Final Report

Leather Alternatives for Cricket Gear

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Executive Summary

The research presented in this report forms part of the 'Vegan Leather Cricket Gear' (VLCG) project led by Professor Martin Charter, Director of The Centre for Sustainable Design ® (CfSD) at the Business School for the Creative Industries (BSCI) at the University for the Creative Arts (UCA).

Cricket is a gear-intensive sport, offering opportunities for sustainable material and design innovation. Cow hide leather, a key material component in both balls and gloves, is a natural material, although with a high environmental impact. This project explores the potential for hide leather to be replaced by sustainable alternatives.

The leather alternatives sector is growing rapidly, bringing with it countless innovative solutions that utilise various (natural) resources. Publicly available information on these new alternative leathers is scarce and limited, as many companies are either in the research and development stage or early commercialisation stages. This report synthesises information on potential alternative materials that could replace hide leather and maps the current market sector. 123 alternative leathers from 87 companies are documented into a database. While many of these materials are in early stages of development, the most common target application appears to be fashion accessories, such as handbags. A few are being developed for footwear, for which mechanical property requirements are more critical.

This report assesses some of these alternative leathers in the context of their potential use in cricket gear, specifically for balls and gloves. The key performance indices for cricket gear leathers are identified. Preliminary mechanical (tensile) testing is conducted on a few alternative leathers that were procured. Some early findings and recommendations are presented. The principal conclusion is that whilst some alternative leathers show potential, much further research in this under-explored area is needed to develop fully functional and sustainable cricket gear with leather alternatives.

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1. Introduction

Cricket has been identified by industry experts as one of the most gear intensive sports, making it a prime candidate for sustainable innovation (Charter and Clark, 2022). Some cricket gear, such as pads and apparel, have evolved significantly with the advent of high-performance and lighter-weight polymeric materials which can be produced in the form of foams and textiles. Other materials, such as willow in the blade of bats and bovine leather in the casing of balls, have remained virtually unchanged for centuries. Cricket ball casings and the palms of batting gloves are exclusively made from bovine leather. Indeed, in the case of cricket balls, this is codified in the standards, and colloquially, the balls are referred to as ‘leather balls’.

While leather is classified as a natural material and has a range of impressive properties – particularly durability and water resistance – leather production has a high environmental impact. For example, the embodied energy (80-100MJ/kg), carbon footprint (4-5 kgCO_2eq/kg) in the primary production of leather are comparable to that of typical petrochemical-derived polymers (e.g. polyurethane, polyester), and leathers require over 3-4 times the water use (1,000-1,200 l/kg) in comparison to polymers (Granta EduPack 2022 Database). Intensive cattle farming and tanning processes (used to stabilise the proteinaceous leather for improved durability) are the two main reasons for this high eco-impact. Alongside the environmental reasons, the ethics of intensive cattle rearing and evolving consumer behaviours (e.g. veganism), are driving many sectors (such as fashion) to innovate and re-create products with ‘leather alternatives’ that are ethically and sustainably produced.

There have been some mentions of the sustainability and ethical shortcomings of bovine leather within the cricket community – such as by Australian fast-bowler Jason Gillespie[1] - and even efforts by Earley Cricket Club to conceive a ‘vegan’ cricket ball[2]. As yet, no vegan cricket ball, or cricket batting, wicket-keeping and ‘inner’ gloves prototypes have been produced so far, and no substantial movement has emerged away from bovine leathers.

This report aims to identify potential alternatives to leather for cricket balls and gloves. Such alternatives are already in early use in the fashion and furniture industries, but their utility in performance applications is yet to be investigated or demonstrated thoroughly. Sporting materials often require high performance properties and uniformity across samples, the latter of which is something that naturally derived materials are less likely to achieve. Similarly, cricket gear leathers require a range of critical material properties. However, this short project does not aim to investigate and assess all these performance indices but does aim to reveal the areas into which future research should be focused to accelerate innovation in this industry. Following some preliminary materials mechanical testing on a few sourced samples, initial recommendations of potential leather alternatives will be offered.

[1] https://metro.co.uk/2016/06/08/vegan-cricketer-calls-for-ban-on-leather-balls-5931403/
[2] https://www.itv.com/news/meridian/2019-09-13/it-s-just-not-cricket-or-is-it-the-new-vegan-ball

The report maps out the currently available biomaterials that self-identify as being alternatives to traditional animal leather. The synthetic leather industry is projected to continue to grow for the next decade (Grand View Research, 2022) but in order to ensure this growth has a positive impact on the environment, the aim should be to increase proportion of alternatives that are bio-based. This report aims to present all currently available materials in a clear manner to ensure growth of the bio-based sector is not neglected in favour of growth of the polyurethane (PU) or polyvinyl chloride (PVC) based leather alternatives. Although, it is recognised that the majority of bio-based or 'vegan' leathers are mixed-materials and include some content of polymer. This market research will categorise companies by the natural resource - that their material is primarily based on - to give a clearer picture of the spread of innovation within the sector.

2. Scope

As this 6-week project was timetabled to run from 11th July 2022 to 19th August 2022 [3], the scope of both the materials considered for physical testing and the applications considered had to be narrowed down to ensure adequate work could be conducted in the timeframe.

This project focuses on materials that are predominantly bio-based and have potential to be used as sustainable alternatives to leather. During initial research, some materials - such as those that are fully-petrochemically derived (100% 'plastics') - were outside the scope of this research. They are noted here for interest: Clarino, Deca, Dinamica, Hemp Black, Lamous, Microfiber Faux Leather, Technik-Leather, Ultrasuede, Volar Bio, Compo-SiL, ELeather and SiLeather.

This research aimed to identify and review the sustainable leather alternatives that are currently on the market or in development. The suitability of these materials to use in cricket gear would then be investigated.

With regards to applications, the casing of cricket balls and the palm of batting gloves are the focus. Initially, protective pads were also considered but discussions with Gunn & Moore revealed that conventional pads now do not utilise any leather.

3. Identifying key performance criteria for leather in cricket gear

In order to compare the alternative materials against animal leather, it was imperative to first understand the criteria and properties most crucial to the leather's performance in the specific application. In simple terms, leather is treated animal hide or skin. For cricket gear, this is usually cow hide (Katewa, n.d.). Note, that 87% of all leather produced in the UK is bovine (Leather UK, 2022). Although, aside from Duke (a producer of premium-end cricket balls) - who acquire their leather for cricket balls from Angus cows in Scotland and have the leather tanned in Derbyshire - the vast majority of cricket balls are produced in India. India is the world's largest exporter of (cow hide) leather, and around 80% of cricket balls

[3] The project was later extended to include an extra 11 days over September.

produced in India are from cow hide, with the remaining being produced from buffalo or ox hide, which are considered inferior[4].

To understand typical characteristics and requirements of leathers in cricket gear – namely, balls and gloves – a standards body (BSI), a manufacturer (Gunn and Moore) and a test house (Sports Labs) were consulted.

The term 'leather' itself is very important. In fact, is ("Leather. Terminology. Key definitions for the leather trade") stipulates leather as a protected term defined as "*hide or skin with its original fibrous structure more or less intact, tanned to be imputrescible, where the hair or wool may or may not have been removed… and where any surface coating or surface layer, however applied, is not thicker than 0.15 mm*". As a protected term, a product that does not meet this definition cannot be sold as 'leather, as this definition is used as a guide in applying consumer protection legislation (such as the Sale of Goods Act and the Trade Descriptions Act). Further, BS EN 15987:2022 stipulates that leather is of natural, animal origin, and that leather "*cannot be used in the denomination of man-made materials*". Moreover, it states that 'reconstituted leather' also cannot be referred to as 'leather' without qualification such as 'reconstituted' or 'recycled': '*if the tanned hide or skin is disintegrated mechanically and/or chemically into fibrous particles, small pieces or powders and then, with or without the combination of a binding agent, is made into sheets or other forms, such sheets or forms <u>are not leather</u>.*' These reconstituted materials may however be referred to as 'recycled fibre leather' if they have a minimum of 50% dry leather fibres. These definitions are particularly important as the standards for cricket balls and gloves refer to 'leather' that meet these definitions. Notably, almost all of the over 100 biomaterials identified in this report 'self-identify' as being leather alternatives, but cannot be classed or referred to as 'leathers'. 'Leather' is also a legally protected term in Belgium, France, Italy, Spain and Portugal, and the term 'vegan leather' has been banned in Portugal[5].

As various cricket gear standards, such as for balls and gloves, directly refer to 'leather', the term leather is still defined by BS EN 15987:2022. Therefore, the current combination of standards and norms currently restricts alternative leathers from being used officially for cricket gear. A number of these standard for cricket gear, particularly PPE such as gloves (batting, wicket-keeping and inners) are being presently reviewed.

4. Cricket balls

BS 5993:1994 ("Specification for cricket balls") specifies the construction and manufacture for the different grades of cricket balls. It requires the cover of the ball to be constructed from "*two or four pieces of alum-tanned leather enclosing a core*", where 'leather' is defined as per BS EN 15987:2022.

In terms of performance characteristics, the BSI standard specifies mass and dimensions/shape of the ball – the latter of which is actively regulated by umpires

[4] https://timesofindia.indiatimes.com/top-stories/howzat-cow-queers-pitch-for-cricket-balls/articleshow/53075463.cms
[5] https://www.thetimes.co.uk/article/portugal-bans-misleading-vegan-leather-term-p76njhb32

(and match referees in the professional game) in deciding whether a ball change is necessary during a game – as well as hardness, impact and wear resistance. However, these are measured for the product (i.e. ball), rather than component material.

Discussions with manufacturers (Gunn & Moore) and test houses (Sports Labs) has offered more insight into the key performance indices important for the selection of the leather cover material.

Ball manufacturers normally receive leather at 4-4.5 mm thickness. During the processing it is then dried and compressed to ~3-3.5 mm thick, a thickness that is required for stitching with linen, wool or nylon yarn. This large thickness is an important criterion – in our experience, procuring alternative leathers in such thickness has proved exceptionally difficult.

Apart from **thickness**, the **density** and '**mass per unit area**' of the leather are also typically recorded as key physical properties in a technical datasheet. Uniformity in these is important for a standardised product.

A range of mechanical properties have been identified as being important for ball leather, including **strength and elongation in tension**, and **abrasion behaviour** (through a taber abraser[6] measuring mass of material lost over time). The tensile strength and elongation in particular are an important indicator of durability.

Water absorption, **dimensional stability** (contraction and expansion when exposed to different levels of humidity), and **UV-stability** (tested through changes in tensile strength after UV exposure) are other important tests to ascertain durability and environmental resistance.

In addition to these, one would expect alternative leathers to replicate **leather's machinability, including flexibility, cutability and tear strength**. **Ability to stitch** is also important for the manufacture of the ball. Moreover, in order to be accepted by the cricket community, the material also needs to appear and feel like real leather, alongside having an appropriate deterioration rate, scuffing properties and the ability to be polished. **Compatibility with lacquers** that are already used is particularly important.

Finally, if replacing leather with a 'sustainable' alternative material is the aim, acceptable indicators of environmental impact – such as **embodied energy, carbon footprint[7], or water use** – need to be measured or estimated reliably. This also means that many widely-used leather alternatives, that are petroleum-derived, are unsuitable for this project. Indeed, a number of alternative leathers identified in this study refer to them as sustainable, but only a couple have shared certified life cycle assessment (LCA) studies to back their claims.

[6] A taber abraser is an instrument that performs accelerated abrasion/wear testing using a standard test procedure. See https://www.taberindustries.com/taber-rotary-abraser

[7] Embodied energy relates to the energy (from renewable and non-renewable sources) required in the primary production of the product. Carbon footprint relates to the equivalent carbon dioxide emissions in the primary production of the product.

Ethical reasons and personal motivation (e.g. vegan lifestyle) may be the principal driver of the substitution of hide leathers – as was the case at Earley Cricket Club (Staff, 2019b), whose Chairman and members are vegan. In their case, plastics were not ruled out. Material, time and funding availability limited the initiator's work but properties including absorption, deterioration and thickness were where the alternative materials fell short. This highlighted the fact that a suitable material will not need optimal properties, instead it needs to replicate the properties of animal leather, good and bad, as closely as possible.

Finally, many of the performance indices discussed above relate to the property of the leather material in isolation. Leather is only a part of the product; product-scale testing is even more critical than material-scale testing for product certification (e.g. CE certification) purposes, such as in the case of cricket balls and gloves. In particular, the **compatibility of the leather casing with the core material** (typically cork, rubber or cork-rubber composites [8]) is important. To determine the synergy between the two materials – the casing and the core materials – a vertical rebound test to determine energy restitution (by dropping the ball from a certain height and measuring rebound height) is used. While not typically employed for cricket balls, repeat impact tests to measure evolution in shape and sphericity may also be informative.

