Final Report

Materials in cricket balls, gloves and pads, and their sustainable alternatives

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1. Introduction

Over 200 million people regularly play cricket, the majority in low and middle income nations. Cricket is one of the most equipment-intensive sports: each of the over 40 types of cricket gear [1,2] comprises multiple component materials that are derived, processed and assembled through complex supply-chains, and notably, designed without consideration for end-of-life disposal.

This report documents conventional materials used in cricket gear, with a focus on balls, gloves and batting pads. Due to the similar material composition and structure of gloves and pads, they are considered together. Following an assessment of some of the functional, technical, manufacturing and performance requirements required by existing standards and manufacturer specifications from these component materials, sustainable alternatives are explored and identified. Emerging material innovation opportunities are also flagged. The work is based on a mix of desk and primary research.

For example, a standard cricket ball weighing c. 156-163g may compose of at least five different materials sourced from different parts of the world: *i)* bovine alum-tanned leather casing from UK or India[3]; *ii)* linen (flax)[4] from France and cotton from India for the stitching thread in the seam, *iii)* wool from UK or New Zealand[3] for the worsted yarn used to wrap the core, *iv)* cork from Portugal[2] and rubber from Malaysia, Thailand or India [5,6] for a cork or cork-rubber composite[5,7,8] hard core, and *v)* nitrocellulose lacquer, polyurethane coating or shellac wax from India[9] for leather finishing. It is estimated that over 1.8 million balls are used every year[1], with Kookaburra (Australia; producing c. 0.5 million balls a year[10]), SG (India) and Dukes (UK) being the largest manufacturers. Many of these balls may have some life beyond a single game (*e.g.* as functional 'net' practice balls or as dysfunctional 'stored waste'), though, once they have split and are beyond use, it is anticipated that the vast majority are landfilled, amounting to ca 300 tonnes per year.

Given the cost, scale of production, environmental impact and lack of circular design of conventional cricket gear, design and material innovation of cricket gear will be critical in improving the reach and sustainability of the sport.

The findings presented in this report form part of the UKRI CE-Hub flexible fund's feasibility study on Circular Cricket Gear (CCG) which aims to develop potential strategies to maintain the value of products, components, and materials in the economic and social systems of cricket gear, as well as explore material innovation for cricket gloves, batting pads and balls. This report builds on findings from the Platform for Acceleration of Sustainability in Cricket

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[1] Charter, M. and Clark, T. (2022), Sustainability, Cricket Gear, Clothing and Apparel: Report on Cricket Gear.
[2] Wetherfield, M., Charter, M., Shah, D., Whitaker, C. (2022) Sustainability, Cricket Gear, Clothing and Apparel: Report on Components, Materials, and Innovation Opportunities.
[3] Hunts County Bats: Balls (2022)
[4] Gunn & Moore Cricket (1976)
[5] Fuss, F.K. (2008) Cricket balls: Construction, non-linear visco-elastic properties, quality control and implications for the game, Sports Technology, 1:1, 41-55
[6] Banarjee, S., (2018) How the Dukes Cricket Ball is Made, Red Bull.
[7] Oxbridge Cricket Balls, About Us (2023)
[8] Jarratt, T.A.W. and Cooke, A.J. (2001), A Comparison Of Cricket Ball Cores, Proc. Materials and Science in Sport, edited by Minerals, Metals and Materials Society.
[9] Mitchell, A. The Guardian (2015). The science of swing: a pink ball's journey from tannery to Adelaide Oval
[10] Kookaburra (2023)

(PASIC)[1,2] and the Vegan Leather Cricket Gear project (VLCG) [11], both led by The Centre for Sustainable Design ® (CfSD) at University for the Creative Arts (UCA).

2. Cricket Ball

In this section, we discuss the key components, materials and their requirements for a typical cricket ball, starting with the ball architecture. We further propose potential alternatives to existing materials. The research papers by Fuss (2008)[5] and Jarratt & Cooke (2001)[8], as well as grey literature (e.g. manufacturer websites, sport-related articles in magazines and newspapers), and our own experimental and desk research was helpful in understanding the diversity in cricket ball architecture and material composition.

2.1 Conventional ball architecture

Law 4 of the 'Laws of Cricket 2017 Code'[12] set by the MCC specifies acceptable tolerances for size and weight of different grades of cricket balls that are actively monitored in a game. The British Standard BS 5993:1994 ("*Specification for cricket balls*") further details the construction and manufacture of the balls. While the standards do specify that the casing of the ball needs to be constructed from "two or four pieces of aluminium-tanned leather enclosing a core", materials for the core, leather coating, and seam threads are not specified. The decision to use two pieces (hemispheres) or four pieces (quarters) of leather would be based on a number of factors, including desired consistency in thickness of leather (e.g. better with quarters), quality of available leather (e.g. stretchability), speed of manufacture and method of stitching (hand vs machine-made), and expected life for shape retention (e.g. format of game) [6,9,10]. It is noteworthy that 'leather' is further defined as per BS EN 15987:2022 ("*Leather. Terminology. Key definitions for the leather trade*"), further explained in Taylor & Shah (2023)[11]. BS 5993:1994 does describe test protocols for the assembled product (i.e. ball) – to measure hardness, impact and wear resistance – but does not specify requirements for the component materials. These are set by manufacturers and seem to be kept as trade secrets.

In terms of architecture, cricket balls have three (or four*) main layers, which from the exterior to interior are:

- A coating, lacquer or polish
- A stitched casing with a seam
- Core layers comprising a
    - A midsole core* - though not all cricket balls have this layer
    - A central core

Two common modern ball architectures are illustrated in Figure 1a) and b): a) has a midsole core in addition to a central core, whereas b) only has a central core. For example, the Duke's cricket ball[6] (Type b)) comprises of four pieces of alum-tanned leather, hand-stitched around

[11] Taylor, B., and Shah, D. (2023) Leather Alternatives for Cricket Gear.
[12] https://www.lords.org/mcc/the-laws-of-cricket/the-ball
* midsole core is an intermediate core layer between the central core and the leather casing in some cricket balls.

a pre-shaped, compressed core, typically cork-rubber bonded composite. A similar construction is also visible in one of Gunn & Moore's cricket ball (Figure 1c)). Another construction method (e.g. typical Kookaburra balls[10]), involves two pieces of machine-stitched alum-tanned leather encasing a moulded central cork-rubber composite core that has been wrapped around with five layers of cork and yarn (the midsole core), as illustrated in Figure 1a). Both architectures have some form of a coating or polish wax. It is interesting to note that the architectures evolved from two distinct forms: i) a 'cork square' (square piece of compressed cork) as the central core that would be wrapped around with twine or twine-cork layers, and ii) a 'rolled' core[8] as the central core that would be processed by layering and rolling alternate sheets of cork/rubber mix and rubber.

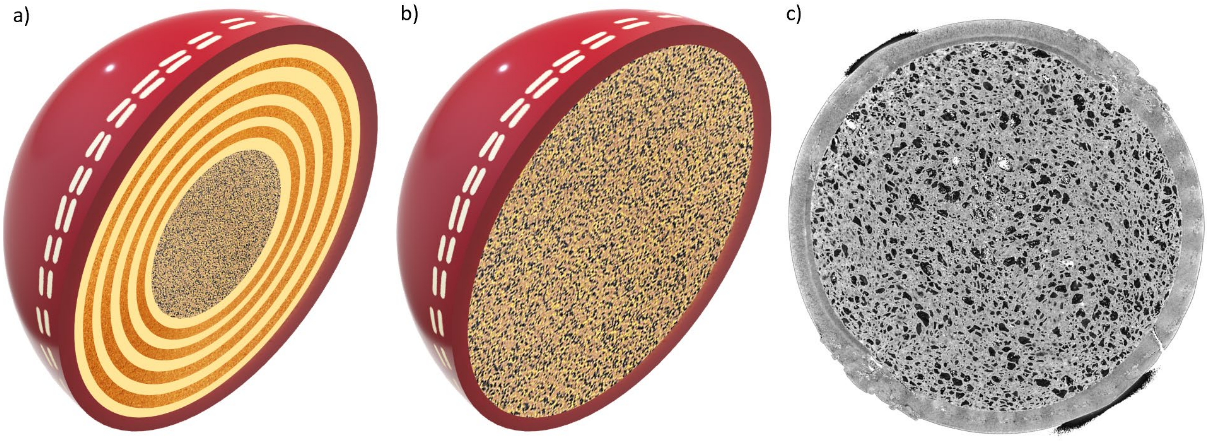


Figure 1. Typical ball architectures. Schematic of a ball with (a) and without (b) a midsole layer. 3D x-ray scan of a Gunn & Moore cricket ball depicting a thick (c. 3.5mm) four-piece leather casing, with visible seam, and a large pre-shaped central core as in type b) ball architecture.

