline chemicals such as lime ($Ca(OH)_2$) are added to dissolve hairs, remaining flesh, such as the upper layer of the skin – called epidermis – and proteins in the collagenous matrix (Nazer et al., 2006). The dissolution of hairs leaves the hair channels open for penetration of subsequent tanning agents. Wastewater resulting from this liming step is a major component of the pollution of the leather industry. Next, these alkali compounds are removed from the skins through de-liming bating with ammonium sulphates and ammonium chlorides. The next step is called pickling, where sulphuric acid, hydrochloric acid and salt are added to the hides to allow for better infiltration of chemicals that will be added later. Finally, detergents and solvents are added to remove fat from the matrix of the skins and to make them more flexible (Sharphouse 1983, p. 104; Dutta 1985, p. 160). The hides can now be split to the favoured thickness for the final leather product. The top layer after splitting is called top grain and is stronger and more valuable than the lower layer, called the leather split (Xu et al., 2016). This lower layer is used to create suede leather for example.

The processes mentioned above, from soaking to de-greasing, are called beamhouse operations.

After these beamhouse operations, the tanning process starts. Tanning of leather is carried out to turn animal skins into a durable material by crosslinking the collagen matrix with tanning agents, thereby preventing decay. The majority of tanneries works with tanning agents that contain chrome (Yu et al., 2021). Leather that has been chrome-tanned but has not been dried yet, is called wet blue leather. The cross-linking with chrome makes the leather product more resilient against thermal changes and enzymatic contact (Covington, 1993; China et al., 2020). Next, a phase called post-tanning ensures that the physical properties of leather, as well as its organoleptic characteristics, such as feel and smell, meet the requirements of the final product (Yu et al., 2021). The material after the post-tanning phase is called crust leather. Finally, the leather is finished by dyeing and embossing it. Embossing means to create a pattern on the leather material (See Figure 2).

The impact of leather

The leather industry is intrinsically linked to the meat industry due to the flow of skins from latter to former industry. As mentioned before, the meat industry has a large environmental impact; especially cattle rearing, which supplies most of the skins used in the leather industry. In order to reach climate goals, this industry must decrease its impact but consistently deliver to the demand of a growing human population. With more than 1.3 billion cattle on earth (Gerber et al., 2015) and an increasing consumption of meat and milk in developing countries (Delgado, 2003), cowhides are widely available at the moment. This could start to change regionally depending on changing diets and governmental climate goals set to reduce emissions. The Dutch government for example, is working towards expropriating and buying out farmers to reduce nitrogen emissions in the Netherlands (Kuiper, 2022).

The production of leather from hides has a large impact in its own right, mainly due to the use of toxic chemicals and the amount of water needed to produce leather (Jones et al., 2020; Joseph & Nithya, 2009). Apart from an impact on climate change, the toxic chemicals used can have a grave impact on the surroundings of leather tanneries if the effluent treatment is not sufficient. This has led to the temporary closure of tanneries in India in 1995 because of incompliance with environmental laws, followed by a series of fines in 2002 due to pollution (Joseph & Nithya, 2009). Within the leather production, the liming and tanning processes are notable for their pollution.

During the liming process, sodium sulphide and lime are added to the skins. In this step, the sodium sulphide can change into hydrogen sulphide gas, which is highly toxic for humans and animals alike (Nazer et al., 2006). Efforts have been made to replace sodium sulphide and lime, for example with enzymatic or oxidative hair removal from the animal skins (Anzani et al., 2017).

The majority of tanneries uses chromium-based tanning agents, as these work very well to create a durable leather that can be modified to fit the end product. Chrome is highly toxic to humans and it is very harmful to the direct environment if disposed of through the effluent. The chrome that is used in the tanning process is non-renewable and Cr(III) atoms in the waste sludge can convert into Cr(IV), which is carcinogenic and mutagenic (Yu et al., 2021; China et al., 2020). Alternatives to chrome tanning are metal-free tanning, also named vegetable tanning, and tanning with a different metal. An LCA by Yu et al. (2021) showed that metal-free tanning with dialdehyde oxidized sodium alginate has a lower environmental impact than tanning with either a chrome agent or a combination of highly oxidized starch with aluminium-zirconium salts.

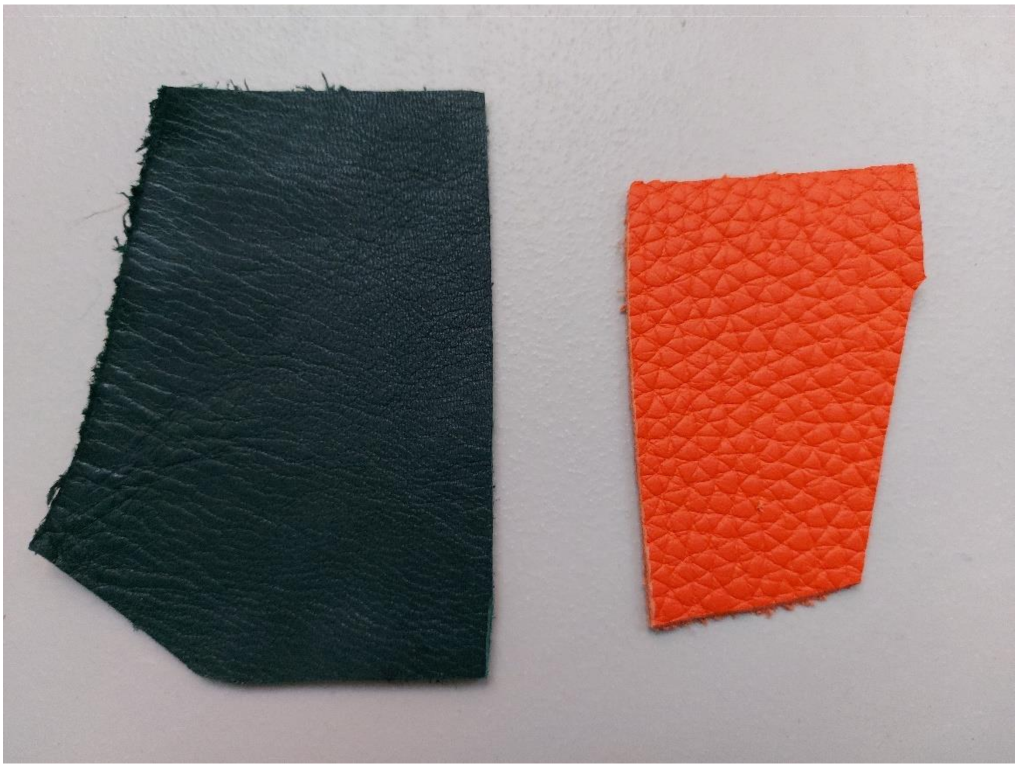

Figure 2: Photo of two types of leather. The left material is a vegetable tanned leather and the right material is a chrome-tanned leather.