As principal target applications for the identified leather alternatives has been for fashion products, such a wide range of testing is and has not been completed. Typically, strength and elongation in tension, water absorption and thickness are the main properties provided, often qualitatively, if any.

5. Cricket batting gloves

While BS 6183-4:2011 ("Protective equipment for cricketers —Part 4: Gloves for batsmen") does not specify that leather needs to be used for any part of the gloves, the palms of batting gloves are typically made from Pittards leather, a specialist 'premium' performance leather. Gloves are multi-material products, and the Pittards leather palm is stitched to the other materials. The leather is treated with special **water repellent** to protect the fibre structure against perspiration and maintain **softness of leather over time**[9], whilst also **enabling a good comfortable grip** of the bat handle. Pittards leather is characterised with **high tensile strength (and durability)**. **Colour fastness, the pH, and the innocuousness and chromium VI content** of the leather are expected to be defined, as per BS 6183-4:2011. Cotton and other fibres are also sometimes used for the batting inner gloves where comfort and grip is a priority.

While Pittards leather palms are commonly used for batting gloves, we note here that there appears to be a preference for chamois leather for wicket-keeper gloves. This was confirmed by Gunn & Moore. Chamois leather is a highly porous leather with incredible **water absorbency** properties – it can absorb over 4 times its weight in water. It also has almost no **abrasive properties**. Chamois leather is commonly used in the automotive industry, including for cleaning and drying cars. While

[8] https://onlinelibrary.wiley.com/doi/full/10.1002/jst.8
[9] https://www.pryzmcricket.co.uk/blogs/news/tagged/what-is-pittards-leather

chamois leather was traditional produced from the skin of the European chamois goat, today it is produced from sheepskin. The British Standard BS 6715:1991 defines chamois leather as, "leather made from the flesh split of sheepskin or lambskin, or from sheepskin or lambskin from which the grain (the top split) has been removed by frizzing, and tanned by processes involving oxidation of marine oils in the skin." There are also synthetic, vegan alternatives to sheepskin chamois leather available, typically produced from PVA (polyvinyl alcohol) – a biodegradable polymer that is also commonly used in the form of wood glue. These synthetic chamois leathers retain the high absorbance behaviours of real chamois leathers, can be more durable and suitable for being laundered, as well as producible in larger sizes (as the largest size of real chamois leather is limited by the size of sheep/lambs).

6. Market research of leather alternatives

6.1 Research methodology

Relevant papers, articles and websites were sourced mainly using Google and Google Scholar. Each time, some of the following keywords were used: sustainable, leather, alternative, vegan, material, bio-based, biomaterial. This method allowed identification of many materials. However, the majority of the materials contained within this review were found using a list on the Material Innovation Initiative website (Material Innovation Initiative, 2022c).

The materials identified were then assessed to determine whether they should be included or excluded in this review. This was discussed in Section 2. Scope.

Within this market summary, materials are listed under their company name where possible. In the cases where the company name is unknown, the name of the leather is used. These exceptions are indicated by an asterix. Other missing data is indicated by a '?'.

The majority of companies summarised had missing data. This, alongside the number of companies discovered, suggests that this market is rapidly growing, with many companies in early production or research and development stages. A number of these companies are also be reluctant to share data publicly for this reason.

6.2 Categorisation of leather alternatives

The market research revealed a distinct lack of publicly available data. Where possible, the following information was noted: natural component(s); plastic component(s); manufacturing process; properties and characteristics; locations(s); sustainability; compliance to relevant regulations. **87 companies producing 123 different leather alternative materials are included in Appendix A.**

A simple classification system was derived to categorise the various materials. **8 categories were devised based on the key biological component of the leather alternative material**: **fungus-based, leaf-based, fruit/vegetable/flower-based, other plant-based, fish scales/shells-based, cell cultured, and other/varying composition. Within each category, four sub-categories were identified: waste-based, grown, harvested, and unknown**. A summary of this is shown in Table 1, with example companies operating in this space listed.

Leaves				Trunk/Stem			
Waste	Grown	Harvested	Unknown	Waste	Grown	Harvested	Unknown
Leaf Leather		Pinatex Desserto + 1 other	Mulbtex + 3 others			Bananatex BarkTex + 4 others	Rewrap + 6 others
Fish scales/Shells				**Fungus**			
Waste	Grown	Harvested	Unknown	Waste	Grown	Harvested	Unknown
Hide BioTech + 7 others				Creation of Sustainable Materials (COSM)	Amadou Bolt Threads + 7 others	FUNGISKIN	AirMycelium + 3 others

Fruit/Vegetable/Flower				Cell-cultured			
Waste	Grown	Harvested	Unknown	Waste	Grown	Harvested	Unknown
Mirum Appleskin + 7 others			Curo Vegetal da Amazonia + 6 others			AirCarbon BioFabbrica + 10 others	
Other Plant-based				**Other/Varied Composition**			
Waste	Grown	Harvested	Unknown	Waste	Grown	Harvested	Unknown
Treekind LOVR + 6 others		Philippine-inspired plant leather	LaVeg BioVeg + 3 others	SOYA C(O)U(L)TURE + 6 other	Coopflora Fungi Line		Flex Tree + 29 others

Table 1: The classification used to sort the sustainable leather alternatives found in the market research. Appendix A includes a database of all the leather alternatives identified.

6.3 Initial conclusions from mapping the sector

Whilst the majority of the leather alternative materials identified target the fashion sector, none of them appear to have looked into sporting applications, which bring with them complex requirements. It is clear from the sheer number of different materials available that the sustainable leather alternatives industry is significant and fast growing. However, it is also clear from the distinct lack on information available publicly (e.g. through published papers or reports, on their website or any communication documents) that most of these materials are still in early stages of development. This makes comprehensive and accurate assessment of their suitability for cricket gear applications impossible at this stage. Indeed, for cricket ball applications, the lack of any alternative leathers of the large thickness required (3-5mm) is limiting and that 'leather' is specifically required in the BS cricket ball standard.

One of the aims of this mapping exercise was to inform further investigations into the use of leather alternatives in cricket gear. If further work in this area proves that this is feasible, cricket gear manufacturers should look to collaborate with and support these bio-material companies in order to accelerate their growth. Currently, many companies are producing what seem to be very similar materials and so it could potentially be beneficial to encourage collaboration between such companies; combining resources and expertise of multiple companies could lead to rapid development of materials that could be integrated into current manufacturing processes in the near future. The Fibral Material Alliance[10] is an example platform for players in the plant-based fibre community to facilitate collective learning and increase market adoption.

It was identified that further research should focus primarily on the following:

(i) The lack of data and information presents significant challenges. It is possible that in their current state, none of the aforementioned materials are a like-for-like replacement for bovine leathers for both balls and gloves – in part as the standards have co-developed with the performance of bovine leathers. In literature, research into nine leather alternatives, entitled '*Comparison of the Technical Performance of Leather, Artificial Leather and Trendy Alternatives*'[11] found that none of the alternatives matched the universal performance of bovine leather in regard to 5 key properties: tensile strength, tear resistance, flex resistance, water vapor permeability and water vapor absorption[12]. For any available materials, performance testing should be completed to assess the feasibility of using them instead of bovine leather in cricket gear, based on many of the key performance criteria identified in Section 3. This testing should attempt to mimic the use of the cricket gear in practice but in doing so should take inspiration from standard leather testing procedures, where possible.

(ii) Where the information is available, the manufacturing processes of each material should be analysed in order to inspire a novel fabrication method to create an appropriate material for cricket gear. This could be done in collaboration with existing companies if (i) reveals a few materials that outperform the rest.

(iii) LCAs should be conducted in order to compare the relative sustainability benefits of each of these materials. This should include an assessment of their circularity and manufacturability. However, economies of scale (or lack of) may present challenges for proper comparisons.

(iv) The cost and supply-chain of vegan leathers needs further clarity, both of which impact the feasibility of manufacture.

7. Preliminary materials testing

Over the course of the project, two types of testing were conducted: tensile testing to measure strength and elongation in tension, and contact angle analysis to measure wettability and absorption behaviour. Results from tensile mechanical testing will form the main focus of this section. Discussions with Sports Labs revealed that tensile testing is an important standard test conducted to determine the performance of a material, and a key piece of information in a technical datasheet for the material.

[10] https://fibral.org/
[11] https://www.mdpi.com/2079-6412/11/2/226
[12] Ibid.

For preliminary testing, two varieties each of four leather alternative materials were procured: Piñatex (Leaf-based, Ananas Anam), BarkTex (Other plant-based material, BarkTex), Bananatex (Leaf-based, QWSTION) and Hide Biotech leather (Fish scales-based, Hide Biotech). Piñatex was found to have the most publicly available information, including LCA and material datasheets. Hide Biotech leather sample was the only leather found to be sufficiently thick for cricket ball applications (>3.5mm thick); it was especially produced for this project using a new formulation and process in comparison to the formulations and processes the manufacturers use for their target high-end luxury, fashion and accessory market, hence the specific test results are not representative of the larger variety of materials they produce. Piñatex, Bananatex and Hide Biotech leathers all had a backing material (for additional tear resistance). While Piñatex, BarkTex and Bananatex are fibrous materials with a textile appearance and feel, the Hide Biotech leathers are reconstituted materials, more uniform, and have a rubber-like feel.

7.1 Tensile Testing Method

The method for tensile testing can influence the findings and make comparison between literature or datasets difficult or invalid. For example, tests carried out at different loading speeds are likely to have different results and therefore are not readily comparable.

Various standard methods were consulted when designing our tensile testing method. BS EN ISO 3376:2020 describes the tensile testing of leather and uses an elongation speed of 100 mm/min. However, 'textile' or fibre-based leather alternatives tend to use different tensile testing methods. Piñatex, one of the few leather alternative materials for which data is publicly available, uses the standard grab tensile test for nonwovens (based on BS EN ISO 9073-18:2008). This test involves pulling a 25mm wide and 100mm long strip to failure. It was noted that this method was likely to induce premature failure at or near the grip.

After considering these various standards, a method was devised in the University of Cambridge's Department of Engineering. Tests were carried out using a 2kN load sensor, as no leather alternatives with publicly available data had maximum failure loads over 1kN (100 kg force). A slow 10 mm/min loading speed was used to enable data collection at a reasonable rate. To prevent slippage of samples in the grip during testing, serrated grips were used to hold the fabric at the clamp. To prevent the materials from being damaged at the serrated grips, the material was held in paper card tabs. On a few of the less fibrous samples (e.g. Hide Biotech material), samples were cut into a dogbone shape to encourage failure at the middle of the sample, away from the grip.

Some of the samples still failed by tearing at the edge of one of the grips or even within the grips themselves when gripped too tightly. When the grips weren't tight enough, some samples slipped or pulled out, again providing substandard data. As BS EN ISO 9073-18:2008 recommends, these failure mechanisms, whilst normally considered to provide data that is unrepresentative of the material, were noted but simply considered to be a characteristic of the material itself, given the natural variability expected in natural materials.

7.2 Results and Discussion

For each material, force was plotted against displacement and stress was plotted against strain. Appendix B contains the graphs for all of the materials tested. This was used to determine failure loads (tensile strength), and elongation (failure strain).

The Hide Biotech ball and glove leather samples had the highest elongation and toughness (ability to withstand fracture). The Bananatex samples were found to be the strongest (highest force at failure). BTX H919-100-002 was the thickest Banantex sample and had the highest breaking force (over 500N) of all the materials tested - shown in Appendix B. BTX 0903-110-002 was a thinner Banantex sample and had the highest breaking stress for its mass (as opposed to breaking force).

Unfortunately, as the University of Cambridge testing method has not yet been applied to bovine leather, it is not possible to comment on the meaning of these results in the context of the potential application to cricket gear as yet. At present, as the type and parameters of a testing method influences the results, we cannot compare our findings with those in literature, and rather can only use these to compare the leather alternatives we tested.

The main point of interest is the variety of failure mechanisms these materials demonstrated. This variety explains why the testing procedure had to be altered to each specific material. Figure 3 below shows how four different materials failed.

Figure 3.1: A Piñatex sample after failure. The backing has snapped and then the pineapple leaf fibres have pulled out from each other.

Figure 3.2: A BarkTex sample after failure. Bunches of fibres have pulled out from each other, with the failure happening near the top

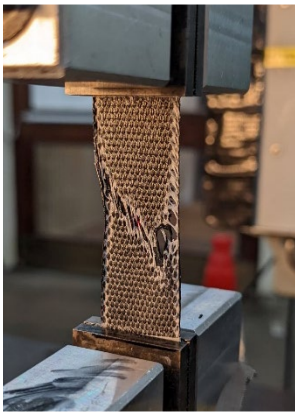

Figure 3.3: A Bananatex sample after failure. The woven fibres and adhesive backing have sheared near the centre of the sample.