With advancements in polymer and rubber technology and machining processes over the past 100-years, ball architecture and materials have also evolved. The most obvious change is that cores are no longer just 'cork', but typically a formulated composite of cork and (nitrile butadiene or styrene butadiene) rubber that is more durable, consistent and 'softer'[5] (less stiff, more compliant, and less rebound). Specifically, granules of rubber and cork – with predetermined sizes and ratios – are bonded together at temperature and pressure to form a hard, robust core material. While the cork is still largely Portuguese, the rubber comes from Malaysia, India or Thailand [5,6,7,8]. Similarly, there have been advancements in the selection of dyes (e.g. water soluble aniline and synthetic buck fat[9]) and coatings for the leathers; for example shellac wax (*female lac bug derived*) is no longer widely used, and has been replaced by specially formulated, sprayable, glossy and durable nitrocellulose lacquers (mostly plant (cotton) derived substance mixed with acids – e.g. also used for guitar body coating) or polyurethane coatings[9,10].

2.2 Materials: conventional and their potential sustainable alternatives

The range of conventionally used materials for the different components of a cricket ball are presented below, as are their suggested potential alternatives. The alternatives are 'sustainable' in that they may be bio-derived (less reliance on petrochemical or non-renewable resources) or have lower embodied energy or carbon footprint; though it is recognised that a full life-cycle assessment is necessary, including consideration of scale-effects and complexities in supply-chains.

Coating and polish

Functional requirements

- Protect the leather from damage (wear and moisture-related)
  - Hard and durable
  - Hydrophobic (water repellent)
- Glossy and maintain 'shine'
- Compatibility with leather
- Can be easily applied (e.g. sprayable)

Current materials

- Aniline and (synthetic) buck fat coating for treatment of leather
- Nitrocellulose lacquer – a predominantly plant (cotton or wood) derived substance mixed with acids
- Polyurethane (PU) coating
- Historically, shellac wax (female lac bug derived)

Example alternative materials to explore

- Beeswax - Existing
  - Offers wear resistance and water repellence and can be buffed to a shine.
  - Is not vegan, but is regenerative.
  - Already widely used for care of leather products.
  - Bananatex (QWSTION), amongst other emerging alternative leather suppliers, use natural beeswax as a water-proof coating.
- Fungkee Supercoating[13] - Future potential
  - Fungi-based coating that can be used to make 'plant-based leather' water-repellent and more durable than the uncoated plant-fibre textile material
  - At proof-of-concept stage
- Bio-polyurethane (BPU) coatings – Growing and at industrial scale
  - The majority of emerging alternative leathers, including Pinatex® and Desserto® use PU coatings for durability and moisture performance, and BPUs may be a drop-in alternative.
  - Such BPUs may also be alternatives to non-fluorinated REACH regulation compliant, polyfluorinated chemicals (PFC) free, Durable Water Repellent (DWR) coatings e.g. PTFE (polytetrafluorethane) which are used by some emerging leather alternative (e.g. Bananatex) for heavy-duty applications.
  - Production of BPUs is at industrial scale (several 100s of tonnes [14]), but small: BPUs account for ca 0.001% of the PU market.
  - Covestro (formerly Bayer MaterialScience; Germany) is developing a range of bio-based PUs and PCs. Bio-based starting/raw materials or resources they use include:

[13] https://emmavanderleest.com/portfolio/fungalsupercoatingfungkee/
[14] https://www.grandviewresearch.com/industry-analysis/bio-based-polyurethane-industry

    - Industrial sugar to make aniline (which is currently use in cricket ball leather coatings) using microorganisms as catalysts, with the raw sugar coming from corn, straw or wood.
    - Waste vegetables or those not intended for human consumption
    - Waste or residual oils and fats (e.g. from the food industry)
- Covestro is developing dispersible and waterborne BPU coatings based on bio-succinic acid from a company called BioAmber. (Notably, Bio-succinic acid can replace adipic acid in applications such as synthetic leather.)
    - This is directed for technical textiles, fashion (including synthetic leather) and sporting goods [15]
    - These coatings are (at least partly) biodegradable as well as (up to 70%) bio-based
- Covestro is also producing INSQIN® and Impranil® BPU coatings[16,17], using Desmodur® eco N 7300 aliphatic bio-based pentamethylene diisocyanate with a 70% bio-content. The bio-based aliphatic isocyanate itself has better performance than hexamethylene diisocyanate (HDI), which is a petrochemical-based aliphatic isocyanate used for elastomers, coatings and sealants.

Casing

Functional requirements

- Encases and protects the hard core
- Provides durability and shape retention for the ball
- Offers a smooth, shiny surface and defined seam to demonstrate bowling craft
- A previous report related to vegan leathers [18] identified the following properties as being particularly important for cricket balls:
    - Physical: thickness, density, 'mass per unit area',
    - Mechanical: strength and elongation in tension, abrasion behaviour,
    - Durability: water absorption, dimensional stability, UV-stability,
    - Machinability: flexibility, cutability, tear strength, ability to stitch
    - Compatibility: with coatings/lacquers and with the core material.

Current materials

- Bovine Hide leather
    - Source
        - India is the largest exporter of bovine leather, and around 80% of cricket balls produced in India are from cow hide, with the remaining being produced from buffalo or ox hide, which are considered inferior[19]. SG cricket balls are made from these Indian bovine leathers, and possibly Kookaburra also.
        - Duke's cricket balls are from Angus cows in Scotland (leather tanned in Derbyshire). However, all manufacturing has now moved to the Indian

[15] https://www.plasticstoday.com/bayer-materialscience-introduces-biobased-pu-fashion-and-footwear
[16] https://solutions.covestro.com/en/brands/impranil
[17] https://solutions.covestro.com/en/highlights/articles/stories/2021/enabling-a-new-era-of-textile-materials-insqin
[18] Taylor, B., and Shah, D. (2023) Leather Alternatives for Cricket Gear.
[19] https://timesofindia.indiatimes.com/top-stories/howzat-cow-queers-pitch-for-cricket-balls/articleshow/53075463.cms

subcontinent – only finishing is completed in England[20]. Consequently, the leather (and other) raw material is shipped from UK to the Indian subcontinent (and then the semi-finished product is shipped back to the UK for final finishing).

  - Notably, a highly-skilled worker is able to hand stitch 4-5 balls per day[6] – this labour-intensive aspect of ball manufacture, alongside the low perceived value (as opposed to price/cost) of cricket balls[20], has been a key driver of taking manufacture of the balls to the Indian subcontinent, away from the UK[20].
  - Therefore, we hypothesis that 'material cost' is not the bottleneck or price-driver for cricket gear, rather it is the 'manufacture and assembly cost' (e.g. related to production time).

- Initial form
  - Uniform thickness is desirable as the leather sheet material needs to be stretched to a complex shape – a sphere – that curves in two directions. 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. Two (hemisphere) or four (quarter) pieces of leather can be used to wrap the core. However, thickness variations in the leather pieces may affect ball quality, and while a more uniform thickness is achievable across the ball surface when four-pieces are used, additional stitching of leather is necessary which may also affect durability as stitches are points of weaknesses.
- Processing and environmental impact
  - Bovine hide leather production has a high environmental impact, primarily due to cattle farming and tanning processes. For example, the embodied energy (80-100MJ/kg), carbon footprint (4-5 kgCO_2eq/kg) in the primary production of leather are higher than 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).
  - Tanning is a key process to stabilise the fibrous protein in the leather and avoid bacterial degradation. However, this is a hugely environmentally-polluting process. Tanning for cricket balls is with chromium and aluminium salts to increase durability, resistance to moisture, and produce skins (whitish base colour) that are easier to dye. 85–90% of leather is created using chrome tanning, which can involve the use of highly toxic and polluting agents, specifically chromium III. Chrome-tanned leather is also easier to make hydrophobic and can be softened more easily. Typically, the chrome-tanning agent will contain 33% basic chromium sulphate and 26% chromium (III) oxide. Up to 50% of the chromium used by some commercial operations can find its way into the environment, being consumed by animals and subsequently humans. This is a substantial amount given that 480,000 tonnes of chrome-tanning agent are produced annually.

[20] http://heritagecrafts.org.uk/cricket-ball-making/

- Studies[21] have revealed that carbon footprints of tanneries vary significantly depending on the energy composition of the grid in different countries. For example, the Australian tannery investigated by the authors had a carbon footprint of 12 kg CO_2–eq/ m^2, compared to the Spanish tannery, which emits 2.5 kg CO_2 –eq/ m^2. Part of this difference is attributed to the Australian tannery's additional and different processing steps of hides (including exotic hides), which causes them to be more energy intensive (49 MJ/m^2 compared to 30 MJ/m^2), but the majority is due to the inherent CO_2 emissions of the energy grid with a higher reliance on non-renewable fossil fuels, particularly coal.
  - Tanning process implies that leather becomes non-biodegradable. This also has end-of-life implications.
- Protected status
  - 'Leather' is a protected term: a product that does not meet the definition stipulated in BS EN 15987:2022 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). This has implications on the use of 'recycled' or 'reconstituted' leathers, as well as 'leather alternatives'. The definitions of leather and its implications on the use of alternative leathers has been discussed in detail in the Vegan Leather Cricket Gear project report [22].