Alongside environmental impacts, animal welfare is a concern for conscious consumers that are looking into fashion products, car interiors and pieces of furniture that contain leather (Lundblad & Davies, 2015; Jein & Sørensen, 2019). An 18th sustainable development goal (SDG) on animal welfare was coined by Visseren-Hamakers (2020) to add to the 17 SDGs from the United Nations (UN DESA, 2016). This additional SDG safeguards the rights of the individual animal within the debate on sustainable development. These rights have long been neglected and it seems like customers are more recently prioritizing this issue through purchasing habits.

Choi and Lee (2021) showed that as a result of growing awareness in animal welfare, global consumer interest has increased in vegan leathers, including synthetic leathers. Consumers are also increasingly aware of the environmental impact of these synthetic leathers and interest has spiked in leathers based on plant material.

Note on leather alternatives

The awareness and interest in the field of sustainable leather alternatives is growing among customers and innovators, as products are needed that fit the movement of society towards a circular economy. The interplay between bio-based, biodegradability and sustainability is complex, but very important for this shift. Bio-based means to be synthesized by living organisms such as animals, fungi or plants (Appels & Wösten, 2021). Animal leather is an example of a bio-based product. Biodegradability is the capability of something to be decomposed by (micro-)organisms. From a circular standpoint, it is preferable that products are decomposed into compounds that are harmless to the natural environment. Leather is bio-based, but not always biodegradable due to the cross-linking compounds added during tanning processes (Smit&Zoon, 2022). The goal for sustainable leather alternative producers is to create a bio-based product from replenishable resources that is bio-degradable and durable at the same time.

Below, a variety of leather alternatives will be discussed. First, synthetic leather alternatives and their environmental shortcomings will be discussed, followed by innovative leather alternatives. These alternatives are categorized based on their most important input components.

Synthetic leather

Many of the "vegan" leathers currently available for consumers are made from fossil fuels. These synthetic leathers are usually made from either polyvinyl chloride (PVC) or polyurethane (PU) (Cao et al., 2013; Meyer et al., 2021). As can be seen in figure 1B, these leathers have a base, which is either woven or nonwoven, a synthetic layer on this base and a coating layer to protect against wear and tear and to make the material waterproof (Zhao et al., 2018).

The production of PVC uses toxic chemicals and produces dangerous by-products, such as dioxins (Cao et al., 2013). Additionally, these material require fossil fuels as their main input which adds the problem of greenhouse gas emissions associated with fossil fuel extraction and refining. There are also a variety of other problems, such as plastic pollution. Around 250,000 tonnes of plastic are estimated to be present in marine environments (Giacomucci et al., 2020). Secondly, the chlorine present in PVC can form different chlorinated chemicals that are toxic to the landfill or marine environments the PVC has accumulated in (Giacomucci et al., 2020). A third problem is that leathers made from PU require toxic chemicals such as N,N-dimethylformamide for their production (Zhao et al., 2018). Unfortunately, neither PVC nor PU are biodegradable in their most common form (Giacomucci et al., 2020; Howard, 2020). Both these plastics contribute largely to the accumulation of microplastics in nature (do Sul & Costa, 2014), which causes a variety of health problems in marine organisms (Zimmermann et al., 2020; Ogo et al., 2022). Recently, efforts have gone into creating versions of PVC and PU that have better biodegradability properties.

As can be seen in Table 1, the environmental impact of synthetic leather compared to bovine leather is smaller when considering global warming, eutrophication and water scarcity factors. However, abiological resource depletion and fossil fuel and chemistry factors are similar (Jones et al., 2020).

Category	Bovine leather	Synthetic leather
Global warming	36.3	10.1
Eutrophication	73.5	4.8
Water scarcity	25.0	1.7
Abiotic resource depletion	14.4	13.0
Fossil fuels and chemistry	13.8	13.4
Total	**163**	**43**

Data from The Sustainable Apparel Coalition (https://msi.higg.org).

Table 1: The environmental impact of bovine leather and synthetic leather according to the Higg index, which is a tool to evaluate the sustainability of fashion products and production processes. Retrieved from Jones et al. (2020).

Renewable leather alternatives

For these ILAs, an introduction on the material source will be given, followed by the general production process. Next, an overview of the sustainability of the product will be given. Finally, examples of companies are given that produce that particular ILA.

Mycelium leather

One of the alternatives for traditional and synthetic leather is based on mycelium, the root structure of fungi. Mycelium consists of a network of tube-like roots, called hyphae. These hyphae have a diameter of 1 – 30 µm and can branch, as well as fuse, to create networks spanning an area of kilometres, making them the largest organisms on earth (Appels & Wösten, 2021; Islam et al., 2018). The character of these networks depends largely on the environment. The outside of hyphae contains mainly beta-glucans, whereas the core consists of chitin crosslinked with polysaccharides (Islam et al., 2018). The chitin microfibrils provide rigidity and strength to mycelium structures.

The details of production process of mycelium-based leathers differ per research group or company and are shrouded in mystery as this is a highly innovative and competitive field. However, a general process outline can be found. Fungi spores are usually combined with sawdust and other organic materials. This sawdust and organic material can be a waste stream from another industry, to increase the sustainability of the production process. Wijayarathna et al. (2022) showed that leftover bread from supermarkets could be used as a basis for mycelium. A company called Mycotech retrieves sawdust from the wood industry, where sawdust is a waste stream (DW News, 2021). The retrieved sawdust is first steamed to remove any microbial competition for the fungi (Jones et al., 2021). Then the fungi mix, sawdust and other organic material are added together and the mycelium growing process starts in an environment with high CO_2 levels. This process is called solid state fermentation (Jones et al., 2021). The temperature and humidity are controlled very precisely during this process, as they are the most influential factors on mycelium growth. During this process, the hyphae grow quickly in search of oxygen, preventing the fungus from producing fruitbodies. After approximately one week the mycelium has grown into a foam-like structure and can then be processed into mycelium leather (Mylo, 2022). It was found by Haneef et al. (2017) that the resulting mycelium structure became stiffer when the provided substrate was tougher to consume.