Figure 3.4: A HideBio Tech sample after failure. The woven fibrous backing has snapped and then the main leather-like material has extended a lot before tearing near the change in cross-section

These images also indicate the elasticity of each material. The Piñatex and BarkTex samples suffered permanent deformation at failure; the Bananatex did not extend very far but appears to have contracted back to its original length; the Hide BioTech material reached a very large extension and then, upon failure, contracted immediately back to its original length. This specific formulation and thickness of Hide Biotech material prepared especially for this exploratory work using appears to behave more as a leather-like extendable material, whereas the other three materials have a failure typical of fibrous textiles.

The testing also revealed information about the integrity of all the material types. Upon cutting, the edges of the Bananatex samples would fray as individual fibres separated themselves from the woven structure. The BarkTex materials also frayed with fibres splintering off due to cutting. The Piñatex material was easier to cut as the backing material held the pineapple leaf fibres and the same was true for the Hide BioTech materials however the thickness of those samples meant the use of scissors or scalpels to create smooth lines was more difficult. Only the Hide BioTech red leather was thick enough to withstand the stitching that would be required in the ball manufacturing process; the effects of stitching on that material were not investigated.

8. Conclusions

Over 100 leather alternatives have been identified in this study. Although limited in scope, this study has revealed many major gaps in research on the suitability of these leather alternatives for performance applications. There are few scientific articles covering the material properties of sustainable leather alternatives. Additionally, as most of the companies' materials are either in research and development stages or are being produced on a small scale, many of the firms are unwilling to share details about the material composition or the manufacturing process for IP reasons. This leads to a significant lack of publicly available research. In addition, as many of the companies are in phases of securing investment funding, they are weary of supplying samples for testing, as publication of any findings in poor light – however exploratory and preliminary - may have a negative bearing on their venture or brand.

The report identified the following properties is being particularly important for cricket balls: thickness, density, 'mass per unit area', strength and elongation in tension, abrasion behaviour, water absorption, dimensional stability, UV-stability, machinability (including flexibility, cutability, tear strength, ability to stitch), as well as compatibility with lacquers and compatibility with the core material. For cricket gloves, weight (mass per unit area), water repellence, softness of leather over time, comfortable grip, tensile strength and elongation, colour fastness, pH, innocuousness and machinability (cutability, ability to stitch) are identified as important properties. Aside from material-scale testing, product-scale testing is critical.

Only strength and elongation in tension have been measured for a few alternative leathers in this report; a much more comprehensive testing regime representative of the needs of cricket balls and gloves need to be completed. The tensile testing conducted as a part of this project enables basic comparison between materials, though a lack of a consistent method means this comparison is limited. The Hide Biotech ball and glove leather samples had the highest elongation and toughness (ability to withstand fracture). The Bananatex samples were found to be the strongest (highest force at failure). Despite the perceived irregularity of the bio-based leather alternatives, it was often shown to be possible to reproduce the results consistently. This consistency was replicated in the failure mechanisms which remained similar from sample to sample, despite the vast differences between different materials.

Other than strength and elongation, we found that most of the alternatives could not be produced to the thickness (>3mm) desired for cricket balls. Hide Biotech samples were an exception, though it is understood that the process is time consuming for such large thicknesses, though this process is ideal for Hide Biotech's target sector of high-end accessories and fashion which do not require such large thicknesses. With fibrous textile-based leather samples, fraying is an issue especially from cutting. Moisture absorption is a similar challenges. Many of these leather alternatives have a backing material which may also lead to sweat and moisture related issues even glove applications. Hide Biotech appears to be a potential material for further exploration for cricket ball applications, and synthetic chamois leather – with existing uses in wicket-keeper gloves – has emerged as a potential material for batting glove palms. Materials such as Pinatex may be tailored further to produce more cricket-gear compliant materials.

If sustainable biomaterials could be fabricated that had adequate properties for cricket balls or cricket gloves, this has the potential to save huge quantities of bovine leather from landfill. Charter and Clark, 2022 estimated that 1,800,000 balls, 300,000 batting gloves and 50,000 wicket keeping gloves go to waste each year in the UK. Whilst these estimates make it clear that replacing the leather used in cricket balls would have the largest impact, the most viable option would be to look at substituting leather used in gloves, as this leather experiences smaller mechanical forces and wear, meaning it is more likely that a leather alternative designed for the fashion-sector will be able to perform equivalently.

9. Recommendations for Further Research

An obvious area for further research is the development of a tensile testing method that can be applied consistently to all materials, despite the materials' variability. This testing method should then be applied to a wide range of materials, ideally at least one from each category in the classification. It should also be applied to a bovine leather sample which will provide benchmark results for comparison. Benchmarks could not be gained from the BS standards as these only specify properties of the final ball.

Other properties directly relevant to specification of cricket balls and gloves, such as abrasion or wear behaviour, moisture resistance (and effects of humidity cycling) also need to be studied. Tensile testing is relevant to the materials' performance in manufacturing and provides a good measure of the materials' strength.

Further investigations should be conducted into the microstructure of the materials; any links between the materials' microstructures and macroscopic properties should then be identified. These links will then inform future development of new materials allowing for more streamlined innovation.

Any promising materials that have been identified through testing should then be subjected to life cycle assessment (LCA) to assess the sustainability implications of using them to replace leather. Prototyping may also reveal insights on the manufacturability with some of the alternative leathers (e.g. stitching, compatibility with lacquers for cricket balls). The disassembly and analysis of current cricket gear will also be useful to help quantify how much material is used in various components of cricket gear. This would inform estimates of the quantity of various sustainable materials that would be required to replace these different components.

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Appendix A: Database of Leather Alternatives

The following is a list of the information collected on all the materials identified in the market research, sorted by their primary bio-based component.

The market research revealed a distinct lack of publicly available data. Where possible, the following information was noted: natural component(s); plastic component(s); manufacturing process; properties and characteristics; locations(s); sustainability credentials; and compliance to relevant regulations. 87 companies producing 123 different materials are included here. A '?' is indicative of any information that is not available or verifiable.

1. Fungus-based

1.1 Amadou

Material Name: Amadou Leather (Amadou Leather, 2018)

Natural Component(s): Amadou

Plastic Component(s):?

Manufacturing Process: Mushroom material is grown on recycled sawdust using edible mushroom cultivation techniques.

Properties: Vegan; feels like suede to the touch; malleable surface; lightweight; flexible; absorbs moisture; insulates heat; remains breathable and cooling; naturally antimicrobial; 'medium use' tensile strength

Location(s): London, UK

Sustainability: Completely compostable and enriches soil

Compliance to Regulations: UE chemicals REACH regulation, ECHA list of candidate SVHC substances

1.2 Bolt Threads

Material Name: Mylo (Bolt Threads, 2019)

Natural Component(s): Mycelium

Plastic Component(s): Non-petroleum based plastics

Manufacturing Process: Grow mycelium cells on bed of organic matter (including sawdust) to form an interconnected 3D network (foamy layer). Harvest mycelium and compost any remaining material. Use processing, tanning and dyeing to make Mylo. (Bolt Threads Inc., 2022)

Properties: Verified Vegan (Eurofins Chem-MAP assessment program)

Location(s): Mycelium partner in Netherlands, tanning partner in Europe, company based in California, USA

Sustainability: Facility is powered by 100% renewable energy, an initial LCA was conducted in 2019; free of chromium and DMFa; not currently biodegradable

Compliance to Regulations: Tanning partner has a gold rating from the Leather Working Group, chemicals selected using Green Chemistry principles; certified bio-based by DIN CERTCO

1.3 Citribel

Material Name: MycaNova (Citribel, n.d.)

Natural Component(s): Mycelium grown on sugar molasses (sugar refineries' waste)
Plastic Component(s): 36% synthetic
Manufacturing Process: Sugar molasses are fermented to produce citric acid. Mycelium, a by-product, is harvested and then dried and milled to generate mycelium powder. Powder is combined with various binders and backing materials.
Properties: ?
Location(s): Belgium
Sustainability: Citribel claims to eb the only genuinely circular producer of citric acid, citrates and other co-products (Citribel, 2022)
Compliance to Regulations: ?

1.4 Creation of Sustainable Materials (COSM)

Material Name: HyphaLite TC (ISA Industrial Ltd., 2022b)

Natural Component(s): Fruiting body of B-grade mushrooms (would be considered waste); non-woven reinforcement of man-made cellulosic fibres produced from forests; natural polymers
Plastic Component(s): None
Manufacturing Process: ?
Properties: Max thickness produced is 2.2 mm; full data available in Appendix A
Location(s): Vietnam, China, USA
Sustainability: 100% biobased and biodegradable; scraps are ground and reused into new material
Compliance to Regulations: Pulp & fibre units meet the standards of FSC (Forest Stewardship Council), SFI (Sustainable Forestry Initiative) and PEFC (Programme for the Endorsement of Forest Certification); regenerated cellulosic fibres received Cradle to Cradle Gold Level Material Health Certification, are certified to OEKO-Tex Standard 100 and certified by TUEV Austria OK scheme; they are 100% bio-based as certified by USDA.

Material Name: HyphaLux (ISA Industrial Ltd., 2022c)

Natural Component(s): Fruiting body of B-grade mushrooms (would be considered waste); plant based natural filler materials; non-woven reinforcement of man-made cellulosic fibres produced from forests; natural polymers – over 90% bio-based material
Plastic Component(s): Unknown
Manufacturing Process: ?
Properties: Max thickness produced is 2.2 mm
Location(s): Vietnam, China, USA
Sustainability: 100% biobased and biodegradable; scraps are ground and reused into new material
Compliance to Regulations: Chain of custody of fibres certified according to FSC, SFI and PEFC; natural binder has VFSC certification; biodegradable in soil as certified

with TUEV Austria OK; all fibres certified to OEKO-Tex Standard 100 and received Cradle to Cradle Gold Level Material Health Certification.

Material Name: HyphaTrim (ISA Industrial Ltd., 2022a)

No further information available

1.5 Ecovative

Material Name: AirMycelium (Ecovative LLC., 2022a)

Natural Component(s): Mycelium

Plastic Component(s): ?

Manufacturing Process: ?

Properties: Customisable by guiding growth

Location(s): ?

Sustainability: ?

Compliance to Regulations: ?

Material Name: MycoComposite (Ecovative LLC., 2022b)

Natural Component(s): Mycelium blended with hemp

Plastic Component(s): None

Manufacturing Process: ?

Properties: Durable; customisable

Location(s): ?

Sustainability: 100% bio-based; home-compostable

Compliance to Regulations: ?

1.6 Mogu

Material Name: Mogu

Natural Component(s) Mycelium, recycled cotton

Plastic Component(s): None

Manufacturing Process: Mycelium is grown on pre-engineered substrates made of agro-industrial residues

Properties: Durable, antistatic

Location(s): ?

Sustainability: Biodegradable

Compliance to Regulations: ?

1.7 MYCL | Mycotech Lab

Material Name: Mylea

Natural Component(s): Mycelium feeds on agroforestry byproducts, 100% natural-based polymer mainly composed as chitin, cellulose and proteins

Plastic Component(s): ?

Manufacturing Process: Partenered with Pusat Penelitian nanosains dan Nanoteknologi (PPNN) (MYCL, 2021b)

Properties: Full data available in appendix B

Location(s): Indonesia
Sustainability: Greenhouse Gas Report available in appendix C; LCA compared to Notarnicola et al (2011) - LCA Bovine Leather Tannery in Italy; designed with circularity in mind (MYCL, 2021a)
Compliance to Regulations: Complies to SNI (National Standardisation Agency of Indonesia)

1.8 Mycofutures North Atlantic

Material Name: Mycofutures (MycoFutures North Atlantic, 2022)
Natural Component(s): Mycelium
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): Newfoundland, Canada
Sustainability: Compostable and focused on circularity
Compliance to Regulations: ?

1.9 Mycoworks

Material Name: Fine Mycelium (MycoWorks, 2022b)
Natural Component(s): Mycelium
Plastic Component(s): ?
Manufacturing Process: Controls the growth of mycelium cells to create desired structures
Properties: Controllable; durable; supple; sustainable
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

Material Name: Reishi (MycoWorks, 2022a)
Natural Component(s): Mycelium, uses Fine Mycelium technology
Plastic Component(s): ?
Manufacturing Process: Tanned by Curtidos Badia
Properties: Full data available in appendix D
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

1.10 Mylium

Material Name: Mylium (Mylium B.V., 2021)
Natural Component(s): Mycelium
Plastic Component(s): None
Manufacturing Process: Place culture of mycelium in a bioreactor to grow. Add other natural ingredients to bind. Mechanically shape the mixture into sheets and dry. Add finish if necessary.

Properties: ?
Location(s): Netherlands
Sustainability: ?
Compliance to Regulations: ?

1.11 NEFFA

NB: NEFFA now focuses on being a fully automated manufacturing method used for biofabricated materials. (NEFFA, 2022)

Material Name: MycoTEX
Natural Component(s): Mycelium
Plastic Component(s): ?
Manufacturing Process: NEFFA,
Properties: ?
Location(s): Netherlands, German manufacturing partner
Sustainability: Home compostable garment
Compliance to Regulations: ?