Example alternative materials to explore

- Alternative 'bio-based' leathers
  - 87 companies producing >123 alternative 'bio-based' or 'sustainable' leather materials have been identified as part of the Vegan Leather Cricket Gear project [23]. Additional testing (tensile mechanical, abrasion, water droplet behaviour, and stitch strength testing) on some alternative leather materials has been carried out and is presented in another report as part of the Circular Cricket Gear project.
  - 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 (e.g. Fine Mycellium™ by MycoWorks), leaf-based (e.g. Pinatex® from waste pineapple leaf fibres from the Philippines, Desserto® from Mexican cactus leaves[24], and Bananatex® cultivated Abaca leaves in the Philippines[25]), fruit/vegetable/flower-based (e.g. AppleSkin and GrapeSkin), other plant-based, fish scales/shells-based (e.g. Hide Biotech), cell cultured, and other/varying composition. Within each category, four sub-categories were identified: waste-based, grown, harvested, and unknown. Example materials for each of the main component categories are illustrated below, which also indicates how these categories are linked by materials that

[21] R. Laurenti, M. Redwood, R. Puig, & B. Frostell, Measuring the Environmental Footprint of Leather Processing Technologies. Journal of Industrial Ecology, 21 (2016) 1180–1187. https://doi.org/10.1111/jiec.12504.
[22] Taylor, B., and Shah, D. (2023) Leather Alternatives for Cricket Gear.
[23] Taylor, B., and Shah, D. (2023) Leather Alternatives for Cricket Gear.
[24] https://desserto.com.mx/why-desserto%3F
[25] https://www.bananatex.info/

utilise multiple components. The full database with known material compositions, properties and production locations amongst other characteristics are found in the VLCG report [26].

- Our investigation revealed that many of these materials were missing basic information, sometimes even the company or material name. The lack of data and information presents significant challenges. None of the tested materials were like-for-like replacements to bovine leather as per the experimental testing conducted in the VLCG project, and it is possible that in their current state, none of the aforementioned materials in development 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, and all leather alternatives so far have been developed for the fashion sector rather than sporting sector. In literature, research by the Freiburg Institute of Leather and Plastic Sheet materials (FILK) into nine leather alternatives, entitled 'Comparison of the Technical Performance of Leather, Artificial Leather and Trendy Alternatives'[27] 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[26]. 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.

- 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. For example, as part of the Vegan Leather Cricket Gear project , a batting glove was refurbished with the worn-out Pittard's leather palm being replaced by a synthetic PVA-based chamois leather; the prototyping exercise informed that the vegan synthetic leather was woo thick and didn't allow the player to have the feel of the bat/bat handle, in comparison to conventional batting gloves.

[26] Taylor, B., and Shah, D. (2023) Leather Alternatives for Cricket Gear.
[27] Meyer, M.; Dietrich, S.; Schulz, H.; Mondschein, A. Comparison of the Technical Performance of Leather, Artificial Leather, and Trendy Alternatives. Coatings 2021, 11, 226. https://doi.org/10.3390/coatings11020226

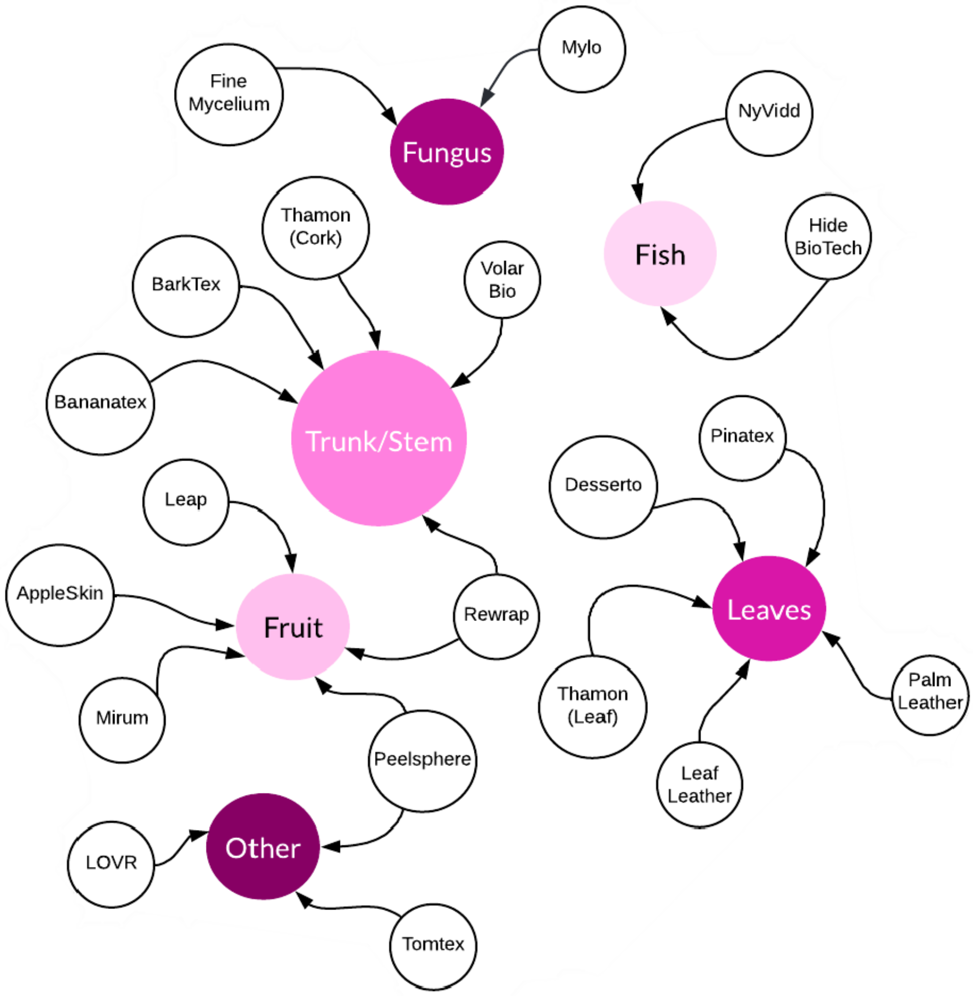


Figure 2. Classification system for alternative leathers, with some example products for illustration purposes. The author's own image.

- Where the information is available, the manufacturing processes of each alternative leather material could 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.

- Furthermore, LCAs should be conducted in order to compare the relative sustainability benefits of each of these materials in comparison to bovine leather. Our own unpublished landscaping review study of LCAs of leather and leather alternative reveals that while many of these alternative leathers perform better than bovine leathers, particularly on environmental impact indicators such as carbon footprint, energy use and water use, their environmental impact is fairly comparable to conventional PU (polyurethane) and PVC (polyvinyl chloride)-based imitation leathers. This is also partly because a number of existing alternative leathers include a large fraction (sometimes as much as 75%) of fossil-fuel based polymers like PU or coatings, principally for improved durability and moisture behaviour. A few alternative leathers can be 100% bio-based (e.g. Bananatex and BarkTex), although in such cases, their moisture performance is severely lacking. Land-use is another environmental impact criteria that might need consideration. At present, most LCAs focus on cradle to gate, rather than cradle to cradle, system boundaries. Therefore, they exclude the *use* phase and beyond, which are particularly relevant vis a vis circularity. More comprehensive LCAs which include an assessment of circularity are needed. An aspect that can present challenges in completing a fair LCA is to do with scale of production. Economies of scale (or lack of) may present challenges for proper comparisons: as production of alternative 'sustainable' leathers is at a comparatively trivial scale in comparison to bovine leather and PU/PVC based imitation leathers, the datasets for the former may have more uncertainty and be more sensitive to production parameters.

- The cost and supply-chain of alternative leathers needs further clarity, both of which impact the feasibility of manufacture. This is particularly relevant as current manufacturing is limited in scale and is targeting non-performance bases sectors (fashion/accessory – e.g. handbags, shoes).
- It is noteworthy that a number of these alternative 'sustainable'/'bio-based' alternative leathers are in the form of fibrous textiles – nonwovens and wovens – or require a backing material or include some polymeric binders/coatings as indicated above.
- Perception (e.g. from players, manufacturers and stakeholders) may also have an important role in penetrating the leather market for cricket gear with alternative leathers. Our own unpublished work – led by Caitlin Mackellar and Darshil Shah – finds that end-users have prejudice/concerns about 'quality' and 'durability' of bio-based leathers, even when they have never interacted with such leathers. Below is a word-cloud of what end-users valued in terms of properties of leathers that needed replication, and durability and waterproof nature were particularly important. These perception studies were conducted through 17 in-depth object-based interviews, each lasting 25 minutes, with Cambridge University students and staff.