First, the mycelium foam structure is chemically treated to remove unwanted soluble components and to create crosslinking sites. The smell of fungi is also removed during this step. Next, crosslinking agents, such as genipin, adipic acid or phenol are added to improve mechanical properties (Jones et al., 2021). Thirdly, the material is compressed to less than half its thickness and a moisturizer is added to keep the material flexible. Finally, the material can be dyed and embossed depending on the preferences regarding the final product.

VTT, a company in Finland, grows mycelium in a bioreactor within a liquid medium instead of on a solid substrate, like in the solid state fermentation process (Appels & Wösten, 2021; VTT Research, 2021). The processing of mycelium created through liquid fermentation can be done with traditional papermaking methods (Jones et al., 2021).

Mycelium leather is a sustainable material owing to the properties of fungi themselves. Growth of fungi does not require light and even though fungi require oxygen, this is partly offset by their stimulation of plant life and the subsequent atmospheric carbon dioxide uptake (Jones et al., 2021). It is however noted that mycelium growth enhances at temperatures slightly above room temperature (Jones et al., 2017). Pure mycelium is readily biodegradable (Zábranská et al., 1994), but the chemical treatment steps might inhibit this biodegradability depending on the chemicals added. For some mycelium-based leathers, such as Mylo™, it has been confirmed that plastic is present in the material (Mylo, 2022). Durability of mycelium leather will be discussed in the quantitative analysis section.


Figure 3: Patch of Muskin®, a mycelium-based leather alternative. Photo taken by Belinda Werschkull.

There is a plethora of companies working on mycelium leather products, but in academia there is less knowledge available (Wijayarantha et al., 2022). USA-based companies Ecovative, Mycoworks and Mylo™, which is part of Bolt Threads, are working on scaling up their mycelium leather production. In January 2022, MycoWorks received a 125 million dollar funding to build a mycelium-producing facility for their leather alternative, among other products (MycoWorks, 2022). The previously discussed Finnish VTT Research and the Indonesian Mycotech are also important players in this field.

Cellulosic leather

Plant-based

Plant-based leathers rely on cellulose present in plant parts to provide rigidity to the final product. Cellulose is a linear polysaccharide that is an important part of the cell walls of green plants. In these cell walls, cellulose is organized in microfibrils that provide rigidity and strength to the plant (Polko & Kieber, 2019). Cellulose is the most prevalent organic polymer on earth (Klemm et al., 2005) and has a renewable character.

Production processes differ depending on the source of cellulose used and they are again challenging to characterize because of the secrecy surrounding companies working on these type of leathers. A similarity for most plant-based leathers found for this research is the use of a woven basis of either cotton or polyester.

One of the leading plant-based leathers is Piñatex®, which is made from the fibres of pineapple leaves, a by-product of the pineapple industry. The fibres are extracted from the leaves and then dried, purified and mixed with polylactic acid (PLA) from corn to create a mesh that is not woven (Ananas Anam, 2022). Finally, this mesh is coated to produce the final product, Piñatex®.

The environmental impact of Piñatex® is described on their own website as very low, thanks to the utilization of a waste stream, the omission of toxic chemicals in the production process and the transparency of their supply chain (Ananas Anam, 2022). It is also stated that the mesh created with PLA is biodegradable. This statement may be overly positive by the company, as PLA can only be degraded in very specific controlled environments. Without these favourable conditions, the degradation of PLA can take between 100 and 1,000 years (Rustagi et al., 2011).

Desserto® is an ILA produced by the company Adriano Di Marti that is partially based on cactus leaves. Desserto® consists of a compact layer, a foam layer and a woven basis made of either polyester, cotton or a combination of both (Meyer et al., 2021; Desserto, 2021). These cacti are cultivated in Mexico and harvested twice a year. Only full-grown cactus leaves are harvested so that cacti at their plantations can live for around 8 years. No irrigation or pesticides are needed here. The cactus leaves are cleaned, ground and then sun dried for three days. Next, the fibres and proteins are extracted from the leaves to create a mixture which is then turned into Desserto® leather (Adriano Di Marti, 2021).

This cactus-based leather has a low environmental impact compared to traditional and synthetic leather, judging from the early LCA on the Desserto® website (Desserto, 2022). However, it is not entirely clear whether Desserto® is fully biodegradable, as it is only claimed to be PVC-free and still contains around 28% bio polyurethane (MoEa, 2022). Adding to the sustainability attributes of this material, the cactus plantations convert carbon dioxide through photosynthesis, lowering the total emissions from this product.

Fruitleather Rotterdam produces an ILA based on leftovers from the mango industry. As the Netherlands imports more than half of all mangos in Europe, this waste stream is significant (Business Insider, 2021). Mango leather is created by mechanically removing the seed from the flesh and subsequent pulping of the flesh. Next, binding agents are added and the mixture is heated in an oven. Sheets of material are retrieved from the oven and coated by a leather finisher (Business Insider, 2021). The mango leather is placed upon a basis of organic cotton (Fruitleather, 2022).

This mango leather appears to have a low environmental impact, thanks to the use of a waste stream. However, an LCA is not available on the website, making it hard to judge the exact environmental impact. Hugo de Boon, one of the co-founders of Fruitleather, did explain in the interview that no plastics are added to their leather. This is a key difference compared to Piñatex® and Desserto®.

Lastly, Appleskin™, created by the company Mabel in Italy, is an ILA with apple wastes partially replacing PU (Mabel Industries, 2022). The production process of this ILA is not entirely clear, however it seems similar to the process applied by Desserto®, with the waste stream collection replacing the harvesting of the plant. The version of Appleskin™ with the highest concentration of apple waste possible contains 39% apple, but the concentration of PU in this particular version of Appleskin™ is 43% (Leerkwartier, 2022). The basis of this ILA is polyester, cotton or a mixture of both. The environmental impact of this apple-based leather is unclear. The inclusion of PU is a drawback of the material.