1.12 Polybion

Material Name: Celium
Natural Component(s): Mycelium
Plastic Component(s): ?
Manufacturing Process: Environment is set up so that cells self-organise and create the cellulose structure as a metabolic by-product. Bacteria are fed with agro-industrial fruit waste. The cell membrane of Celium undergoes a “sustainable stabilisation process”.
Properties: Vegan; easy to tailor; customisable colour, graining, embossing; water resistance
Location(s): Madrid, Spain
Sustainability: Processing occurs within a 30-mile radius with no significant biomass outputs and zero hazardous chemicals released.
Compliance to Regulations: EPA; REACH; ZDHC
(Polybion™ Spain, 2022)

1.13 Spora Biotech

Material Name: Sporatex (SPORA BIOTECH PLATAFORM, 2022)
Natural Component(s): Mycelium
Plastic Component(s): ?
Manufacturing Process: Uses genetic engineering to develop the mycelium DNA pre- and post-harvest
Properties: ?
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

1.14 ZVNDER

Material Name: FUNGISKIN (ZVNDER, 2017)

Natural Component(s): Single Tinder fungus (Fomes Fomentarius), 100% natural
Plastic Component(s):
Manufacturing Process: ?
Properties: ?
Location(s): Harvested in Transylvania, processed in Berlin
Sustainability: No chemicals used; residues can be used as smoked products in beekeeping; left over material can be processed into FUNGI-fibres for paper and non-wovens
Compliance to Regulations: ?

2. Leaf-based

2.1 Ananas Anam

Material Name: Piñatex

Natural Component(s): Waste pineapple leaf fibre
Plastic Component(s): Piñatex original/mineral use a water-based PU resin = 10% of total material composition; Piñatex Performance is coated with a high solid PU and bio-based PU = 42% of material composition.
Manufacturing Process: Long fibres are extracted from plant leaves using semi-automatic machines. Fibres are washed, sun-dried (ovens are used in rainy season) and purified to create PALF (pineapple leaf fibre). PALF is mixed with PLA and is mechanically processed to create Piñafelt, a non-woven mesh. Rolls of Piñafelt are then shipped from Philippines to Spain or Italy for finishing. (Piñatex, 2019a)
Properties: Technical data is available in Appendix E.
Location(s): HQ in London, sourced in the Philippines, finished in Spain or Italy.
Sustainability: Base material (pineapple leaf fibres and PLA) is biodegradable. 264 Co2 tons are saved by using instead of burning 825 tons of waste leaves.
Compliance to Regulations: PETA approved and registered with The Vegan Society; REACH compliant resins; GOTS certified pigments

2.2 Carbonwave

Material Name: Vega (plant-based) leather (CARBONWAVE, 2022)

Natural Component(s): Sargassum (Seaweed)
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): Processing in Cataño, Puerto Rico; harvesting in Puerto Morelos; México, research in Boston, US.
Sustainability: Aims to use seaweed to capture, use and store carbon and restore natural carbon sinks; developed a circular economy for seaweed.
Compliance to Regulations: ?

NB: Leather alternative seems to be the least developed of their products

2.3 Circumfauna - Gunas New York

Material Name: Mulbtex (GUNAS USA, 2019)

Natural Component(s): Mulberry plant leaf pulp with a cotton base

Plastic Component(s): None

Manufacturing Process: ?

Properties: Lightweight, waterproof, ages/weathers like real leather

Location(s): Company based in New York, USA; material appears to be manufactured in Korea.

Sustainability: ?

Compliance to Regulations: PETA Approved Vegan

2.4 Desserto

Material Name: Desserto

Natural Component(s): Nopal cactus, organic renewable biopolymers. Maximum 90% plant-based

Plastic Component(s): Backers made of recycled cotton, polyester, nylon and mixes

Manufacturing Process: Harvest mature leaves of a prickly pear cactus, extract proteins & fibres to make an organic bio resin that's coated on a carrier (Steiber, 2021). New harvest every 6-8 months. Plantation is perennial, lasts for a cycle of 8 years (Livingswood, 2021)

Properties: High tear and tensile strength, high abrasion resistance, durable, soft, natural aroma, low-maintenance, easy to clean (DESSERTO, 2022b)

Location(s): Manufactured in mexico (Livingswood, 2021)

Sustainability: Biodegradable under anaerobic thermophilic conditions (percentage depends on formula)

Chemically or mechanically recyclable (DESSERTO, 2022b). Cactus fields are a carbon sink, doesn't use much water (rainwater only), no soil disturbtion (Steiber, 2021). Leftovers exported and sold in food industry (Livingswood, 2021) For a full e-LCA, see (DESSERTO, 2022a)

Compliance to Regulations: OEKO-TEX Standard 100, PETA and V-Label Vegan verified, USDA Organic and Certified Biobased Product, OKO-GARANTIE BCS, DAkkS, Global Recycled Standard, SGS UKAS Management Systems

2.5 Fiquetex

Material Name: Fique Vegan Leather (Fiquetex, 2021)

Natural Component(s): Fique fibre and natural rubber latex

Plastic Component(s): None

Manufacturing Process: ?

Properties: Adaptable and durable

Location(s): Medellin, Columbia and London UK

Sustainability: 100% biodegradable, raw materials absorb Co2 and require 10% of energy needed to produce synthetic fibres

Compliance to Regulations: ?

2.6 Studio Tjeerd Veenhoven

Material Name: PalmLeather (Studio Tjeerd Veenhoven, n.d.)

Natural Component(s): Palm

Plastic Component(s): ?

Manufacturing Process: Dry leaves from Arecae Betel Nut are dipped into bio softening solution for a few days to allow them to be processed conventionally.

Properties: ?

Location(s): The Netherlands

Sustainability: Aims to use a maximum of 20 litres per m2 in the production process

Compliance to Regulations: ?

2.7 Tree Tribe

Material Name: Leaf Leather

Natural Component(s): Teak or banana leaves

Plastic Component(s): Thin outer layer of non-toxic BOPP to seal the leaves

Manufacturing Process: Hand made in Thailand. Teak leaves are collected from fallen leaves, soaked in water and dyed. They're then arranged flat together to dry. Leaves are then mended with cotton fabric.

Leaves are mended with cotton fabric and the outer layer is added. (Joe, 2020)

Properties: Vegan, waterproof and durable

Location(s): Thailand

Sustainability: ?

Compliance to Regulations: ?

2.8 Young-A Lee (R&D at Iowa State University)

Material Name: N/A (College of Human Sciences, 2022)

Natural Component(s): Fermented green tea

Plastic Component(s): None

Manufacturing Process: Multilayered

Properties: Model of shoe had similar properties to leather aside from a disadvantage in wettability

Location(s): Iowa, US

Sustainability: Biodegradable

Compliance to Regulations: ?

3. Trunk/Stem -based

3.1 BarkTex

Material Name: BARKTEX_No-Buffalo_0714 (Bark Cloth, 2017b)

Natural Component(s): Over 99% biobased.

Plastic Component(s): ?

Manufacturing Process: ?

Properties: Not all materials are purely vegan as some use liquid lanolin (sheep's wool wax derivate) and a mixture of hard carnauba wax, shiny beeswax and orange peel oil Bark Cloth, 2017a)
Location(s): Uganda, Germany
Sustainability: ?
Compliance to Regulations: ?

3.2 Blackwood

Material Name: Blackwood
Natural Component(s): Cork
Plastic Component(s): ?
Manufacturing Process: In general: Cork is hand cut from the tree, dried for 6 months, boiled in water, flattened and pressed into sheets. Then fabric backing (ideally cotton) is pressed on the cork sheet, bonded by suberin (naturally occurring adhesive present in cork). (Rose, 2021)
Properties: ?
Location(s): Mediterranean, China, India
Sustainability: Biodegradable. Harvesting cork does not harm the trees; it prolongs their life
cork forests absorb 14.7 tons of Co2 per hectare (Rose, 2021)
Compliance to Regulations: ?

3.3 Filbo

Material Name: Filbo Flexwood (FILBOsrl, 2022)
Natural Component(s): Wood NB: Glued on leather, eco-leather or other materials such as fabric
Plastic Component(s): ?
Manufacturing Process: 98% parallel and perpendicular to wood grain. Not thermoformable but is resistant up to 80 °C. Can be laser engraved, sewn like normal leather and is water resistant.
Properties: ?
Location(s): Italy
Sustainability: ?
Compliance to Regulations: CITES certified forests.

3.4 JORD

Material Name: Suberhide (JORD. Inc, 2022)
Natural Component(s): Bark from Quercus Suber (Cork Oak)
Plastic Component(s): Polymeric layer is fused over agglomerated cork
Manufacturing Process: Cork bark harvested from main trunk and larger branches. Bark rests for 1 to 6 months to dry it naturally. Raw cork is processed for sterilisation and preparation for production; this includes boiling for hours without chromium/formaldehyde. Cork is then arranged and pressed to form composite cork blocks which are shaved into thin veneers which can be dyed under high

temperatures and pressures. These pieces are then fused to a natural or synthetic backing (cotton, vinyl, other vegan leathers)
Properties: Resists scratches, stains and tearing, hypoallergenic, water resistant, flame retardant, anti-static, highly elastic.
Location(s): HQ in Missouri, US
Sustainability: ?
Compliance to Regulations: FSC, ASTM standards

3.5 Lino Leather

Material Name: Lino Leather (Don Yaw Kwaning, 2018)
Natural Component(s): Linseed, oil, wood, fibres, pine resin and lignin
Plastic Component(s): ?
Manufacturing Process: A fibre net is pressed in between two layers of lino leather
Properties: Flexible, self-supporting, two usable sides
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

3.6 MB Cork

Material Name: Cork Fabric (MB Cork, 2022)
Natural Component(s): 63% cork
Plastic Component(s): 37% recyclable polyester
Manufacturing Process: ?
Properties: Durable and flexible
Location(s): Massachusetts
Sustainability: ?
Compliance to Regulations: ?

3.7 NUVI Releaf

Material Name: Releaf (NUVI Releaf, 2022)
Natural Component(s): Tobacco/Chalk/Marble
Plastic Component(s): None
Manufacturing Process: ?
Properties: Vegan, durable, easily integrated into manufacturing techniques
Location(s): Germany, raw materials sourced from within the EU
Sustainability: Biodegradable. 90% reduction in carbon footprint compared to leather
Compliance to Regulations: DIN tested – full results available in appendix F.

3.8 Ono Collaborations

Material Name: Cork tencel fabrics (Ono Collaborations, 2019)
Natural Component(s): Cork, organic cotton NB: uses water-based glue and finishing
Plastic Component(s): No polyester backing, plastic layer, harmful glue or additional finishing

Manufacturing Process: Trees grown in sustainable forests. Cultivation does not require additional water irrigation. Close-loop process using non-toxic solvent that can be reused for every batch

Properties: Durable, stain and liquid resistant.

Location(s): Cork hand-applied by Portuguese experts

Sustainability: Fully biodegradable

Compliance to Regulations: Tencel certified by OEKO-TEX.

3.9 PROYECTO MENOS ES MAS

Material Name: Bambuflex (Proyecto Menos es Más, 2021)

Natural Component(s): Bamboo, vegetable pigments

Plastic Component(s): None

Manufacturing Process: Colouring does not involve water

Properties: Flexible, customisable and versatile. Vegan.

Location(s): Argentina

Sustainability: 100% biodegradable

Compliance to Regulations: ?

3.10 QWSTION

Material Name: Bananatex (QWSTION International GmbH., 2022a)

Natural Component(s): Abacá banana plant stalks

Plastic Component(s): None

Manufacturing Process: Fibre is extracted from harvested stalks and made into paper (leaves are left to decompose and fertilise the soil). This is then spun into yarn, weaved and coated with beeswax to give the material that is ready for manufacturing. DWR (PFC free) or natural wax coatings are sometimes added.

Properties: Vary between specific material types

Location(s): Collaborates with a yarn specialist and a weaving partner, both based in Taiwan. Design and development in Zurich, Switzerland (QWSTION International GmbH., 2022b).

Sustainability: Fully biodegradable

Compliance to Regulations: Cradle to Cradle Certified Gold; Yarn dying method certified to Oeko-Tex Standard 100

3.11 reWrap

Material Name: reWrap (Fashion ComPassion, 2022)

Natural Component(s): Coconut fibre , sun-dried rubber and walnut wood

Plastic Component(s): None

Manufacturing Process: Coconut fibres pressed together with sun-dried natural rubber which forms the inside of the bags. Walnut wood used for closure and handle. Beeswax coating protects wood and makes it waterproof (Greenpicks, 2022)

Properties: Vegan

Location(s): Bags sewn in Amsterdam

Sustainability: Fully biodegradable. Compostable after two separable screws have been removed.
Compliance to Regulations: FSC, Cradle to Cradle

3.12 Volvo

Material Name: Nordico (Material Innovation Initiative, 2022b)
Natural Component(s): Recycled cork, biomaterials sourced from forests
Plastic Component(s): Recycled PET bottles
Manufacturing Process: ?
Properties: ?
Location(s): Materials sourced from Sweden and Finland
Sustainability: ?
Compliance to Regulations: ?