Figure 3. Word-cloud illustrating qualities of leather that end-users feel need to be replicated in alternative leathers. The author's own image.

- A survey of cricket players interviewed as part of the Vegan Leather Cricket Gear project also lead to the following relevant user perceptions of vegan leathers for cricket gear:
  - 71% of respondents would consider replacing their existing gear for a plant based vegan leather alternative.
  - The main reasons highlighted were related to the alignment with lifestyles such as veganism, or increased awareness of sustainability considerations.
  - It was also highlighted that to consider switching to cricket gear incorporating 'plant-based'/vegan leather alternatives, new equipment would be required to match existing products' durability, quality, and performance.
  - Likewise, new products would have to be affordable.
  - 29% of respondents indicated they would not consider using cricket gear made from a 'plant-based'/'vegan' leather alternative, due to perceiving plant based vegan leathers as being of lower quality, durability, and performance. e.g., 'not as hard wearing' as 'true' leather.

- Alternative 'fossil-fuel-derived' leathers
  - Aside from bio-based alternative leathers, there is a possibility of using imitation leathers based on PU, PVC and other fossil-fuel derived polymers, or even BPUs. It is noteworthy that some studies have demonstrated they have lower environmental impacts than bovine leathers, particularly due to not requiring cattle farming or tanning processes.
  - As a natural material with a very complex internal structure, bovine hide leather is understandably difficult to make synthetically but the first major attempt came in 1963 as Dupont released 'Corfam' made of Polyester and PU. From there the demand for and research into synthetic leathers has only increased and they have become more and more prevalent in society. For example, the global artificial leather market (dominated by PU and PVC) sits at 33.7 billion USD, compared to the global leather goods market which is valued at almost 250 billion USD (in 2022).
  - Our ongoing unpublished work, led by Caitlin Mackellar and Darshil Shah, based on systematic reviews and LCA analyses finds that fossil-fuel derived imitation leathers (e.g. WiniwPU and Volarbio) have significantly lower environmental impact than bovine leathers, and a slightly higher but not vastly dissimilar environmental impact in comparison to 'sustainable'/'bio-based' alternative leathers (such as Pinatex and Bananatex).

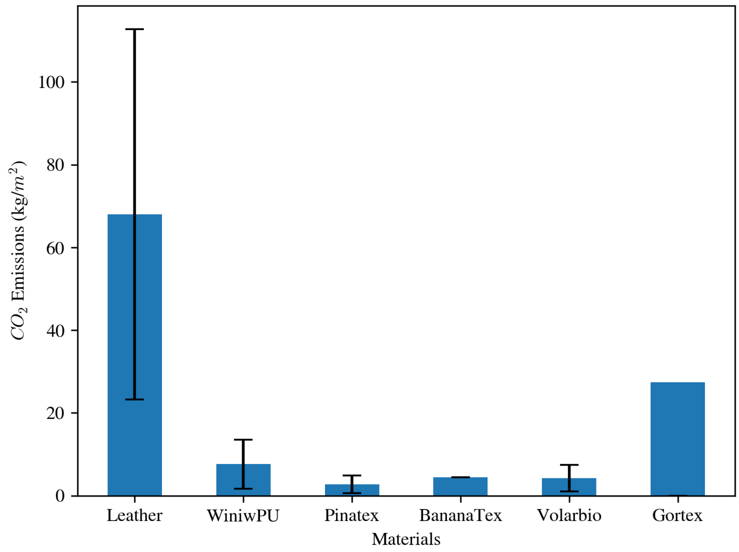


Figure 4. Carbon footprint of leather and leather alternatives in kg CO2 emissions per m^2 of material, based on an extensive literature survey. The author's own image.

- Recycled leathers
    - Aside from 'bio-based' and 'fossil-fuel-based' alternative leathers, it could be interesting to explore the use of recycled or reconstituted leathers for cricket ball applications, particularly for lower-grade cricket balls. Some companies already refurbish and recycle leather in the UK. As a cricket ball leather casing is in quarters or hemispheres (for 4-piece and 2-piece ball, respectively), the leather material sheet size required is relatively small in comparison to other industry applications (such as bags, upholstery and furniture). Hence, off-cuts or refurbished leathers from these sectors may be interesting sources of leather for lower-grade cricket balls. This would extending the material life and offer a route to circularity.

- Stitching and un-stitching are identified as challenging processes in terms of product circularity. And in many ways, it is the multi-component and intricate nature of cricket gear – including balls – that presents circularity challenges. Therefore, overcoming this through redesign may be significantly more impactful than simply selecting alternative sustainable materials.

Seam stitching

Functional requirements

- Bind the pieces of leather casing together
- Retain ball shape within required tolerances
- Provide a pronounced seam that enables skilled bowling (e.g. seam bowling, swing through differential shining/roughening of the ball hemispheres)
- Provide durability
- Can be hand stitched (Dukes, SG) or machine stitched (Kookaburra, SG)

Current materials

- Linen flax stitching thread

- Flax is a high-quality, strong and durable plant fibre with a significant history for high-performance applications.
- Flax linen thread is the stitching thread of choice for high-grade cricket balls
- Flax fibres have good moisture behaviour (with their yarns increasing performance when wet)
- Flax is predominantly produced in France (over 80% of the world's textile flax fibre)[28], with China and Russia also being major producers. A number of EU countries grow flax at scale. Ireland used to be a powerhouse of linen production (and the Northern Ireland Assembly logo are five flax flowers), though flax production in UK has diminished significantly since the 1900s due to increased costs and the declining fibre trade in the UK (with cotton mills in Northern England and jute mills in Scotland and wool mills across the country closing down) during that period. In addition, flax (and other bast fibre, such as hemp and jute) agro-processing requires 'retting', wherein the strong phloem fibres are allowed to naturally separate (enzymatically) from the woody outer bark using water and sunlight. Retting used to be traditionally done through water-retting in ponds, rivers and lakes – but this led to significant water pollution and eutrophication (algal blooms). Water retting practices were progressively discouraged or banned in the EU and field retting (leaving the harvested flax stems in the field for a few weeks) has become the norm, however, the climatic conditions in Ireland did not allow such field retting to naturally separate the fibres from the woody outer bark well, and consequently fibres were not of high quality (individualised into single fibres).
- Flax is already a very sustainable natural fibre, with each kg of flax fibre sequestering 1.4-1.8kg of CO2, and a 1 hectare field of flax sequestering c. 3-5 tonnes of CO2eq per year – comparable to or higher than that of some softwood forests.
- Flax fibres need to be extracted from the stalks (post-retting) through a series of mechanical processes, including decortication, combing, hackling, scutching, and thereafter spinning to producer yarns and plies. A few of these processing steps (which also apply to many other natural plant fibres) are described schematically below. These require an entire supply-chain and specialist equipment, which France/Belgium/Poland/Germany are equipped well for, but UK is currently not.

[28] Bourmaud, A., Beaugrand, J., Shah, D.U., Placet, V., Baley, C. Towards the design of high-performance plant fibre composites. Progress in Materials Science (IF = 39.6), 2018. 97: p. 347-408. https://doi.org/10.1016/j.pmatsci.2018.05.005