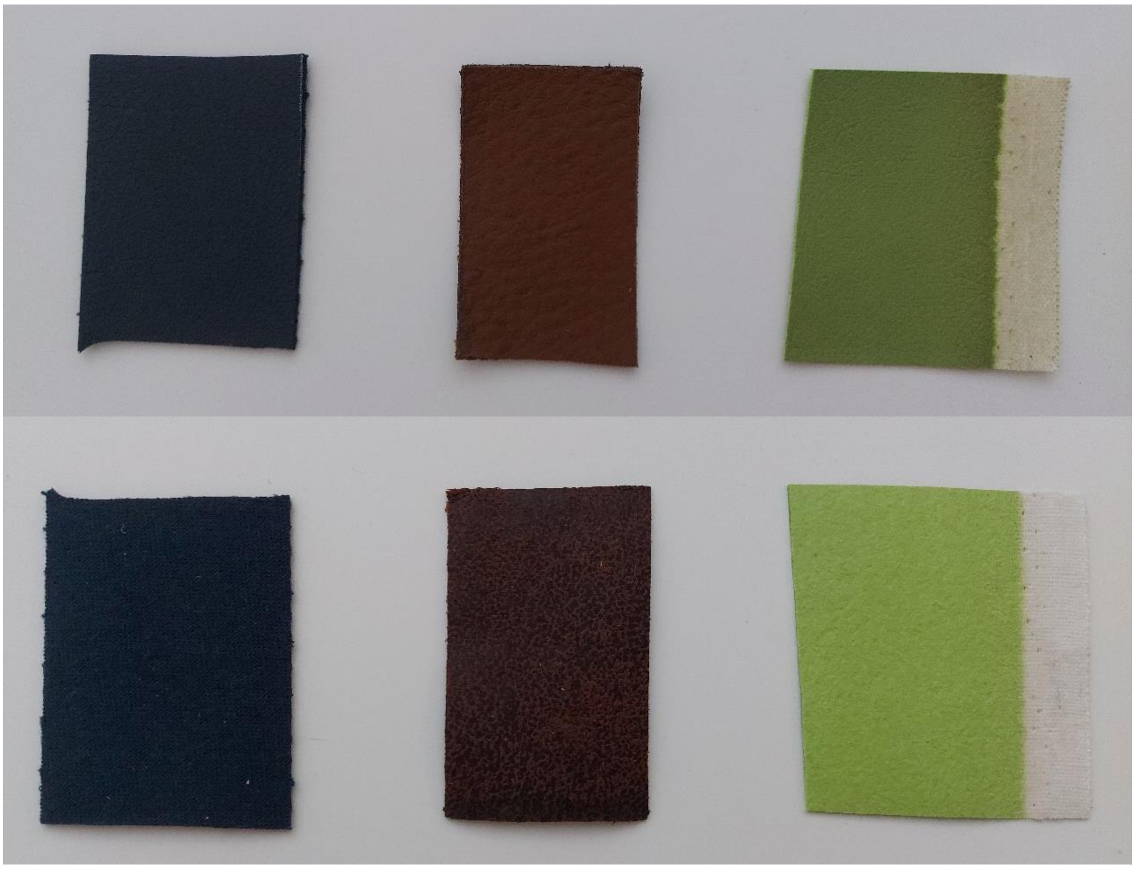

Figure 4: The upper photo shows the top-side of Desserto, Fruitleather and Appleskin leathers from left to right. The lower photo shows the bottom-side of Desserto, Fruitleather and Appleskin leathers from left to right, revealing their woven basis.

Kombucha leather

Kombucha tea is a sugared tea that has been fermented through the introduction of a symbiotic culture of bacteria and yeast (SCOBY) (Penciu, 2022). The SCOBY culture uses sugar in the tea as a nutrient to make the tea sourer and add bubbles. Bacteria create cellulose and provide structural integrity to the SCOBY culture. This SCOBY culture, along with the cellulose formed, is retrieved from the tea when the right taste has been achieved. When this bacterial cellulose is dried, it becomes a leather-like material.

Bacterial cellulose (BC) is a very flexible, durable and biodegradable (Nguyen et al., 2021). Additionally, bacterial cellulose is highly hydrophilic. Thanks to these properties, BC has been applied in different fields, varying from medicinal to electronical applications (García & Prieto, 2019). Until recently, bacterial cellulose gels were usually produced using mediums similar to a Hestrin and Schramm medium, which contains peptone and yeast extract among other ingredients (Nguyen et al., 2021).

Due to the costs of this Hestrin and Schramm (HS) medium, the research field started investigating other medium possibilities (Azeredo et al., 2019). Various waste streams, mainly from food and agricultural industries, have been evaluated for their nutrient availability. One combination tested is the kombucha mixture discussed above. *Komagataeibacter xylinus* is often the cellulose-producing bacterial component of choice when producing a kombucha-derived bacterial cellulose. Domskiene et al. (2019) added a very simple mixture of tea, water, sugar (sucrose) and yeast extract, whereas Nguyen et al. (2021) activated the bacterial strain first in a HS medium and then added the bacteria to apple juice, sour whey, brewer's grains, black tea and sucrose. The apple juice, sour whey and brewer's grains were all waste streams. The leathers could be retrieved after one or two weeks and could be grown at room temperature.

The environmental impact of kombucha leather seems low as renewable resources are used and the production process does not require toxic chemicals or a high amount of energy or water. This impact is lowered when waste streams are used as a nutrient source. Additionally, the ILA produced is not toxic to the skin (Nguyen et al., 2021).

As of now, there are no major companies working with kombucha leather yet. However, the production process can be carried out at home, opening the door for designers to experiment with this innovative material.

Figure 5: Kombucha-derived cellulose. From a bundle of cellulose layers on the right, a single sheet of cellulose is rolled out to the left.

Collagen-based leather

As explained in the traditional leather section, the material that forms the main support for leather is collagen. The collagenous matrix of animal skins provides the perfect basis for leather, as it can be modified to fit various functions and it is very durable.

Efforts have gone into producing this collagen matrix without killing the animal. Modern Meadow, a company situated in New Jersey, started research into lab-cultured leather. This lab-cultured leather is created by taking cells from a cow without seriously harming it. These cells are multiplied in the lab and put on the right medium to promote collagen production. Jakab et al. (2019) noted that even though it was possible to produce a leather-like material through this tissue-engineering approach, the structure of the collagen is very different from the collagen structure in skins. Collagen in animal skins consists of various layers with different coordination of collagen fibrils. The resulting matrix is able to withstand a high level of wear. For example, collagen in the corium layer of the skin is coordinated in a weave-like structure, which was not successfully reproduced with the lab-cultured collagen. Additionally, the collagen concentration in the leather created by Jakab et al. (2019) was 30%, while this concentration is around 80% in bovine skins.