3.13 Von Holzhausen

Material Name: Banbū Leather (VON HOLZHAUSEN, 2022)
Natural Component(s): 83% bamboo
Plastic Component(s): ?
Manufacturing Process: Bamboo plants are harvested and cut to create a soft pulp. Fibres are extracted and spun into yarn which is then woven into the leather alternative and treated with a topcoat
Properties: 1/3 of the weight of cow leather. Vegan. Stain, scratch and water resistant
Location(s): US
Sustainability: 33% lower carbon footprint than animal leather. Biodegradable and recycled. No toxic by-products
Compliance to Regulations: ?

4. Fruit/Vegetable/Flower -based

4.1 Beyond Leather

Material Name: Leap
Natural Component(s): Apple waste from cider production. 64% apple waste
Plastic Component(s): 20% non-bio-based, small amount of fossil-fuel-derived material
Manufacturing Process: ?
Properties: ?
Location(s): Denmark
Sustainability: 99% less water and ~85% less CO_2 (Leap, n.d.). Three layers can be disassembled.
Compliance to Regulations: ?

4.2 Fiscatech

Some of this company's documents were in Italian and the time limit on this project meant that such documents could not be translated and included In this summary.

(Fiscatech, 2021)

Material Name: Rinnova
Natural Component(s): Corn
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Vegan
Location(s): Italy
Sustainability: ?
Compliance to Regulations: Solvent free TPU on certified cotton supports

Material Name: E-Ultra
Natural Component(s): ?
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Vegan
Location(s): Italy
Sustainability: ?
Compliance to Regulations: Solvent free TPU on certified cotton supports

Material Name: Fly Tela Eco
Natural Component(s): Bio-based
Plastic Component(s): 28% fossil-fuel-derived
Manufacturing Process: ?
Properties: ?
Location(s): Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: Ultra-wer
Natural Component(s): 35% bio-based
Plastic Component(s): 15% fossil-fuek-derived, 50% recycled PET
Manufacturing Process: Combines E-ultra (see above) and recycled plastics
Properties: ?
Location(s): Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: LAI-PORELLINA 2.0
Natural Component(s): 76% bio-based
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?

Location(s): Italy
Sustainability: ?
Compliance to Regulations:

4.3 Fruitonauts

Material Name: Frutazing (Fruitonauts, n.d.)
Natural Component(s): Fruit waste
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Vegan, scented
Location(s): ?
Sustainability: Biodegradable, zero waste
Compliance to Regulations: ?

4.4 Frumat

Material Name: AppleSkin (Material Innovation Initiative, 2022b)
Natural Component(s): Minimum 50% apple fibre waste (Staff, 2019)
Plastic Component(s): PU
Manufacturing Process: Waste from apples cultivated in Italy is dried and crushed into a fine powder. Powder is mixed with pigments and a binder and spread over a canvas until it solidifies
Properties: ?
Location(s): Italy
Sustainability: ?
Compliance to Regulations: ?

4.5 MINK

Material Name: N/A
Natural Component(s): Reclaimed vegetables and fruits (MINK VEGAN SHOES, 2022)
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

4.6 Mirum

Material Name: Mirum
Natural Component(s): Virgin natural materials e.g. Coconut husk fibre (coir) natural latex, rice hulls, woodsy blend of essential oils (Hahn, 2022) and upcycled agricultural sidestreams, 100% plants and minerals (Mirum, n.d.). Fibres and fillers, natural rubber, structural colorant, 'plant-based curative' (Natural Fiber Welding, 2021)
Plastic Component(s): None

Manufacturing Process: Material is grown and then NFW's patented chemistry platform and biofabrication process takes place. Dry mixed ingredients are mechanically formed into the desired shape and finished with or without a backer (Natural Fiber Welding, 2021).
Properties: ?
Location(s): ?
Sustainability: Decomposes and composts or can be re-manufactured. 100% recyclable and circular (Mirum, n.d.). No waste water, water input from the natural ingredients (Natural Fiber Welding, 2021).
Compliance to Regulations: ?

4.7 Oleago

Material Name: Oleatex (Oleago, 2021)
Natural Component(s): Bio wastes from the olive industry. Varying amounts of bio-based contents, usually more than half.
Plastic Component(s): Some PU is used. Backing is REC PES or cotton. Coating is a combination of BioTex and PU.
Manufacturing Process: ?
Properties: ?
Location(s): Turkey – all activities completed in a 100 km radius. Subsidiaries in USA, Germany, UK, Bangladesh
Sustainability: 100% biodegradable. Reduces carbon emission at least 6 times compared to petroleum-based materials. No materials derived from resources with nutritional value, such as PLA, are used.
Compliance to Regulations: USDA and DIN certified 50-85% biobased. V-label certification from the European Vegetarian Union to certify it's 100% vegan. Intertek have run 35 physical and chemical tests on Oleatex.

4.8 Persiskin

Material Name: Persiskin (Persiskin, 2022)
Natural Component(s): Wasted persimmon
Plastic Component(s): None
Manufacturing Process: No additional environmental resources are required
Properties: Vegan
Location(s): Valencia
Sustainability: Zero waste
Compliance to Regulations: ?

4.9 Phool

Material Name: Fleather (Crossley, 2022)
Natural Component(s): Recycled flowers from Temples
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?

Location(s): Kanpur, India
Sustainability: ?
Compliance to Regulations: ?

4.10 Seringueira

Material Name: Couro Vegetal da Amazônia (Material Innovation Initiative, 2022e)
Natural Component(s): Vegetables, cotton and latex
Plastic Component(s): ?
Manufacturing Process: Cotton fabrics are bathed in latex already mixed with stabiliser
Properties: ?
Location(s): North Brazil
Sustainability: ?
Compliance to Regulations: ?

NB: Only digital presence is an Instagram

4.11 Vegatex

Material Name: Apple Skin (Vegatex, 2022)
Natural Component(s): 50-66% bioproduct, using leftover pomace and peel.
Plastic Component(s): Waterborne PU
Manufacturing Process: Waste is recovered and reduced to a powder than it then mixed with natural agricultural fibres and PU. This mixture is coated on a plant-based material
Properties: Durable and breathable
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

4.12 Vegea

Material Name: Vegea (Vegea SRL, n.d.)
Natural Component(s): Grape leftovers from wine production
Plastic Component(s): ?
Manufacturing Process: Free of toxic solvents, heavy metals and dangerous substances.
Properties: ?
Location(s): Italy
Sustainability: ?
Compliance to Regulations: ?

4.13 Vegskin

Material Name: ? (Material Innovation Initiative, 2022f)
Natural Component(s): Banana and mangoes waste
Plastic Component(s): ?
Manufacturing Process: ?

Properties: ?
Location(s): France
Sustainability: ?
Compliance to Regulations: ?

5. Other Plant-based Materials

5.1 Amadeu Materials

Material Name: LaVeg (AMADEU DESIGN, 2021)
Natural Component(s): Natural rubber and cotton twill
Plastic Component(s): ?
Manufacturing Process: Laminated surface
Properties: Waterproof outer layer and vegan
Location(s): Brazil
Sustainability: Biodegradable and recyclable, works with local farms
Compliance to Regulations: ?

5.2 Biophilica

Material Name: Treekind (Biophilica, 2022)
Natural Component(s): Urban plant waste, agricultural waste and forestry waste
Plastic Component(s): None
Manufacturing Process: Combine lignocellulosic feedstock with a natural binder
Properties: Vegan (uncertified), 1-4 mm thick and a variety of colours.
Location(s): London, UK
Sustainability: Uses less than 1% of water used in leather production, local, fully biodegradable and recyclable.
Compliance to Regulations: Over 50 ISO tests.

5.3 Coronet

Material Name: BioVeg (CORONET S.P.A., 2022)
Natural Component(s): Bio polyols derived from no-food and GMO-free grains. Some articles are over 80% organic.
Plastic Component(s): Post-consumer recycled polyester
Manufacturing Process: ?
Properties: ?
Location(s): Italy
Sustainability: 13% lower contribution to global warming, 44% less depletion of natural resources and 33% less ozone depletion
Compliance to Regulations: FSC certified viscose, recycled polyester is GRS certified, USDA certified with BioPreferred Program.

5.4 Jacinto & Lirio

Material Name: Philippine-inspired plant leather (Jacinto & Lirio, 2022)
Natural Component(s): Water hyacinth

Plastic Component(s): ?
Manufacturing Process: Harvest the hyacinth. Cut, clean and dry the stalks. Then dye, scrape and flatten them so they can be bundle and secured to a backing. Apply coatings and then sew the desired product.
Properties: ?
Location(s): Philippines
Sustainability: Removes water hyacinth which has infested Philippine waters
Compliance to Regulations: ?

5.5 LOVR

Material Name: LOVR (LOVR, n.d.)
Natural Component(s): Hemp crop waste
Plastic Component(s): None
Manufacturing Process: Made from agricultural residues
Properties: Durable and long-lasting
Location(s): Hesse, Germany
Sustainability: 100% biodegradable
Compliance to Regulations: ?

5.6 Native Shoes

Material Name: Native shoes
Natural Component(s): Pineapple husk, linen, kenaf, lactae hevea, cotton (Native Shoes, 2022b)
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): Pineapple from Philippines. Manufactured in China and Vietnam. (Native Shoes, 2022a)
Sustainability: Run a recycling scheme
Compliance to Regulations: PETA Approved Vegan

5.7 Nova Milan

Material Name: ?
Natural Component(s): Waste from farmers in Costa Rica including pineapple, orange, hemp, mushroom, cotton and water hyacinth.
Plastic Component(s): ?
Manufacturing Process: For pineapples: Harvest pineapple, collect the leaves, extract fibres, produce leather and donate converted waste to farmers, sell excess leather and sell own products.
Properties: ?
Location(s): San Jose, Costa Rica and London, UK
Sustainability: 100% biodegradable
Compliance to Regulations: ?

5.8 Ohoskin

Material Name: Ohoskin (Ohoskin, 2022)

Natural Component(s): Waste Sicilian oranges and Barbary fig cacti

Plastic Component(s): Latest version contains 32% bio-based materials, 43% green solvents, 20% non-fossil and phthalate-free PVC and 5% additives and pigments. Biopolymer is mixed with a sustainable material from organic feedstock and recycled plastic.

Manufacturing Process: ?

Properties: 100% cruelty free, durable

Location(s): Sicily

Sustainability: Main ingredient is 100% bio-based and biodegradable however the material is not. Recyclable.

Compliance to Regulations: ISO 9001:2015 certified; REACH and PROP65 compliant; phthalate-free; VVV+ Animal Free Fashion. PVC certified by Roundtable for Sustainable Biomaterials.

5.9 Panama Trimmings

Material Name: Viridis (PANAMA TRIMMINGS, 2022)

Natural Component(s): 69% plant-based raw materials – corn/wheat

Plastic Component(s): 31% petroleum-derived

Manufacturing Process: Organic polyols are extracted from corn/wheat which can then be turned into Viridis. Viscose is used as a backing.

Properties: Customisable

Location(s): Italy

Sustainability: "LCA (Life Cycle Assessment) shows that Viridis is more sustainable than any other similar fake-material."; not recyclable of biodegradable.

Compliance to Regulations: Animal free, VV in the Animal Free Fashion rating designed by LAV; USDA bio preferred, Okeo Tex standard 100, FSC

5.10 Peelsphere

Material Name: PEELSPHERE (PEELSPHERE, 2022)

Natural Component(s): Fruit waste and algae

Plastic Component(s): ?

Manufacturing Process: Fruit wastes are mixed, ground up and blended with bio-binder in a mixer. This mixture forms sheets of materials that can be made into products

Properties: Flexible, strong, water resistant, transparent and antibacterial. Can be laser cut, sewn, embroidered and moulded.

Location(s): Berlin, Germany

Sustainability: Zero waste and biodegradable. Full LCA planned.

Compliance to Regulations: Oeko Tex certified dyes.

5.11 Planet of the Grapes

Material Name: ?

Natural Component(s): Waste grape skins (Finney, 2022)
Plastic Component(s): ?
Manufacturing Process: Grape marc collected from vineyards in France and dried in natural sunlight. It's then ground into a powder, blended with natural ingredients to create a liquid and poured onto a fabric of natural stem fibres
Properties: Lightweight and flexible
Location(s): France
Sustainability: ?
Compliance to Regulations: ?