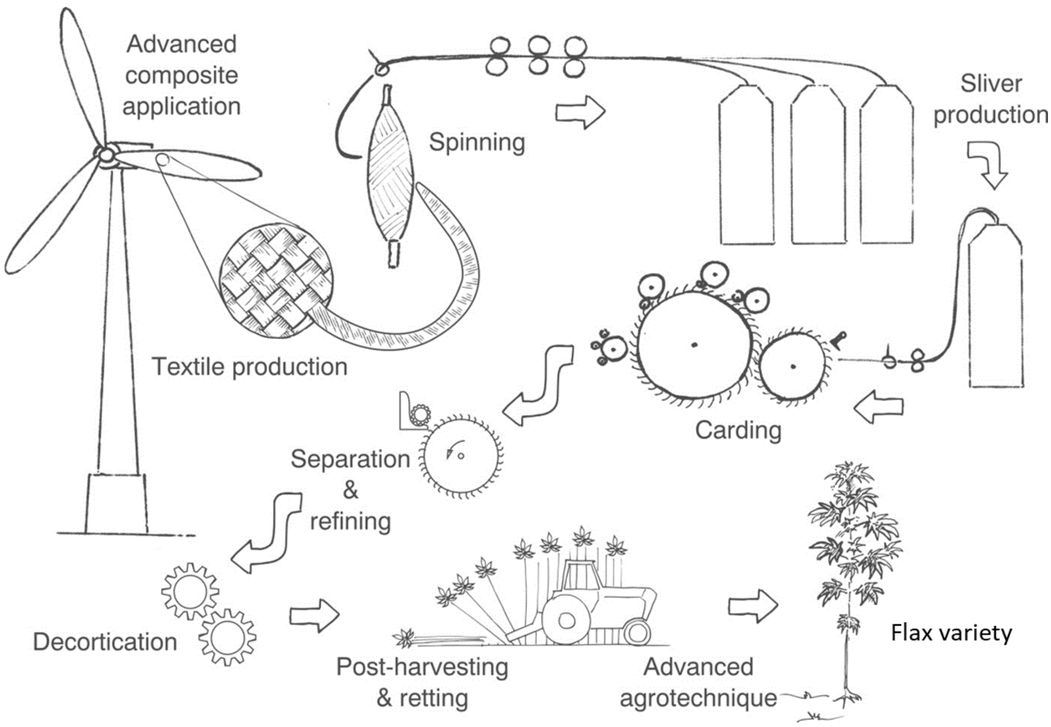


Figure 5. Value-chain and processing steps of natural fibre crops, such as flax, to progress from a plant crop to an extracted fibre, and then intermediate products (such as yarns, slivers and tows) and end-uses (such as textiles and composites). The author's own image [29].

- Cotton or nylon
    - Lower grade cricket balls may use cotton (a plant seed fibre) or nylon (polyamide; a fossil-fuel derived fibre). Both of these have significantly higher environmental impacts than flax (and other natural fibres). This is mainly due to cotton agriculture (use of pesticides and fertilisers, and requiring high quantities of water), as well as the thermo-chemical nature of processing nylon from petrochemically derived precursors.
    - Cotton, however, is a widely available natural fibre with over 25 million tonnes being produced annually. In comparison, c.5-6 million tonnes of nylon is produced annually, whereas c. 0.5 million tonnes of flax fibre is produced. Cotton and nylon can also be significantly cheaper than linen fibres.

Example alternative materials to explore

- Plant fibres
    - A range of different plant fibres are available for use as stitching threads. Examples from different plant origins/source are schematised in the below figure.

[29] Müssig, J., Amaducci, S., Beaugrand, J., Bourmaud, A., Shah, D.U. Transdisciplinary top-down review of hemp fibre composites: from an advanced product design to crop variety selection. Composites Part C, 2020. 2: 100010. www.doi.org/10.1016/j.jcomc.2020.100010

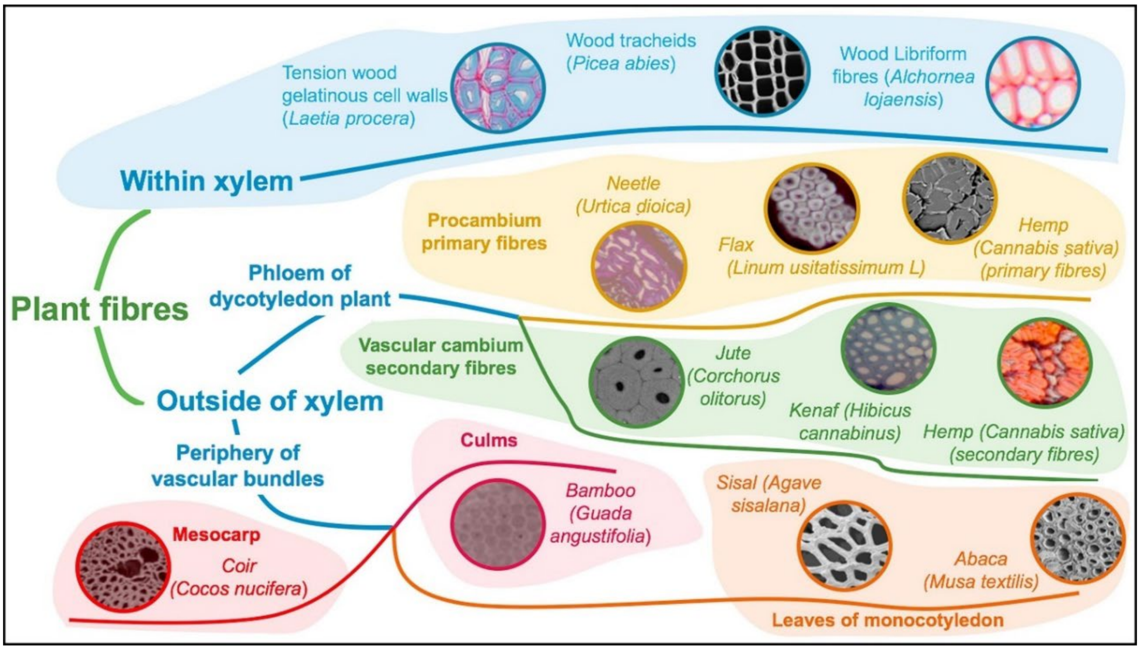
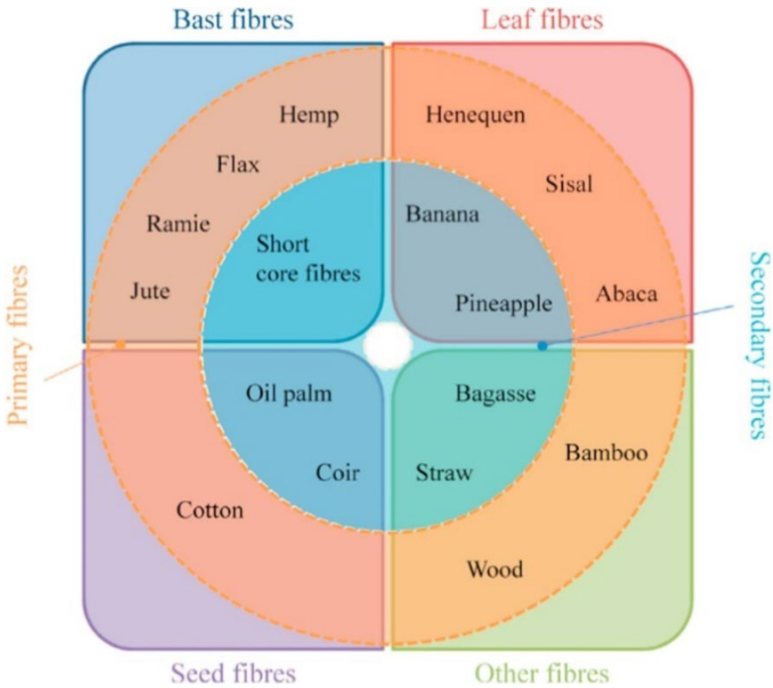


Figure 6. A plethora of plant fibres can be extracted from diverse plant species. Each fibre has a unique structure and properties. The author's own image.

- Plant fibres display different classes of fibres such as 'bast' (phloem), straw, seed, grass, leaf, and wood fibres. Due to their specific functions and location in plants, these fibres exhibit a range of structural properties, and consequently mechanical performances. For example, coconut mesocarps provide coir fibres which play the role of environmental and mechanical protection around the fruit, while hemp fibres are the supporting tissues of the stem, and cotton fibres are wrapped around the seeds in order to facilitate their spreading by the wind. Consequently, these fibres have diverse structures and properties. Invariably, fibres from the same category tend to bunch together in their material property profiles.
- Plant fibres can also be categorised according to their utilisation upon extraction. Primary plants (like flax, sisal, cotton, bamboo, hardwood/softwood trees) are cultivated specifically for their fibre content, while fibres from secondary plants (like pineapple leaf, coir, oil palm (empty fruit bunch), bagasse, rice straw) are a by-product from some other primary utilization. As secondary fibres are by-products or even waste products, the environmental impact is likely to be smaller in comparison to primary fibres. An LCA of a primary fibre would, for example, have to account for the environmental impacts associated with the agriculture of the crop, whereas as secondary fibres are waste/by-products, the system boundary of their LCA would not have to account for environmental burden associated with agriculture of that plant. Secondary fibres are probably less interesting as stitching threads, typically due to lack of availability of long fibres that can be produced readily into continuous yarns, although there are some exceptions (e.g. including Pinatex's pineapple leaf fibre yarn).



- Primary bast fibres in particular, such as flax, hemp and jute, may be interesting for stitching threads, and they have long illustrious histories in hard-wearing uses in naval sectors for ropes where fibre strength, durability and moisture behaviour are critical. Other fibres such as ramie and sisal are also interesting as stitch threads.