In 2014, Modern Meadow decided to move away from tissue engineering to work with a mixture of enzymes and yeast cells that were DNA edited to produce collagen (Anzilotti, 2017). The technique used to modify the yeast cells is called recombinant DNA technology. This technique has been used successfully around the 1980s to create synthetic insulin by modifying the bacteria species *Escherichia* *coli* (Tibaldi, 2012) and is also used frequently to create proteins that were usually retrieved from animals, such as whey and casein (Teng et al., 2021). Confusingly, an LCA of Bioleather1, the flagship ILA of Modern Meadow, was published in 2022 which stated that this material consisted of soybean protein and polyurethane on a textile basis of nylon, which is also a plastic (Locker & Theregowda, 2022). This suggests that Modern Meadow has abandoned the idea of yeast-derived collagen. Unfortunately, no mechanical properties of Bioleather1 can be found as of the time of writing.

Mechanical properties of leather and its alternatives

For the analysis of the mechanical properties of leather and its alternatives, values were retrieved from various sources and put together in Table 2. These values include thickness of the sample, tensile strength, elongation at break, tear strength and flex resistance. The meaning of these properties will be discussed below.

As mentioned by Islam et al. in 2018, only a small number of studies focus on the mechanical properties of mycelium materials and this is true for a large part of the field of ILAs. The use of different testing methods between various studies further complicates data selection. The values in table 2 were retrieved using two different test methods. This should be taken into account when comparing the values.

Tensile strength tests are performed by fitting a rectangular sample of the material between two clamps which are then slowly moving away from each other until the sample tears. The maximum force applied on the sample divided by the surface area of the sample yields the tensile strength. Tensile strength values can help understand the rigidity of a material. Unsatisfactory tensile strength values indicate that a material is not strong enough for certain purposes as a leather substitute. During this test, elongation of the sample is measured by dividing the length of the sample right before the breaking moment by the length of the sample without forces applied. Elongation at break percentages describe the flexibility of a material. Insufficient values could mean that the leather alternative is too brittle or not comfortable enough.

Tear strength tests are performed by creating a tear in a sample of the tested material. Both sides perpendicular to the tear are fitted in clamps and slowly moved in opposite direction. The tear strength is determined by dividing the applied force by the distance the clamps have moved while applying this force. The tear strength can also be described as the resistance a material expresses against tearing. Low tear strength values indicate that a material is not durable, as a small tear in the material requires a low force to become larger.

Flex resistance tests are performed by fixating two sides of a material sample between clamps. These clamps are then successively moved towards and away from each other for a set amount of cycles. After the set amount of cycles, possible cracks in the sample are analysed and graded. The values flex resistance values given in Table 2 are all based on samples that showed either no cracks or only minor cracks. The flex resistance is another indication of the durability of a material. Low flex resistance means a material starts to show cracks with low usage.

Finally the thickness of all samples is given. It is not clear whether the thickness directly influences the other mechanical properties but it helps create an image of the material at hand. If a cell is marked with an 'x', no value could be found for this property.

The requirements found for shoe upper leather, as well as values found for bovine shoe upper leather and suede leather will be used as benchmarks and all properties explained above will be discussed.

Table with mechanical properties of leather and alternatives

Material name	Material type	Thickness in mm	Tensile Strength in N/mm² or MPa*1	Elongation at break in %*2	Tongue tear strength in N/mm*3	Flex resistance in cycles*4	Source
Requirements for shoe upper leather	N/A	1	x	> 40	> 50	> 50,000	Godthi & Rawling (2020)
Bovine shoe upper leather	Animal leather	1.93	39.5	30 - 80	82.9	> 200,000	Meyer et al. (2021)
Suede	Animal leather	2.03	29.15	40.68	x	x	von Hoven et al. (2002)
commercial PU leather	Synthetic leather	~ 2.00	5.28	31.54	79.2	x	Saha et al. (2020)
PU-coated textile	Synthetic leather	1.37	10.2	x	17	200,000	Meyer et al. (2021)
Fruitleather	Plant-based leather	1.05	7.74	49.2	19.38	10,000	Fruitleather (2022)
Piñatex®	Plant-based leather	1.43	4.5	x	31	150,000	Meyer et al. (2021)
Desserto®	Plant-based leather	0.88	20.8	x	37.2	30,000	Meyer et al. (2021)
Appleskin™	Plant-based leather	1.14	14	x	18.4	50,000	Meyer et al. (2021)
Reishi™ Brown Natural	Mycelium leather	1.06	5.6 - 7.4	51 - 52	6.7	20,000	Scullin & Rigas (2020)
Reishi™ High strength	Mycelium leather	1.00 - 1.10	8.8 - 12.5	55 - 80	52.6	100,000	Scullin & Rigas (2020)

Muskin®	Mycelium leather	6.22	0.2	x	0.5	10,000	Meyer et al. (2021)
Mylea™		3 - 9	8 - 11	22 - 35	24	x	Mylea (2022)
Kombucha-derived bacterial cellulose (KBC)	Microbial cellulose	1 - 2	1.69 ± 0.33	14.54	25.44	x	Nguyen et al. (2021)
Kombucha		0.29	9.7	x	5.1	10,000	Meyer et al. (2021)
Chrome-tanned biofabricated leather	Tissue-engineered collagen	0.079	19.03	11.43	x	x	Jakab et al. (2019)
Vegetable tanned biofabricated leather		0.114	12.18	1.9	x	x	

Table 2: Mechanical properties of leather and its alternatives.

Test methods used to retrieve results:

*1 = ISO 3376 or ASTM D2209

*2 = ISO 3376 or ASTM D2209

*3 = ISO 3377 or ASTM D4533 / D4704

*4 = ISO 5470-2 or ASTM D6182

Results

Tensile strength and elongation

Bovine shoe upper leather has a higher tensile strength than suede leather. This is not surprising, as suede leather is made from the weaker lower layer of animal hides (Xu et al., 2016). None of the synthetic leathers or ILAs reach the tensile strength of suede leather, let alone animal shoe upper leather. Interestingly, tensile strength values of synthetic leathers are far below animal leather values, but the elongation percentages are similar.

Desserto®, along with chrome-tanned biofabricated leather, comes closest to the tensile strength of suede leather, reaching around 2/3 of suede leather tensile strength. Fruitleather, Piñatex® and Appleskin™ have lower tensile strength values, but Fruitleather does have a sufficient elongation percentage.

The mycelium leathers have similar tensile strength values, which are well below suede leather values. Muskin® has a very low tensile strength, which might be problematic for the use of this material in any load-bearing capacity. The elongation percentages of the Reishi™ are up to par with the animal leathers, whereas Mylea™ is close to these values.

The tensile strength and elongation percentage of both microbial cellulose leathers are low when compared to suede leather.