5.12 Tessiltoschi

Material Name: Cartina
Natural Component(s): Recycled paper (Lees 2020)
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

NB: Company and material have no clear digital presence

5.13 Ultraw

Material Name: Ultraw
Natural Component(s): Cellulose obtained from agricultural waste/by-products
Plastic Component(s): ?
Manufacturing Process: Bio-mimicry replicates collagen fibres structure found in animal skin
Properties: Similar to leather in strength, flexibility and appearance.
Location(s): India
Sustainability: Bio-based and 100% biodegradable. Carbon negative process and zero effluent discharge.
Compliance to Regulations: ?

5.14 Veja

Material Name: ?
Natural Component(s): 73% corn
Plastic Component(s): 27% recycled polyester
Manufacturing Process: ?
Properties: ?
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

NB: Veja is the fashion brand that has used this material. The company that makes the materials does not seem to have any significant digital presence.

5.15 Volkswagen

Material Name: ?

Natural Component(s): Coffee waste/ silverskin from Heimbs. More than 50% organic materials (Volkswagen, 2021)
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Durable
Location(s): Wolfsburg, Germany
Sustainability: ?
Compliance to Regulations: ?

6. Fish scales/Shells -based

6.1 Hide BioTech

Material Name: N/A

Natural Component(s): Fish scales, collagen, cellulose fibre backing
Plastic Component(s): ?
Manufacturing Process: Customisable
Properties: Customisable
Location(s): Cambridge, UK
Sustainability: Dyes have “less environmental impacts” and are without heavy metals
Compliance to Regulations: ?

6.2 Nordic Fishleather

Material Name: Atlantic Salmon Leather

Natural Component(s): Fish skin
Plastic Component(s): ?
Manufacturing Process:
Properties: Even scale pockets, easily dyed. Stronger than normal leather (Moskvitch, 2018)
Location(s): Iceland
Sustainability: 100% electricity from a hydro-electric power plant (Nordic Fishleather Iceland, 2022). Fish waste is bought from nearby processing plant that uses geothermal energy (Moskvitch, 2018).
Compliance to Regulations: Global gap and ASC certification

Material Name: Atlantic Cod Leather

Natural Component(s): Fish skin
Plastic Component(s): ?
Manufacturing Process: Scales remain on the skin after the tanning process
Properties: Stronger than normal leather (Moskvitch, 2018)
Location(s): Iceland

Sustainability: 100% electricity from a hydro-electric power plant (Nordic Fishleather Iceland, 2022). Fish waste is bought from nearby processing plant that uses geothermal energy (Moskvitch, 2018).
Compliance to Regulations: MSC certified

Material Name: Spotted Wolffish Leather
Natural Component(s): Fish skin
Plastic Component(s): ?
Manufacturing Process: ?
Properties: No scales but often scars. Stronger than normal leather (Moskvitch, 2018)
Location(s): Iceland
Sustainability: 100% electricity from a hydro-electric power plant (Nordic Fishleather Iceland, 2022). Fish waste is bought from nearby processing plant that uses geothermal energy (Moskvitch, 2018).
Compliance to Regulations: ?

6.3 NyVidd

Material Name: Salmon Eco-friendly Leather
Natural Component(s): Salmon skin
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Flexible. Average 0.6 mm thick. Strength = 90 N. Absorbs colour well, for full properties see (NYVIDD, 2022c).
Location(s): Scandinavia
Sustainability: All salmon skins come from salmon farms in Scandinavian countries
Compliance to Regulations: ?

Material Name: Wolffish Eco-friendly Leather
Natural Component(s): Wolffish skin
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Smooth. 0.4-0.8 mm thick and strength = 50-60 N, for full properties see (NYVIDD, 2022d).
Location(s): Iceland
Sustainability: ?
Compliance to Regulations: ?

Material Name: Cod Eco-friendly Leather
Natural Component(s): Cod skin
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Random alternation of rough and smooth shells, 0.4 thick on average, for full properties see (NYVIDD, 2022a).
Location(s): Iceland and north Norway

Sustainability: ?
Compliance to Regulations: ?

Material Name: Perch Eco-friendly Leather
Natural Component(s): Perch skin
Plastic Component(s): ?
Manufacturing Process: ?
Properties: 0.8 mm thick on average and strength = 90 N, for full properties see (NYVIDD, 2022b).
Location(s): Fished for in Lake Victoria by Kenya, Tanzania and Uganda.
Sustainability: Iceland and north Norway
Compliance to Regulations: ?

7. Cell Cultured

7.1 Newlight

Material Name: AirCarbon
Natural Component(s): PHB
Plastic Component(s): None
Manufacturing Process: Water, minerals and renewable energy are used to give microorganisms the right conditions to produce PHB which is then filtered, washed and dried to a powder. (NEWLIGHT TECHNOLOGIES, INC., 2022b)
Properties: ?
Location(s): California, US
Sustainability: ReFvegetalcycled using biological digestion, carbon negative - used third parties such as SCS Global Services and Carbon Trust (NEWLIGHT TECHNOLOGIES, INC., 2022a).
Compliance to Regulations: ?

7.2 Modern Meadow

Material Name: BioFabbrica (Joint venture with Limonta) (MODERN MEADOW, 2022)
Natural Component(s): Proteins
Plastic Component(s): Bio-based polymers
Manufacturing Process: Uses the Bio-Alloy Application Platform
Properties: Durability, long-lasting colour vibrancy, lightweight, natural look, feel and patina. Abrasion-resistant, water-resistant and breathable; strength and resilience comparable to cartilaginous materials; age naturally and soften with oils like natural leather.
Location(s): New Jersey
Sustainability: Lab-to-Brand traceable
Compliance to Regulations: ?

Material Name: Bio-Tex (MODERN MEADOW, 2022)
Natural Component(s): Proteins
Plastic Component(s): Bio-based polymers

Manufacturing Process: Uses Bio-Alloy technology.

Properties: Is a coated textile. Durability, long-lasting colour vibrancy, lightweight, natural look, feel and patina. Abrasion-resistant, water-resistant and breathable; strength and resilience comparable to cartilaginous materials; age naturally and soften with oils like natural leather.

Location(s): New Jersey

Sustainability: Reduces GHG emissions by >90% compared to traditional chrome-tanned leather.

Compliance to Regulations: ?

7.3 BuchaBio

Material Name: Shorai (BuchaBio, 2022a)

Natural Component(s): Bacterial nanocellulose and 100% plant-based components

Plastic Component(s): None

Manufacturing Process: Innoculate by moving grown liquid media into a clean tub. Extract by removing a finished growth layer and neutralising bacteria. Co-polymerise with natural dyes and other plant-based ingredients. Finish as required (BuchaBio, 2022b).

Properties: Tensile strength of 37 N/mm^2. Flex bally test of 120,000+ cycles; water contact angle of 90º (BuchaBio, 2022c)

Location(s): New Yrok, US

Sustainability: Completely biodegradable

Compliance to Regulations: ?

7.4 Center for Renewable Materials

Material Name: Renewable Polyurethanes (Regents of the University of California., 2022)

Natural Component(s): Algae oils and other biologically-sourced materials

Plastic Component(s): ?

Manufacturing Process: Isolate palmitoleic acid from algae oils and convert it into azelaic acid which serves as a precursor for production of PU products.

Properties: Created as a foam

Location(s): San Diego

Sustainability: Biodegradable

Compliance to Regulations: ?

7.5 FairCraft

Material Name: ? (FairCraft, 2021)

Natural Component(s): ?

Plastic Component(s): ?

Manufacturing Process: Lab grown

Properties: Same touch and feel, high mechanical strength and durable.

Location(s): Paris, France

Sustainability: 90% cut in CO2 emissions and tanning chemicals

Compliance to Regulations: ?

7.6 Modern Synthesis

Material Name: ?

Natural Component(s): Uses a genetically modified organism to weave material made of cellulose and melanin (Modern Synthesis, 2020)
Plastic Component(s): None
Manufacturing Process: Weaved by bacteria
Properties: ?
Location(s): London
Sustainability: 100% compostable, low energy and requires less than 10L water to grow and process
Compliance to Regulations: ?

7.7 Next-Gen Leather

Material Name: BacLeather (Next-Gen Leather, 2022)

Natural Component(s): Cell cultured and bio-fabricated
Plastic Component(s): ?
Manufacturing Process: Bio-fabrication
Properties: ?
Location(s): Madrid, Spain
Sustainability: ?
Compliance to Regulations: ?

7.8 Provenance

Material Name: ? (Provenance Bio, 2021)

Natural Component(s): Non-animal proteins
Plastic Component(s): ?
Manufacturing Process: Complex protein production
Properties: ?
Location(s): California, US
Sustainability: ?
Compliance to Regulations: ?

7.9 Qorium

Material Name: Cultured leather (Quorium, 2022)

Natural Component(s): Cell cultured collagen based
Plastic Component(s): None
Manufacturing Process: Grown
Properties: ?
Location(s): Netherlands
Sustainability: 90% less water, 66% less energy, 36% less chemicals, no methane produced – compared to animal leather
Compliance to Regulations: ?

7.10 ScobyTec

Material Name: ScobyTec BNC (ScobyTec, 2022)

Natural Component(s): Bacterial nanocellulose

Plastic Component(s): ?

Manufacturing Process: ?

Properties: High mechanical strength, water absorption and crystallinity. Ultra-fine and pure nano-fibre structure. Non-flammable

Location(s): Germany

Sustainability: ?

Compliance to Regulations: Uses standard testing procedures

7.11 Gozen Institute

Material Name: Xylozen (Gozen Institute, 2022)

Natural Component(s): Bacterial nano-cellulose

Plastic Component(s): None

Manufacturing Process: 100% natural input is fermented. Ultra-fine fibres grow and form an interconnected 3D network. Vegan tanned.

Properties: ?

Location(s): Turkey

Sustainability: Tonnes of water saved, carbon neutral, non-toxic and animal free process.

Compliance to Regulations: ?

8. Other/Varying Composition

8.1 Aivan

Material Name: 6 different bio-engineered materials (Panda, 2019)

Natural Component(s):

Trichoderma Ressei used for soft ear-paddings.

Biosynthetic spider silk for the Korvaa mesh.

Phanerochaete chrysosporium (fungal mycelium) is used to imitate leather.

Other materials are a combination of mycelium and bacterial cellulose.

Plastic Component(s): ?

Manufacturing Process:

Trichoderma Ressei generated hydrophobin which supports fungal cell growth into the air and is mixed with plant cellulose, resulting in a soft structure.

Biosynthetic spider silk is created by microbes and then processed using electro-spinning to obtain yarn.

Other materials are microbially produced.

Properties: Mesh is durable and flexible.

Location(s): Finland

Sustainability: ?

8.2 XXLab

Material Name: SOYA C(O)U(L)TURE (ARS Electronica, 2022)

Natural Component(s): Soy production waste which is comprised of toxic residues and polluted water

Plastic Component(s): ?

Manufacturing Process: Wastewater from tofu factories is put in a starter culture medium. Acetobacter xylinum (a bacteria) converts the glucose into cellulose fibres to form microbial cellulose sheets. These are then pressed, dried, coloured and coated.

Properties: ?

Location(s): Indonesia

Sustainability: Removes toxic waste from the intensive soya production

Compliance to Regulations:?

8.3 Life Materials

Material Name: Flex Tree (Life Materials, 2022a)

Natural Component(s): treated wood backed with 100% hemp canvas

Plastic Component(s): ?

Manufacturing Process: ?

Properties: 98% flexible in the direction parallel and perpendicular to the wood grain; resists temperatures up to 80 ºC; sewable; washable and water-resistant; soft to touch.

Location(s): Bangkok, Thailand

Sustainability: ?

Compliance to Regulations: CITES and FSC/PEFC certified

Material Name: Korteccia (Life Materials, 2022b)

Natural Component(s): Mutuba fig tree bark fleece

Plastic Component(s): None

Manufacturing Process: ?

Properties: ?

Location(s): Bangkok, Thailand

Sustainability: ?

Compliance to Regulations: ?

Material Name: MuSkin (Life Materials, 2022c)

Natural Component(s): Phellinus ellipsoideus (large parasitic fungus) feeds on vegetables

Plastic Component(s): None

Manufacturing Process: ?

Properties: ?

Location(s): Bangkok, Thailand

Sustainability: ?

Compliance to Regulations: ?

8.4 Allbirds

Material Name: ?

Natural Component(s): Vegetable oil, natural rubber, “other natural bio-based ingredients” (Allbirds, n,d,)

Plastic Component(s): ?

Manufacturing Process: Natural pigmented

Properties: ?

Location(s): New Zealand

Sustainability: Fully biodegradable. More than 40x less carbon than animal leather, 17x less carbon than synthetic plastic leather.

Compliance to Regulations: ?

8.5 Bioleather

Material Name: Plant based (Bioleather, 2022b)

Natural Component(s): Tomatoes

Plastic Component(s): ?

Manufacturing Process: ?

Properties: ?

Location(s): Mumbai, India

Sustainability: Landfill biodegradable, PU free

Compliance to Regulations: ?