- Semi-synthetic fibres (e.g. viscose)
  - It may also be possible to use reconstituted cellulosic fibres, such as viscose Rayon, modal fibres, reconstituted bamboo fibres, to produce yarns and stitching threads.
  - This gives the opportunity to use waste resources from the agroforestry sector (e.g. from short wood fibres) to chemically breakdown the material to the basic polymeric building blocks (e.g. cellulose) and thereafter reconstitute these as an engineered fibre with reasonable mechanical properties.
  - As such semi-synthetic fibres are processed from renewable plant-derivative precursors though require some form of thermos-chemical processing, their environmental performance is intermediate to plant fibres (such as flax and pineapple leaf fibres) and polymer fibres (such as polyester and nylon).

Core

Functional requirements
- Low density (light weight)
- Shape retention upon repeated impact
- Springyness/bounce (elastic rebound properties)
- Precise moulded shape for the casing material to attach to
- Durability and uniform properties

Current materials
- Cork

- Used to be the material of choice for cores in cricket balls (and other sporting balls, including baseballs)
- Chosen for ability to absorb impacts whilst maintaining its shape. Cork is also lightweight and 'springy' due to its viscoelastic (time-dependent mechanical) properties, leading to good bounce.
- Harvested from the bark of Portuguese cork oak (*Quercus suber*) trees, typically of higher densities. Such cork trees absorb up to 3 times more CO2 when regrowing their bark after harvesting. [30] There is an increased availability of cork due to reducing demand for wine corks (due to polymeric and other corks becoming used), though demand for other sectors is increasing (e.g. building and construction sector and furniture sector).
- However, it takes 25 to 30 years for cork trees to mature. Thereafter, the tree bark can be harvested every decade, for up to 150 years, though the first two extractions almost always produce inferior quality cork. Climate change (and associated issues with disease, forest fires and infestations) poses a serious threat to cork oak forest conservation and the future supply of cork. [31]
- There is currently a huge missed opportunity to explore exploitation of used or recycled cork for cricket ball cores.

- Rubber and cork-rubber composites [32]
  - For the past several decades rubber is more commonly used alongside cork, in a 'moulded composite' in the cores of balls (in cricket, as well as in baseball, for examples). Cork is a relatively light-weight material, but there can be natural variability in its properties. The addition of rubber can improve standard/quality (and reduce variability between cores of cricket balls). Rubber is also cheaper, reducing the material costs for ball production.
  - A precise mix of cork and rubber granulates are moulded to an exact spherical form. The 'mix' (e.g. 75% cork-25% rubber, 50% cork-50% rubber and so on) will affect properties such as 'springyness' (elastic rebound properties/rebounce), shape retention upon repeated impact and so on.
  - There is significant R&D around rubbers for sporting applications – these are used extensively and sometimes exclusively for a range of balls – from footballs to rugby balls, to tennis balls, to baseballs and cricket balls. Consequently, a range of formulations are possible. It is common to combine a mix of 'natural rubber' (NR) and 'synthetic rubber' (Isoprene Rubber (IR) or Styrene Butadiene Rubber (SBR)). Natural rubber (NR) accounts for 40-50% for all rubber produced worldwide. NR is produced from the latex collected from the *Hevea brasiliensis* tree – grown extensively in Thailand, Malaysia and India. NR has impressive mechanical properties, with strength and tear resistance increasing upon straining/stretching (i.e. when stressed more). The same basic polymers in NR can be produced synthetically (from fossil-fuel feedstocks) – IR and SBR are possible variants of

[30] https://www.tinyecohomelife.com/is-cork-environmentally-friendly
[31] https://ec.europa.eu/eip/agriculture/en/find-connect/projects/adapt-your-cork-oak-forests-resist-forest-fires
[32] https://onlinelibrary.wiley.com/doi/full/10.1002/jst.8

synthetic rubber. SBR is the most widely used synthetic rubber as its properties are comparable to NR. Natural rubbers (NRs) however can be relatively more expensive and have natural variability in properties compared to synthetic rubbers. While synthetic rubbers are prone to oil-price fluctuations, NRs can be subject to climate issues (in terms of harvesting latex from trees), and supply-chain issues (e.g. in trying to stop the raw material from 'going off' due to its short natural shelf-life), leading to some variability in properties. It is common to mix proportions of NR and SBR (e.g. 25%-75%) to achieve desirable functionality (e.g. strength)-price profiles.

- Lower-grade cricket balls may completely use rubber (and no cork) for the cores.
- In the UK companies like Oxbridge Cricket Balls, Tiflex and the Flexible Cork Company[33] are designing and manufacturing highly advanced rubber bonded cork materials.

Example alternative materials to explore

- Circular cork - Recycled/waste cork granulates
    - As the norm is to produce moulded 'cork-rubber composite' cores using granulated cork and rubber compounds, there is a huge opportunity to use recycled cork or post-first-use (e.g. from wine stopper, furniture or building industry waste) as granulates for the moulded cores.
    - With a move towards bio-based materials across industries, including the construction sector and the furniture sector, where sheet or bulk forms of cork are important/desirable, there is an opportunity to recycle them at end-of-life, as part of cascading use philosophy/design, as granulates for ball cores.
    - A number of companies, such as Recorked UK[34] and ReCORK[35] are looking at recycling corks (including wine corks, off-cuts) for reconstituted and moulded cork products. These can be granulated for moulding with rubber into a composite. Cork also has very interesting thermal properties, in that it can expand (irreversibly) when heat is applied and therefore can also be moulded into products easily.
    - A range of recycled cork-rubber mixes can be explored, particularly focussing on natural rubbers NRs (rather than SBRs) to achieve specific core properties.

- Coconut palm wood
    - Coconut timber is a hardwood-substitute typically from farmed plantations of old coconut palm trees. Coconut trees bear fruit until 70 years of age, after which they are felled and a new sapling is planted. Several million palms are felled annually, and the trunks are waste by-products that can be useful wood resources. As coconut trees are monocots (like bamboo), they don't have annual rings, rays, heartwood or branches and are 'free' from imperfections. Coconut timbers are increasingly being considered as alternative timber resources. They come in a variety of densities and their properties are comparable to corks. In particularly, they could be granulated to make palm wood/rubber composite cores.

[33] https://www.oxbridgeballs.co.uk/pages/about-us
[34] https://recorkeduk.org/
[35] https://recork.com/us/

- Agro-forestry waste granulates – e.g. woody barks, hemp shives, rice husk, straw, bamboo
    - Given that cork is commonly granulated to mould the core material, the morphological structure of the filler is not significant. It is conceivable that other hardy and lightweight bioresources with similar properties may be alternatives. The agro-forestry sector and end-of-life products may be a useful resource. Woody barks, hemp shives (also referred to as shivs or hurds, and 2-3 times the volume of hemp shives is extracted from a hemp stalk in comparison to the higher-value long fibres), rice husks and shredded straws and bamboos may be interesting granulate materials for moulding with rubber for composite cores.
    - Again, the mix (ratios of materials) and bonding between the rubber and these natural granulates will be important areas of work to achieve the desired property profile for the core.

Fibrous wrapping materials for mid-sole core (worsted yarns)

Functional requirements
- As with core materials
    - Modulating springiness/bounce (elastic properties)
    - Shape retention upon repeated impact
    - Low density
    - Ductile
    - Able to be tightly wound around the core

Current materials
- Worsted wool yarn wrapping
    - High quality, lightweight long-staple pasture type of wool from specific English and New Zealand sheep breeds is used for wrapping the core.
    - Multiple (3 to 6) layers quilted between layers of cork, wrapped around a cork core inside leather casing, with or without tension. The yarn is typically wrapped with a machine, but can be hand-wrapped.
    - An essential feature of worsted yarn is straight, parallel fibres. In particular, long (c. 50mm length) and fine (small diameter), and therefore high quality, wool fibres are spun to created worsted yarns.
    - Wool is derived from sheep. It can be a waste product from the meat industry, but more often sheep are bred specifically for their wool. Consequently, unlike leather which can be referred to as a waste product, if not a co-product or by-product of the meat industry, wool fibre cultivation has very high environmental impacts, as sheep are ruminants. For example, wool has an even higher carbon footprint and embodied energy than cotton – than the highest environmental impact plant fibre, as well as polymeric fibres like polyester, nylon and acrylic.
    - Wools from other species (e.g. cashmere from goats) may already be actively used, especially for lower-grade cricket balls. These still present similar environmental challenges to sheep wool.

Example alternative materials to explore
- Recycled wool

Worsted wool yarns could also be produced using wool fibres (of sufficient length – c. 50mm) reprocessed from another primary product (e.g. from the carpet or clothing industry). This is particularly noteworthy as the dyes and other surface properties of the wool are not relevant, hence mixed fibres can be used. Moreover, discrete lengths of fibres of ca 50mm are acceptable for the processing of worsted yarns, and this is also true for recycled wool fibres.