Chrome-tanned biofabricated leather reaches higher values than its vegetable tanned counterpart. This chrome-tanned lab-cultured leather is not as flexible as animal leather, judging from its elongation at break percentage. Vegetable tanned biofabricated leather is even less flexible.

Tear strength and flex resistance

Even though the tensile strength of synthetic leather is not close to the tensile strength of animal leather, the tongue tear strength of one of these plastics is similar to that of bovine shoe upper leather. Additionally, the flex resistance of one of these synthetic leathers is similar to animal leather flex resistance.

Desserto® and Piñatex® have a tongue tear strength of about ½ compared to animal leather, whereas the tear resistance of Fruitleather and Appleskin™ products is about ¼ of the benchmark leather. None meet the tear strength requirement of 50 N/mm of shoe upper leather. Both Piñatex and Appleskin meet flex resistance requirements for shoe upper leather and Piñatex® is the only plant-based leather with flex resistance similar to that of bovine shoe upper leather.

The high strength version of Reishi™ exhibits tear strength and flex resistance values that meet the requirements for shoe upper leather. Mylea™ reaches a tear strength values which corresponds to 1/3 of the tear strength of animal leather. The brown natural version of Reishi™ and Muskin® do not come close on either tear strength or flex resistance values.

One kombucha derived bacterial cellulose leather showed a tear strength of approximately 1/3 of bovine shoe upper leather and approximately ½ of the requirements for shoe upper leather. Microbial cellulose leathers do not express promising flex resistance values.

No durability values were given for biofabricated leathers.

Discussion of results

The values of animal leathers are higher for all four mechanical properties discussed. Interestingly, the tensile strength of synthetic leather is low compared to these animal leathers and other alternatives to leather. The other three mechanical properties of synthetic leather are very similar to those of animal leather. As synthetic leathers are widely used globally, lower tensile strength might not be a deciding factor on the utility of a leather-like material. Alternatively, it might be possible to enhance tensile strength in the final product.

Fruitleather has low tensile and tear strength, as well as flex resistance. Its elongation is as high as animal leather. The decision to omit plastic in this product might be the reason for the low flex resistance, tensile and tear strength, when compared to the other plant-based leathers. Desserto® shows great tensile strength and modest tear strength, but low flex resistance. This might result in low durability. Piñatex® on the other hand has a low tensile strength, but modest tear strength and high flex resistance. This might result in a partially durable product that cannot withstand certain high forces. Appleskin™ shows modest properties across these four properties.

All mycelium leathers have low tensile strength values, but sufficient elongation percentages when compared to animal leather and shoe upper leather requirements. The high strength version of Reishi™ also exhibits high flex resistance and a tear strength which meets the demands of shoe upper leather. Its brown natural counterpart does not show high mechanical properties, just like Muskin®. This was confirmed by one of the interviewed designers, who noticed that a sample of Muskin® was easily punctured and cut. Mylea™ has average tear strength and no flex resistance available. These last three materials will need improvements along these metrics to improve usability.

KBC leathers show low tensile strength and elongation, along with average tear strength and low flex resistance. This field of leather alternatives requires more research for it to be considered in the fashion industry as a leather replacement.

It is difficult to judge tissue-engineered leather as no tear strength and flex resistance values can be found. The tensile strength is moderate when tissue-engineered leather is chrome-tanned. However, chrome tanning is one of the most polluting processes of leather production, increasing the environmental impact of the product.

Reishi™'s high strength product is the only ILA that reaches the requirements for shoe upper leather. Other ILAs, such as Desserto® and Piñatex® do meet the demands of furniture upholstery leather (Godthi & Rawling, 2020).

The field of ILAs is new and further development may help improve the mechanical properties of these alternatives.

Qualitative analysis of leather and its alternatives

As mentioned by Wijayarathna et al. (2022); “there is a lack of knowledge in academia on fungal leather substitutes”, and companies have more knowledge on this topic. The same seems to be true for the other leather alternatives mentioned in this review. Because of competition, companies usually do not publish their results, making it tougher to analyse the field. For this reason, I decided to conduct interviews to show a perspective on these alternatives which cannot be found in literature.

The following four stakeholders in the leather (alternative) industry were interviewed:

- **Hugo de Boon**, co-founder of Fruitleather Rotterdam. Fruitleather specializes in the production of mango-based leathers.

- **Sven Kurstjens**, head of Research & Development at Richard Hoffmans in Nettetal, Germany. Richard Hoffmans is a company that focuses on the production of leather, but not the tanning and liming process.

- **Belinda Werschkull**, designer at own Studio Macnas. Belinda owns a small company in Utrecht where she makes and sells hand-made bags and accessories. She works with the following materials:
    - Chrome-tanned leather
    - Vegetable tanned leather
    - Muskin®
    - Desserto®
    - Fruitleather
    - Appleskin™

  Belinda uses these materials to make products in consultation with the customer.

- **Anna Treurniet**, designer at her own company. Anna owns a small company where she makes and sells hand-made bags and accessories. She works with the following materials:
    - Vegetable tanned leather
    - Recycled leather from furniture upholstery
    - Piñatex®

  She has also experimented with Fruitleather, but this is not yet part of her collection. Anna uses the three materials mentioned above to create her products and they are available in her web shop.

All opinions expressed in the following section on the interviews are credited to the interviewees and do not represent necessarily my opinion.

Materials and sustainability

The lower durability of plant-based alternatives compared to animal leather was confirmed by all interviewees.

Both designers showed examples of this lower durability. Belinda created a laptop bag from Desserto®, which she had used regularly for five months as of the time of the interview. This bag showed some signs of use but appeared to be in a good shape.

Anna Treurniet has been using a self-made laptop bag made of Piñatex®, which showed clear signs of use, mainly in the form of abrasion on the edges of the bag. She noted that this kind of wear and tear only occurs for animal leather after around 10 years of use, which is substantially longer than this new bag had been used. Anna suggested that applications of Piñatex® in products with higher forces exerted on it would probably cause the products to have a short lifetime.

Both Belinda and Anna noted that ILAs require different and often more time-intensive methods to create similar products as made with animal leather. Additionally, when creating a product from bovine leather, parts of the material go to waste due to the restrictions that are tied to the dimensions of a cowhide. ILAs do not have this inherent dimensional constraint, which may reduce waste. Belinda proposes the production of ILAs in a shape that fits the final product.