Material Name: Microbial (Bioleather, 2022a)

Natural Component(s): Microbes

Plastic Component(s): ?

Manufacturing Process: All-natural dyes

Properties: Vegan

Location(s): ?

Sustainability: Carbon neutral, biodegradable

Compliance to Regulations: ?

Material Name: Tomato composite (Bioleather, 2022a)

Natural Component(s): Tomatoes and microbial

Plastic Component(s): ?

Manufacturing Process: All-natural dyes

Properties: Vegan, combination improves strength of fruit leather

Location(s): ?

Sustainability: Biodegradable

Compliance to Regulations: ?

8.6 Equilibrium - Gucci

Material Name: Demetra (Equilibrium, 2021)

Natural Component(s): Animal-free raw materials

Plastic Component(s): ?

Manufacturing Process: ?

Properties: ?
Location(s): Italy
Sustainability: ?
Compliance to Regulations: ?

8.7 Coopflora

Material Name: Fabric of the Forest (Material Innovation Initiative, 2022a)
Natural Component(s): Rubber latex and cotton.
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): Amazon forest, Brazil
Sustainability: 100% renewable, does not contain toxic chemicals
Compliance to Regulations: ?

8.8 Meatfactory

Material Name: ?
Natural Component(s): Cow blood (Livne, 2020)
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): ?
Sustainability: To ensure if a cow is slaughtered for meat, every part of it is used
Compliance to Regulations: ?

8.9 Nat-2

Material Name: Algae Line (nat-2, 2019a)
Natural Component(s): 50% algae upper, bioceramic lining, recycled cork insoles, natural milk rubber outsoles
Plastic Component(s): Recycled pre-consumer PET bottles
Manufacturing Process: Dead algae is picked from nature, powdered, cooked and poured into moulds to dry
Properties: Semi-transparent, vegan
Location(s): Israel, Germany, France, Italy
Sustainability: Sheets can be reused by re-cooking or will biodegrade
Compliance to Regulations: ?

Material Name: BKK Flower Mrkt (nat-2, 2022a)
Natural Component(s): Flowers, real rubber, cork, bioceramic
Plastic Component(s): Recycled PET bottles
Manufacturing Process: ?
Properties: Vegan
Location(s): Thailand, Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: Beyond Line (nat-2, 2019b)

Natural Component(s): 50% red pepper material

Plastic Component(s): Recycled PET bottles

Manufacturing Process: ?

Properties: Vegan

Location(s): Germany, Austria, Italy

Sustainability: ?

Compliance to Regulations: ?

Material Name: Blood Line (NB: This is a collaboration with Shahar Livne who designs The Meat Factory leather) (nat-2, 2019c)

Natural Component(s): Fat, bones and blood from slaughterhouse waste streams. Nappa leather, real cork and rubber.

Plastic Component(s): ?

Manufacturing Process: ?

Properties: ?

Location(s): Italy

Sustainability: Water-based glue

Compliance to Regulations: ?

Material Name: Coffee Line (nat-2, 2018a)

Natural Component(s): Coffee, coffee beans and coffee plant (50% of shoe surface). Real cork insole and rubber outsole

Plastic Component(s): Recycled PET bottles

Manufacturing Process: ?

Properties: ?

Location(s): Germany, Italy

Sustainability: ?

Compliance to Regulations: PETA Vegan Approved

Material Name: Cannabis Line (NB: This is a collaboration with LOVR) (nat-2, 2019d)

Natural Component(s): CBD hemp material, agricultural residues (50% of shoe surface). Real cork insole and rubber outsole

Plastic Component(s): Material is plastic free

Manufacturing Process: ?

Properties: Vegan

Location(s): Germany, Austria, Italy

Sustainability: 100% biodegradable and climate-neutral

Compliance to Regulations: ?

Material Name: Diamonds Line (nat-2, 2019e)

Natural Component(s): Recycled Swarovski rhine stones (50% of shoe surface). Real cork insole and rubber outsole

Plastic Component(s): Recycled PET bottles

Manufacturing Process: ?

Properties: Vegan

Location(s): Germany, Austria, Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: Flower Line (nat-2, 2019f)
Natural Component(s): Rose leaves (50% of shoe surface). Real cork insole and rubber outsole. Bioceramic lining.
Plastic Component(s): Recycled PET bottles
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Vegan
Location(s): Germany, Austria, Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: GPA Bananatex (NB: This is a collaboration with Bananatex) (nat-2, 2022b)
Natural Component(s): Honey impregnated Bananatex, Lactae Hevea natural rubber soles, real cork insole and bioceramic lining.
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): Switzerland, Italy, Germany
Sustainability: ?
Compliance to Regulations: ?

Material Name: Sleek Low Fruit (nat-2, 2022b)
Natural Component(s): Recycled scraps of orange and cacti harvest, real cork insole, 100% real rubber outsole
Plastic Component(s): Upcycled bubble wrap
Manufacturing Process: ?
Properties: Vegan
Location(s): Italy
Sustainability: ?
Compliance to Regulations: PETA approved vegan

Material Name: Fungi Line NB: This is a collaboration with Zvnder (nat-2, 2018b)
Natural Component(s): Fungus leather, bio-textiles and a coating (50% of shoe surface). Real cork insole and rubber outsole. Bioceramic lining.
Plastic Component(s): Recycled PET bottles
Manufacturing Process: Leather like material is created from the Trama of the tinder sponge, Fomes Fomentarius
Properties: Vegan, Antiseptic and anti-bacterial
Location(s): Berlin, Italy
Sustainability: Chemical free
Compliance to Regulations: ?

Material Name: Hayfield Line (nat-2, 2018c)
Natural Component(s): Austrian/Bavarian meadow hayfield. Real cork insole and rubber outsole.
Plastic Component(s): ?
Manufacturing Process: Hayfield is pressed and applied to a layerbase
Properties: Vegan
Location(s): ?
Sustainability: ?
Compliance to Regulations: PETA approved vegan

Material Name: Milk Line (nat-2, 2018d)
Natural Component(s): Non-food milk to make Milk-Felt, real cork insole, real rubber outsole and vegetarian tanned lining
Plastic Component(s): ?
Manufacturing Process: Biopolymer developed consisting of the milk protein casein
Properties: ?
Location(s): Germany, Italy
Sustainability: Milk-felt is compostable
Compliance to Regulations: ?

Material Name: Moss Line
Natural Component(s): Upcycled Tyrolian mountain forest moss (50% of shoe surface). Real cork insole and rubber outsole. Bioceramic lining.
Plastic Component(s): Recycled PET bottles
Manufacturing Process: ?
Properties: Vegan
Location(s): Germany
Sustainability: ?
Compliance to Regulations: ?

Material Name: Ocean Line (NB: This seems to be a collaboration with Nordic Fish Leather or NYVIDD) (nat-2, 2019g)
Natural Component(s): Salmon and wolffish skin
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): Iceland, Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: Prime Corn Series (nat-2, 2013)
Natural Component(s): 15% recycled non-food corn, 80% rubber upper
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Waterproof
Location(s): Germany, Italy

Sustainability: ?
Compliance to Regulations: ?

Material Name: Skeleton Line (nat-2, 2019h)
Natural Component(s): Skeleton leaves (50% of shoe surface). Real cork insole and rubber outsole. Bioceramic lining.
Plastic Component(s): Recycled PET bottles
Manufacturing Process: ?
Properties: Anti-bacterial and antiseptic linig
Location(s): Germany, Austria, Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: Stone Line (nat-2, 2017)
Natural Component(s): Slate stone. Real rubber outsole.
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Light, soft, flexible
Location(s): Germany, Italy
Sustainability: ?
Compliance to Regulations: ?

Material Name: Wooden Line (nat-2, 2016)
Natural Component(s): Sustainable wood covers up to 90% of the shoe's surface. Real cork insole and real rubber outsole.
Plastic Component(s): ?
Manufacturing Process: ?
Properties: Vegan, soft, smooth and flexible
Location(s): Italy
Sustainability: Ethically managed forests
Compliance to Regulations: PETA Approved Vegan

8.10 Slow Factory Labs

Material Name: Slowhide (Slow Factory Labs, n.d.)
Natural Component(s): ?
Plastic Component(s): ?
Manufacturing Process: ?
Properties: ?
Location(s): ?
Sustainability: ?
Compliance to Regulations: ?

NB: Website exists but contains no information

Appendix B: Tensile test graphs

For all Force-Displacement graphs, the solid lines are the Instron's displacement measurements and the dashed lines are the laser's measurements; for all Stress-Strain graphs, the solid lines are straight lines of best fit and the dashed lines are the calculated data.

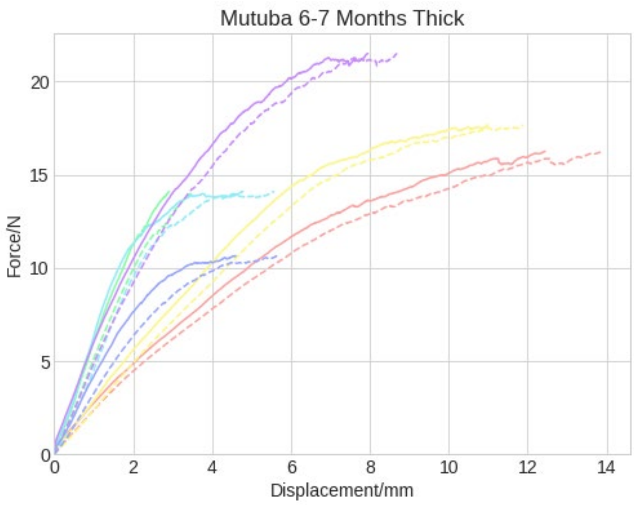

Figure 4.1: Force against displacement for 6 samples of BarkTex: Mutuba 6-7 Months Thick.

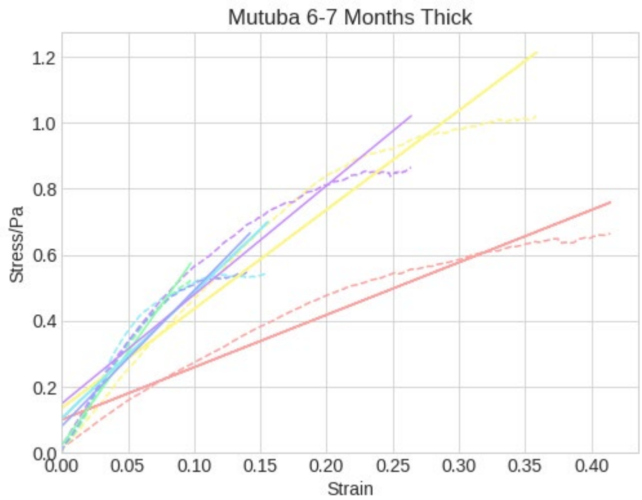

Figure 4.2: Stress against strain for 6 samples of BarkTex: Mutuba 6-7 Months Thick.

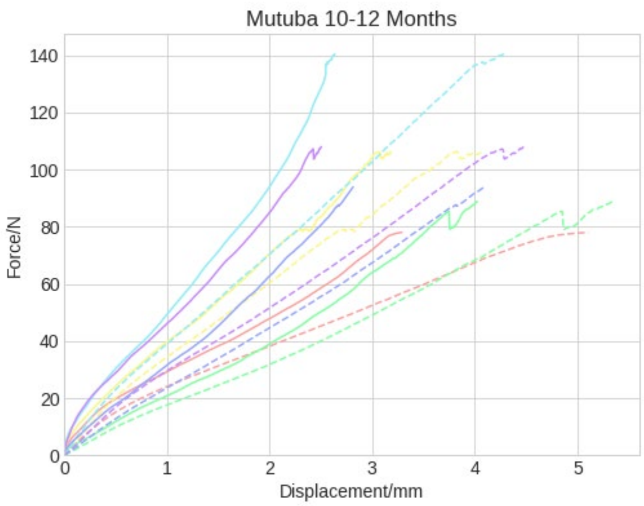

Figure 5.1: Force against displacement for 6 samples of BarkTex: Mutuba 10-12 Months.

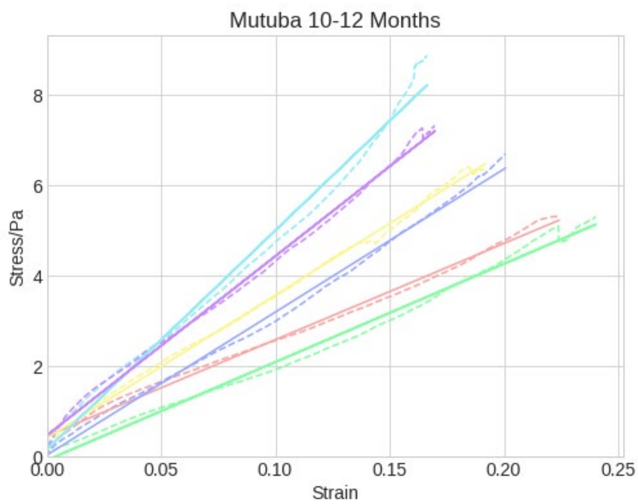

Figure 5.2: Stress against strain for 6 samples of BarkTex: Mutuba 10-12 Months.