- Blending wool with other fibres
  - Wool (including recycled wool fibres) can be blended with other fibres, such as polyester/nylon (of variable cut lengths of 75-100mm) can also be used to produced worsted yarns
  - For worsted yarns, short natural fibres (such as cotton) are not suitable, but long natural fibres may be possible.
- Viscose/Rayon (Lenzing Tancel)
  - Reconstituted cellulosic fibres which are semi-synthetic fibres, such as viscose, Rayon, modal and reconstituted bamboo fibres, may also be used to produce worsted yarns. These can have particularly interesting ductile properties, viscoelastic and energy absorbing properties and therefore shape retention for the cores, however may impact the springiness/bounce of the core.
- Cationic polyester and nylon (virgin or recycled)
  - Synthetic polymer fibres derived from fossil-fuel resources such as polyester and nylon can also be used to produce worsted yarns. They have lower environmental impact (in terms of carbon footprint or energy use) than sheep wools, and are produced in significantly higher quantities worldwide.
  - It maybe be particularly interesting to use recycled polyester fibres (e.g. from beverage bottles) or nylons for such worsted yarns. This would be an interesting circular use story.

3. Gloves and Pads

This section discusses the conventional materials used for gloves and pads, as well as potential sustainable alternatives to these materials. Gloves and pads are looked at together for a number of reasons. Firstly, they are both personal protective equipment (PPE) products that are worn by players, and their associated BSI standards do not specify materials. In addition, both are highly intricate, multi-material products. The relevant performance criteria are also similar: light-weighting, impact absorption, durability (abrasion and wear) over time, breathability and moisture behaviour, colour fastness and ability to incorporate advertising features.

For batting gloves, BSI 6183-4:2001 (‘*Protective equipment for cricketers. Gloves for batsmen*’) is the relevant standard. For pads, BSI 6183-3:2000 (‘*Protective equipment for cricketers. Leg protectors for batsmen, wicketkeepers and fielders, and thigh, arm and chest protectors for batsmen*’) is the relevant standard. The BSI standards principally specify the dimensions and norms for different types of cricket gear PPE depending on the player’s characteristics (e.g. sex, height), the effectiveness of the restraint system (to ensure it is in designed to remain in place during normal play and impacts), as well as impact performance.

Dr Lilian Sanchez-Moreno has carried out product disassembly exercises for gloves and pads [36] as part of the Vegan Leather Cricket Gear and Circular Cricket Gear projects which illustrate and account for the various components and typical materials used for these products.

Here, for simplicity and to avoid significant repetition, as well as to acknowledge crossovers and overlaps, component materials with similar functions are grouped together when exploring potential sustainable alternatives. For example, polypropylene (PP) finger/thumb inserts in gloves and polystyrene (PS) knee caps in pads are grouped under 'High impact resistance, rigid, moulded components'; whereas, leather in the palm of gloves and polyester meshes in gloves and pads are grouped under 'Breathable linings and skins'.

3.1 Components materials: conventional and their potential sustainable alternatives

High-impact resistant, rigid moulded components

Functional requirements

- High-impact resistance and toughness/strength
- Light weight
- Ability to be moulded to precise shape

Current component materials

- Polypropylene (PP) finger/thumb inserts (gloves)
- Polypropylene (PP)/Polystyrene (PS) connectors for straps on pads
- Polystyrene (PS) kneecap (pads)
    - Both polypropylene and polystyrene are petrochemically-derived thermoplastic polymers that can be processed through injection moulding (high-volume, low cost manufacture). Injection moulding implies processing at temperatures between 150-200C. Presumably these are bulk processed/ordered through subcontractors, probably in the Indian sub-continent or China/Southern Asia.
    - These are used in the un-filled form (i.e. no filler is used, just neat polymer).
    - These components are covered (e.g. by fabric) in the product and are not 'visible', hence their aesthetic properties (e.g. colour) are not important.

Example alternative materials to explore

- Recycled synthetic thermoplastics
    - An easy win is to consider the use of recycled PP or PS, following a first life in some other product. As visual properties of the components are not important, mixed 'waste' resources could be used for the recycled thermoplastic components. PP and PS are widely used injection-moulded thermoplastics and particularly product from the food and packaging industry could be used in their second life for this product.
- Semi-synthetic or Natural Biopolymers
    - Polylactic Acid (PLA)

[36] https://cfsd.org.uk/wp-content/uploads/2023/05/Final-Streamlined-LCA_batting-pads.pdf

  - An increasingly common biopolymer derived from corn, beetroot and other bioresources. This thermoplastic can be processed like PP/PS (including injection moulding and 3D printing) and has good mechanical properties. It is also compostable (not home compostable, but in an industrial facility) at its end of life.
- Sugar-based plastics
  - Plant materials, particularly cell walls, are made from polysaccharides (which are carbohydrates). Cellulose and hemicellulose are the two most abundant cell wall polysaccharides; they are loosely referred to as 'sugars'. Hemicellulose has mainly xylose and cellulose mainly glucose.
  - A range of bioresources, such as corn, beetroot, sugarcane bagasse waste, can be used to produce sugar-based plastics with good properties. They are prone to be more moisture sensitive.
  - Sugar-derivatives, such as furans and isosorbides, are most commonly investigated for the synthesis of bioresins. Furans can be extracted from cellulose (hexose; e.g. converted in hydroxymethylfurfural) or hemicellulose (pentose; e.g. converted into furfuryl alcohol), and this is currently done commercially.
  - The global market size for furfuryl alcohol is c. 0.3-0.5 million tonnes. Their aromatic characteristics lead to high flame retardance/temperature resistance, including for the resulting epoxy resins. However, this also implies that high temperatures may be necessary during curing.
- Starch based thermoplastics
  - A range of bioresources, such as cassava, potato, corn, can be used to produce sugar-based plastics with good properties. They are prone to be more moisture sensitive.
- Seed-oil based plastics (Cashew-nut, soybean oil etc)
  - Globally, plant seed oils are the most widely used renewable raw material resource in the chemical industry, with established applications in paint formulations, coatings, plasticizers, lubricants, surfactants, cosmetic products, and even polymers.[37]
  - The global annual production of plant seed oils was around 186 million tonnes, mainly palm oil (33%), soybean oil (29%) and rapeseed oil (15%)[38,39]. In comparison, global thermosetting polymer production is around 35 million tonnes [40], of which only 2-3 million tonnes[1] is accounted by epoxy resins, the majority (40-50%[41]) of which find applications as coatings. Therefore, abundant amount of non-nutritional feedstock exists for the purposes of resin applications.
  - Plant seed oils compose of mostly (95%) triglycerides, which are units of three long chain fatty acids joined at a glycerol juncture. Due to the presence of

[37] Auvergne et. al., Biobased Thermosetting Epoxy: Present and Future, Chem Revs, 2014. 114: p. 1082−1115.
[38] https://www.statista.com/statistics/263933/production-of-vegetable-oils-worldwide-since-2000/
[39] https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf
[40] https://www.prnewswire.com/news-releases/global-thermosetting-plastics-market---segmented-by-type-industry-and-geography---trends-and-forecasts-2015-2020---reportlinker-review-300145372.html
[41] https://ihsmarkit.com/products/epoxy-resins-chemical-economics-handbook.html

various fatty acids, several permutations of triglycerides may exist in the oil (which may need purification); and indeed, different seed oils have different combinations of fatty acids (and therefore triglycerides).

- The three key chemical parameters influencing the amenability of the seed oil for (epoxy) polymer production and the resultant polymer properties are:
  - The length of the carbon chain of the fatty acids,
  - The degree of unsaturation of the fatty acids (i.e. the presence of carbon-carbon double and triple bonds, which are ‘reactive sites’ and can be ‘functionalised’),
  - The stereochemistry of the reactive unsaturated/functional sites on the fatty acid chains (which can hinder or facilitate functionalisation or polymerisation). The triglyceride structure and multiple internal functionalities (as opposed to epoxide groups at the ends, as is the case in man-made epoxy polymers) may lead to poor yield, slow/incomplete reactions, and low glass transition temperature (less than 30-50C, even sub-zero).
- There are three principal approaches in producing epoxy polymers from seed oils:
  - Direct polymerisation: Some naturally-occurring epoxy-functionality containing fatty acid triglycerides exist (e.g. Vernonia seed oils with 80% vernolic acid)[42]. *This route is very challenging.*
  - Functionalisation of the triglycerides (e.g. epoxidation of C=C sites on the fatty acids) followed by polymerisation. *This route received much attention since the 1960s.*
  - Chemical transformation of triglycerides into monoglycerides and their monomers, and their subsequent functionalisation and polymerisation. *This route is currently widely studied and has yielded fruitful results.*

- Lignin-based plastics
  - Lignin is found in all plant materials - it is the second most abundant renewable carbon source on Earth (>300 billion tonnes), however significantly less is annually available/produced/synthesised for commercial applications.
  - Lignins (and ligno-sulphates) are a by-product of the pulp and paper-making industry. The pulping method used influences the form and purity of lignin. Kraft/sulphite pulping processes involve hydrolysis in an acid/basic medium producing degraded/highly modified sulphonated lignins, whereas the cellulose process involves alcoholic pulping leading to high purity, non-sulphonated lignins.
  - Lignin is a category of natural biopolymers with a wide range of molecular weights, usually having aromatic/phenolic functionalities (which confer good thermostability to the resulting resins but may also require high processing/ curing temperatures).