Hugo noted that the durability of Fruitleather is low compared to animal leather and other leather alternatives, mainly due to the difficulty of protecting their material from wear and tear. However, their process is more sustainable, thanks to the omission of synthetic binders such as polyurethane. This choice for plastic omission lengthens their development process, but it fits their ideology. Through their development, the tear strength has improved, as well as the scale of their material.

When asked what kind of efforts the Richard Hoffmans puts into becoming more sustainable, Sven Kurstjens replied that the company works on reducing the energy and water needed during processes. The company also aims to bind chemicals to the leather better to prevent leaching, the company has its own water treatment system and recently built their own solar park. Additionally, all their products and production processes are in harmony with the Roadmap to Zero, an initiative that provides emission targets for businesses in the fashion industry (Sadowski et al., 2021). Sven explained that it can sometimes be tough to adhere to new emission requirements, as the production process needs to be overhauled and the quality of the product needs to remain high.

The leather that is used at Richard Hoffmans is usually chrome-tanned, but they are working on receiving leathers that have been tanned with different, less toxic, agents.

The Hoffmans tannery works together with green chemistry company Evolved by Nature and designer Anya Hindmarch to create a biodegradable and compostable leather that requires less harmful chemicals (Cernansky, 2021). The line with products containing this leather is called Return to Nature and these products decompose in 45 days in composting conditions. The main drawback are reduced mechanical properties of this material.

ILAs are not yet of interest to Richard Hoffmans. The company has experimented with mycelium leathers, but the mechanical properties were simply not good enough at the moment of testing.

Organoleptic properties

Organoleptic properties are the properties of the leathers that are noted with sense organs. Examples of these properties are the look, feel and smell.

For Fruitleather, consumers appreciate the feel and look of the product. Additionally, people quickly note the smell of the product as an important factor. Part of these people enjoy the smell, whereas others dislike it. Also, the unequal thickness of Fruitleather makes the material sometimes tough to work with, as the flexibility of the material changes with its thickness. Finally, consumers would like Fruitleather to produce their material on a roll instead of separate patches, because material on a roll gives consumers more freedom with their creations.

Sven Kurstjens explained that at Richard Hoffmans, all products are evaluated by hand and look. This is due to the fact that they are not a large company and because they use aniline and semi-aniline leathers for their products. Aniline leather is a soft type of leather of high quality. There is currently no equipment available to analyse the colour and feel for these types of leather.

Anna noted that Piñatex® is more stiff than the vegetable tanned leather she uses. Additionally, Piñatex® is covered in a coating to make the material water resistant. This coating fades through usage and this makes the material look worse in her opinion. She added that leather seems more luxurious than Piñatex®, but this might be something that she and her customers still have to get used to.

Financial side and marketing

Hugo noted that the price of Fruitleather is not yet very competitive compared to animal leather and other alternatives. They currently sell brand-to-brand to provide continuity for their company and provide sample sets in their website for individual customers.

For Richard Hoffmans, it is financially beneficial to become more sustainable, as it often saves energy, water and resources. This saves costs.

The two designers explained that they did not notice a large price difference between animal leather and ILAs. It was noted that more transparency of animal leathers, for example increasing traceability of the hides to their origins, increased the price of these leathers. ILAs could provide a cheaper alternative in the future, according to Belinda.

Perception of leather alternatives by interviewees and their customers

Hugo de Boon indicated that there is an increasing amount of attention for animal-free leathers. He expressed that consumers prefer a product that is durable, animal-free and sustainable while remaining the same price of a leather product, which is currently not possible. For this reason, consumers might switch to synthetic leather, which causes indirect harm to animals through the use of fossil fuels for its production and microplastic accumulation. Fruitleather expects the field of ILAs to grow in the coming years as a result of rising fossil fuel prices which might make synthetic leathers less attractive. The animal leather industry will probably remain large due to meat consumption, which was also noted by Sven Kurstjens.

Among customers at Richard Hoffmans there is a lot of interest in sustainability in the leather industry, but this interest is more directed towards transparency and sustainability of the production process rather than towards the source of the material itself. The future of ILAs really depends on the developments of their mechanical character. Only if these materials become as mechanically robust as animal leather and more sustainable, then the position of animal leather will really be questioned. This was confirmed by Belinda, who noted that her customers are generally not willing to pick a material that has lower quality.

Leathers from East-Asia and South-America could decrease in popularity if ILAs become more useful, since leathers from these areas have a less transparent production process and are of lower quality, which makes them more intensive to process.

Anna noticed different opinions on ILAs and leather among her colleagues and customers. Some people prefer animal leather as it is a long-lasting product which forms a by-product of the meat industry. Other people prefer cruelty-free materials and are then more interested in ILAs. Most customers of both designers were not aware of the various material options and their differences.

Anna also mentioned that the general secrecy surrounding ILAs and their marketing tools made it difficult to select a material that fits her needs and preferences. Both designers found it difficult to place an order with some ILA producing companies, as the minimum order amount was too large for their respective companies. This was especially true for mycelium leathers, according to Belinda.

Material applications

Both quantitative and qualitative analyses confirmed that ILAs do not have the mechanically robust and durable character of traditional animal leather. This does not mean that ILAs cannot be used and indeed, various products containing ILAs have been produced.

Major brands are interested in these ILAs and some have developed prototypes with these materials. Adidas created a mycelium-based iteration of their iconic Stan Smith shoe together with Mylo™ (Adidas, 2021) while luxury design house Hermès created a mycelium bag with help of Mycoworks (Reishi™, 2021).

Products containing plant-based leather are already available for individual customers. MoEa is a company that creates shoes from plant-based leathers such as Desserto®, Appleskin™ and Piñatex® among others (MoEa, 2022). One review on a corn-based pair of sneakers from MoEa could be found, which was very positive (Herbert, 2021). In this review, the shoes are said to be more flexible than synthetic leather shoes while being as comfortable as sneakers from major sneaker brands. The durability of the shoes was not discussed. MoEa shoes have a carbon footprint of approximately 5 kg of CO_2/m^2 while shoes made of animal leather emit approximately 60 kg CO_2/m^2 (MoEa, 2022). All sneakers by MoEa are priced at 149 euros as of the time of writing.

Luxtra London provides a wide variety of hand-crafted plant-based leather bags and wallets (Luxtra London, 2022). Materials from Desserto®, Appleskin™, Piñatex® and Fruitleather are used in these products. 37 reviews of their products were found on Trustpilot. These reviews all marked the experience with Luxtra London as “excellent”, while complimenting the quality of the material and product (Trustpilot, 2022).

As of the time of writing, bacterial cellulose- or tissue-engineered leather prototype products have not been created.