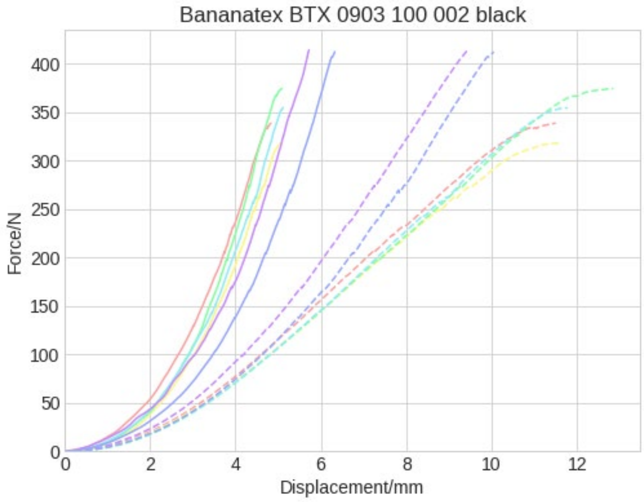

Figure 6.1: Force against displacement for 6 samples of Bananatex BTX 0903 100 002 black.

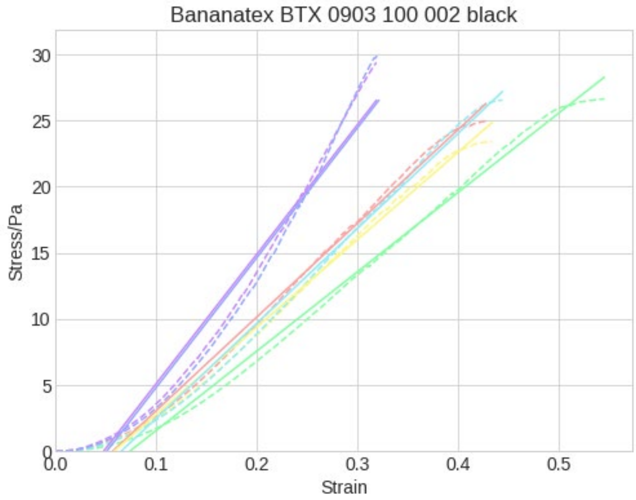

Figure 6.2: Stress against strain for 6 samples of Bananatex BTX 0903 100 002 black

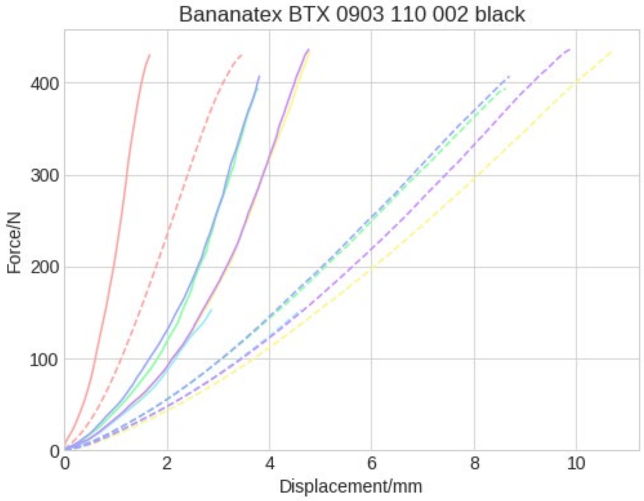

Figure 7.1: Force against displacement for 6 samples of Bananatex BTX 0903 110 002 black.

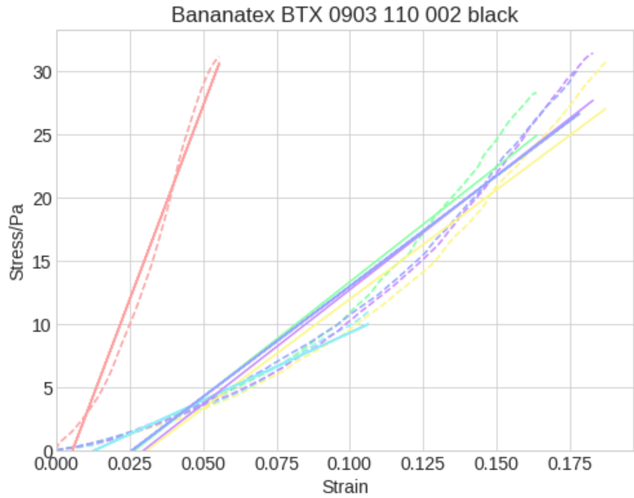

Figure 7.2: Stress against strain for 6 samples of Bananatex BTX 0903 110 002 black

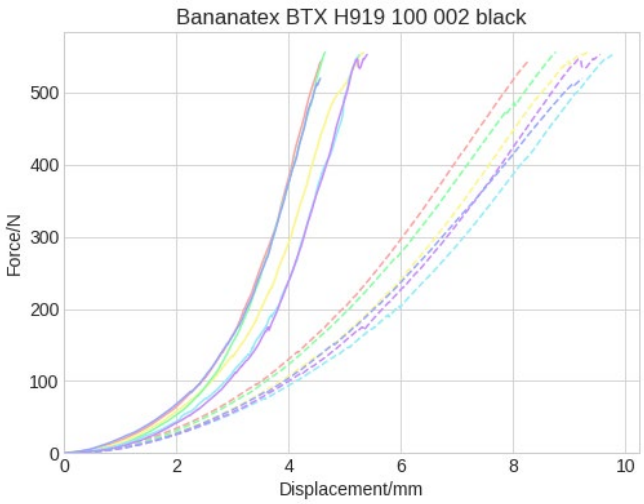

Figure 8.1: Force against displacement for 6 samples of Bananatex BTX H919 100 002 black.

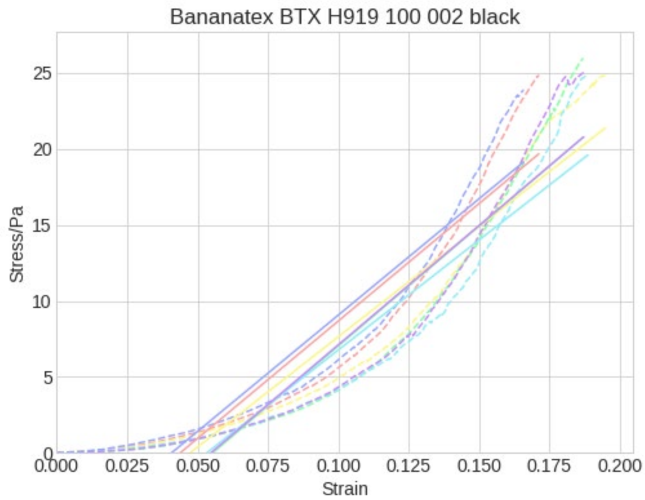

Figure 8.2: Stress against strain for 6 samples of Bananatex BTX H919 100 002 black

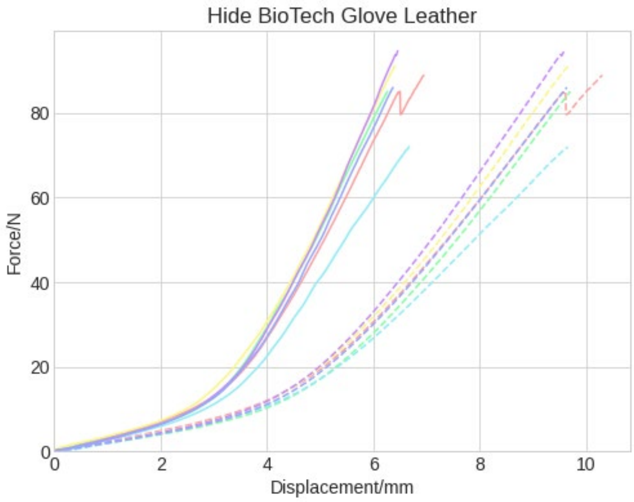

Figure 9.1: Force against displacement for 6 samples of Hide BioTech Glove Leather.

Figure 9.2: Stress against strain for 6 samples of Hide BioTech Glove Leather

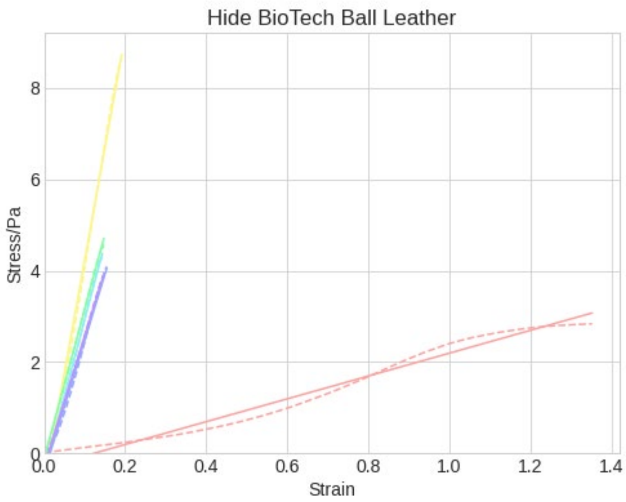

Figure 10.1: Force against displacement for 6 samples of Hide BioTech Ball Leather.

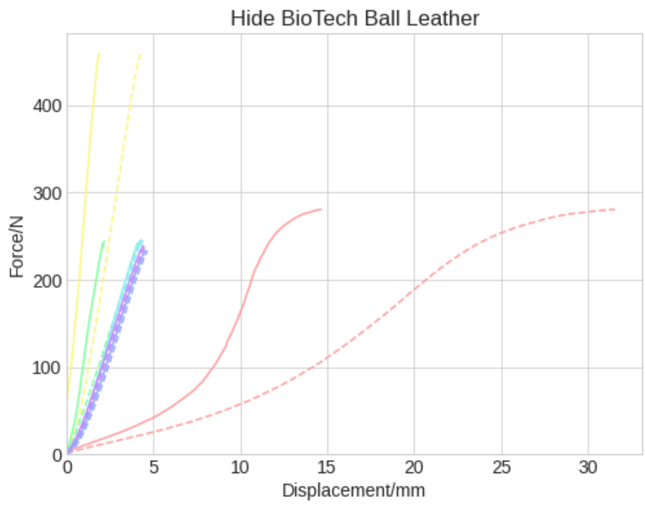

Figure 10.2: Stress against strain for 6 samples of Hide BioTech Ball Leather

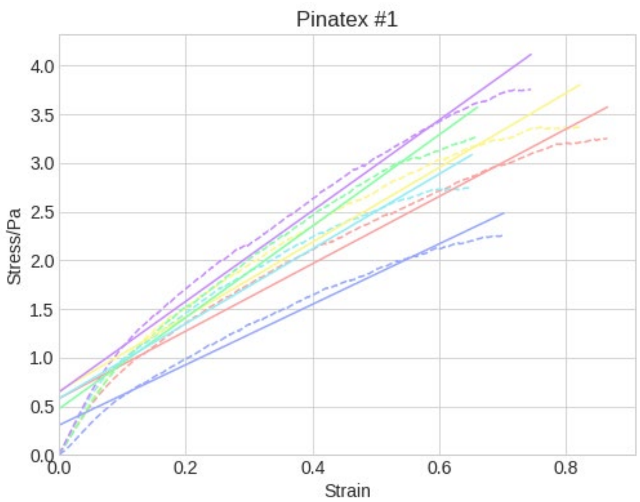

Figure 11.1: Force against displacement for 6 samples of Piñatex #1.

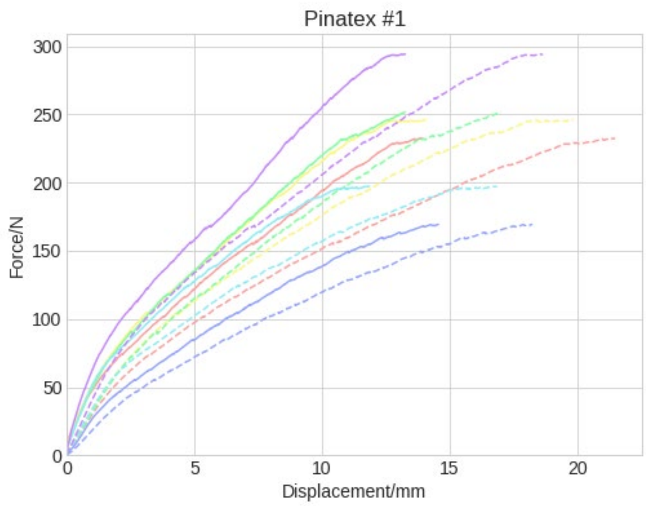

Figure 11.2: Stress against strain for 6 samples of Piñatex #1.