Consumer behaviour

There is no clear answer to the question "which leather material is the best?". The answer depends among other factors on the requirements of the final product, the ideology of the production company and the preferences of customers. The first two factors mentioned have been discussed before in this research, but consumer behaviour has only been mentioned briefly in the animal leather and interview section.

Customer beliefs and preferences might help explain the recent success of companies such as MoEa and Luxtra London. A study by Szejda and Urbanovich (2021) on consumer adoption of innovative materials in the fashion industry showed that out of a group of 2,051 US participants, 45% was highly likely to purchase these materials. Around sixty percent of early adopters were willing to pay more for these materials than for traditional materials. Early adopters are a group of consumers that starts using new products before the majority of consumers does. The main arguments for the purchase of innovative materials over traditional materials were animal welfare, lower environmental impact and product quality. Szejda et al. (2021) showed in a different study that out of a group of 501 participants across China, 70% expressed that they were highly likely to buy plant-based, mycelium or tissue-engineered leather alternatives. 62% of the group mentioned in the previous sentence was willing to pay more for these ILAs compared to traditional leather. Both studies showed that younger participants were more inclined to buy these innovative materials.

These results indicate that consumers are interested in these ILAs and a part of this group is also willing to pay more for these materials to align their purchasing habits with their beliefs and values. This might be the reason why companies such as MoEa and Luxtra London managed to build a business model around ILAs.

Discussion and conclusion

The goal of this research is to provide a clear and elaborate overview of the field of animal leather and ILAs to assess the likelihood that animal leather will be replaced by these innovative materials. A quantitative analysis was performed to compare the technical properties of ILAs and animal leather. The perspectives of various stakeholders in the leather and ILA industries were shown through interviews. Finally, the current applications of such ILAs and consumer behaviour regarding ILAs were explained.

None of the ILAs are up to par with animal leather regarding technical properties, but some do meet requirements for upholstery materials or shoe upper leather. Mycelium leather from Reishi™ and plant-based leathers from Desserto® and Piñatex® show promise in this regard. During interviews, the lower technical performance of ILAs compared to animal leather was mentioned by certain stakeholders as a reason for reduced consumer and industry interest. ILAs do fill a niche, as they provide a cruelty-free alternative to leather with lower plastic content than synthetic leather and lower emissions associated with their production. Companies such as MoEa and Luxtra London have created a business model based on the application of plant-based ILAs in their products. Their products have been well received judging from the few reviews available online. Additionally, consumer behaviour studies show high customer interest in innovative materials for the fashion industry. These studies also reveal a focus on low environmental impact and cruelty-free products among interested consumers.

Challenges

As mentioned before, the gathering of data from literature on innovative leather alternatives is difficult, due to the lack of information in academia and the secrecy of companies working on these materials. The use of different test methods also makes it harder to compare the mechanical properties found. Exceptions to this secrecy are Fruitleather, Mycotech and also Reishi™ to a certain extent.

Additionally, sources found do not always give a completely unbiased view. On the website of Reishi™ for example, the mechanical properties of their material are compared to the properties of bovine leather. However, the values given for bovine leather are significantly lower than values of bovine leather found in literature. No source is cited for the bovine leather values given on the Reishi™ website. It could be that the minimum requirements for cowhide leather in a certain low load-bearing product are given on their website. On the other side, Meyer et al. (2021) state in their analysis of leather and its alternatives that "leather is a bio-based and biodegradable material". However, while leather is indeed a bio-based material, it is not always biodegradable (Smit&Zoon, 2022).

This literature review could have been more elaborate with the addition of an interview with a large party selling ILA-based products. Multiple companies that fit this description have been approached but none were available for an interview. Finally, further research should find an explanation for the current use of synthetic leathers in various products while tensile strengths exhibited by these materials are low compared to values of animal leathers.

Outlook

Future studies should look into comparing additional mechanical properties such as abrasion resistance, water vapor permeability and flammability. It will also be interesting to investigate the durability of ILA end-goods such as shoes from MoEa and bags from Luxtra London. More interviews with different stakeholders in the fashion industry should help create an even clearer overview of the field of leather and ILAs. A qualitative analysis of these materials with a grading system of organoleptic properties could also add a new perspective on the topic. This future research would depend on wider availability of novel materials and greater transparency from producers regarding material properties. It is expected that this information will become more accessible as technologies mature.

I believe that the leather industry will not be completely replaced by the ILA industry anytime soon, due to the sheer size of the animal leather industry and the habit of meat consumption globally. However, I do think that innovative materials have the potential to disrupt the leather industry regionally and possibly globally over time. I believe that these innovative materials will be noticed and supported by early adopters, since these materials provide a more environmentally conscious alternative to animal leather. The mechanical properties of certain plant- and mycelium-based leathers already meet the requirements for either upholstery or shoe upper leather, which is of major importance for consumer adoption. As mentioned in the interviews, these innovative materials could eventually replace lower quality hides that require more intensive processing to create a suitable end product. Alternatively, the disruption caused by these ILAs in the leather industry might provide an incentive for animal leather producers to create a more sustainable product. ILAs are free of the inherent constraints on dimensions of animal leather, which might reduce waste in the innovative leather industry. The lifting of these restraints could also be interesting from a creative standpoint.

Adopting ILAs in our everyday goods

The properties of ILAs are not yet up to par with the physical performance of animal leather, but maybe this does not need to be the case for ILAs to become part of our lives. In the hypothetical case that these materials last about half as long as animal leather does, but they do have an environmental footprint which is tenfold smaller than the footprint of animal leathers, this trade-off in durability seems worth it from an environmental perspective. These kind of questions should be answered truthfully by ILA producing companies to create transparency and awareness. The hypothetical example mentioned above illustrates my idea that the switch to a more circular economy by implementing innovative materials requires a different, more flexible, way of thinking. These materials may not have the same properties as previous materials, but if we use them in a different manner, this might not pose a problem. I do realize that this change of mindset for society as a whole might take decades to unfold.

It will be interesting to see how the physical performances of ILAs develop and whether these innovative materials can eventually challenge the mechanical robustness of animal leather. The adaption of the leather industry to more stringent sustainability requirements will also be intriguing to follow, as this might entail large changes in the industry.

Acknowledgements

I would like to thank Sasha Madhavji and Han Wösten for their extensive support during this project. I also want to thank Hugo de Boon, Anna Treurniet, Belinda Werschkull and Sven Kurstjens for being open to an interview. I want to thank Hugo and Belinda for providing samples of ILAs.

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