[42] http://www.thescitech.com/admin/includes/abstractpdf/2014-10-1254880cb0e43dc.pdf

- While 70-100 million tonnes of lignins/ligno-sulphates are produced annually, >98% are burnt for energy recovery. <2% (1.3 million tonnes) of the lignin/ligno-sulphates are isolated and sold - major uses are as plasticisers (for concrete) and dispersants (e.g. of solids and dyes into water) and binders and adhesives (e.g. in particle boards).[43] Value-added products from lignin are a current market driver, which presents opportunities for thermosetting resin production.
- Three principal approaches in producing lignin-based bioepoxy resins:
    - Blending of natural/modified lignin and conventional epoxy resin (e.g. to improve heat resistance), sometimes forming interpenetrating networks
    - Modification of lignin (and lignin-derivative compounds) before epoxidation,
    - Direct epoxidation of lignin
- Currently, multiple research groups are looking into lignin-based biomass resources for polymer production, including bioepoxy, as adhesives[44] (alternatives to formaldehyde-based wood adhesives), coatings[45], and resins – including a patented process[46] (by Hitachi Ltd) for a recyclable epoxidised lignin resin and a lignin-based acid anhydride curing agent, yielding a glass transition temperature of 200C (though used mainly as a varnish for 'small-scale' applications, e.g. semiconductors).
- However, even though lignin is under intense investigation, these approaches are not a mature technology yet. The chemical structure of lignin is very variable (depending on many parameters e.g. type of wood, extraction process), and complex (various chemical linkages) making the processing difficult and often times low yield[47]. This is why many researchers have explored lignin-derivative model compounds (such as vanillin, eugenol, and guaiacol) as they have a constant structure, but they are obtained at low yields from lignin.

- Natural resin (terpine and rosins) based plastics
    - Many plants and trees secrete natural resins (e.g. as a protective response to injury)
    - Most plant resins are composed of terpenes (which are structurally related to isoprenes e.g. natural rubber). Rosin (consisting of diterpenes) is solid resin from which volatile terpenes have been removed (e.g. by heating, distillation).

- Short-fibre biocomposites
    - The various plant fibres introduced in a previous section as alternatives to synthetic fibres can be used a fillers or reinforcement materials in polymeric materials to produce composites. Short-fibre composites in particular, with very short fibres (e.g. hundreds of micrometers in length in injection-moulded composites) or moderately short fibres (sub-25mm in length for non-woven materials in compression moulded or liquid resin moulded) can be used to produce a range of different products. With

[43] https://www.reuters.com/brandfeatures/venture-capital/article?id=4789
[44] http://pubs.rsc.org/en/content/articlelanding/2018/gc/c7gc03026f/unauth#!divAbstract
[45] https://www.sciencedirect.com/science/article/pii/S030094401730382X
[46] https://patentimages.storage.googleapis.com/5c/3a/dd/423743b249385d/US20110024168A1.pdf
[47] https://pubs.acs.org/doi/abs/10.1021/acs.chemrev.7b00588

fibre volume fractions typically in the range of 20-30weight% for injection moulded composites (i.e. 20-30% of the composite by weight is the bio-based fibre, with the other 70-80% being a polymer matrix) , and 30-50 weight% for non-woven random fibre composites (i.e. 30-50% of the composite by weight is the bio-based fibre, with the other 50-70% being a polymer matrix) have mechanical properties higher than that of the base polymer and environmental impact less than the base polymer. Recycled thermoplastics (such as recycled PP) or bio-based and biodegradable thermoplastics (such as PLA, PBS and PHA/PHB) can be used as matrices for these natural fibres. Thermoset resins, including bio-based thermoset resins such as those derived from plant seed oils (cashew nut, canola, soybean and so on) or furfuryl alcohol, amongst others may be used.
- The use of primary fibres (such as flax, jute, hemp) or secondary fibres (such as pineapple leaf fibres, date-palm fibres) would influence the resulting composite properties. Typically, primary fibres will perform better mechanically, but have a relatively higher environmental impact, though still less than the polymer on its own, or if a synthetic fibre reinforcement were to be used.
- Waste fibres, such as end-of-life denim cotton or carpet wool, may also be suitable reinforcements for such short-fibre composites.

Summary
- A large number of potential alternatives have been presented in this section. It is perhaps useful to emphasise that **seed-oil based plastics, lignin-based plastics** and **natural resin based plastics** are not yet mature markets, though have attracted a large amount of research. In comparison, **PLA, sugar-based plastics and starch-based plastics** are strongly emerging material sectors. Similarly, the **recycled synthetic plastics** sector and the **short-fibre biocomposites** sectors are fairly mature sectors in comparison to the previously mentioned material alternatives. These should be explored in further depth.

High-impact resistant, rigid components

Functional requirements
- Absorb impact energy
- Tough and strong
- Light weight

Current materials
- Cane (pads)
- Paperboard (pads)
    - The specifications and key characteristics of cane and paperboard used in pads are unclear, hence detailed discussion of alternative materials is challenging. Both cane and paperboard are internal components of pads, therefore aesthetic properties are not relevant. Cane is used as strips whereas paperboard is used in the form of sheets.

Example alternative materials to explore

- Waste or short-length timbers
    - Timber is a vastly under-utilised natural resource, with over 50% of wood harvest annually being used for wood fuel in its first life (i.e. straight after harvest). In England, over 80% of hardwood annually is used for bioenergy, and 50-60% of softwoods are used for pallets or fencing. Consideration of cascade use strategies is particularly relevant from a circular design perspective.
    - Short-length timbers or waste timbers are typically landfilled or incinerated. Strips of these may be potential alternatives to cane. The species, density, stiffness, strength and energy absorption properties of the timber will be important.
- Waste plastic materials (e.g. PVC piping)
    - Plastic reuse and recycling rates are low globally. Waste plastics in thick extruded sheet or tube form (e.g. PVC plumbing pipes) could be useful alternatives for cane strips in pads. Plastic is light-weight, and can have the necessary strength and energy absorption characteristics required for padding.
- Recycled cardboards including corrugated cards

    The specifications and characterisations of paperboard used in pads is unknown and unclear. Nevertheless, it is envisaged that the addition of some recycled paper content or adoption of certain structural forms (e.g. corrugations) can help attain the desirable properties for this application, rather than the use of virgin paperboard.

Cushioning Foam and Filling

Functional requirements

- Absorb impact energy
- Deform and retain shape
- Light weight

Current materials

- High-density Polyurethane (PU) Foam
    - Foam element used to form the main energy-absorbing skeleton of modern pads.
    - PU (which has been discussed previously) is a synthetic material derived from non-renewable natural resources e.g., oil, which contribute to global warming and have limited end-of-life disposal routes. The volatility in prices of oil-based polymers also influences its pricing.
    - Production of such polymeric materials comes under REACH regulations – e.g. isocyanates (critical to the manufacture of PUs) are toxic, classified as CMR (Carcinogen, Mutagen and Reprotoxic), and are already regulated by

Environment Protection Agencies and Occupational Safety and Health Administration; this may tighten further.[48]

- They are strong and light-weight, and the chemistry of polymer foam materials is highly tailorable – this enables the production of a range of foam materials that can meet diverse specifications and criteria for the various protective pad applications.

- Wadding (cotton/polyester blends)
  - This is used as a fluffy filler material to give 'shape' to the product, and possibly absorb some energy upon impact without adding substantial weight to the product.

Example alternative materials to explore

- Non-isocyanate PUs (NIPUs)
  - The production of conventional PUs requires the use of two main components: polyols and isocyanates. There is also an effort to move towards non-isocyanate PUs (NIPUs), given the toxic nature of isocyanates and for worker safety. This is particularly exciting and disruptive, and the industry and regulations are changing towards this direction[49].
    - Bio-based NIPUs and polyhydroxyurethanes can have properties suitable for rigid and flexible foams.
    - Example feedstocks would include, bio-based trimethylpropane and pentaerythritol or Sorbital (sugar alcohol)-based polyols, which are cured with conventional diamines (rather than diisocyanates). Reasonable mechanical properties are possible already.

- Bio-based PUs (Bio-PUs)
  - As discussed in a previous section (on Coatings), Bio-PUs are an emerging industry for flexible and rigid foams also.
  - There are a number of examples of bio-based rigid and flexible polyurethane (PU) foams, such as Baymer®, Desmodur®, Elastoflex® E by Bayer, SPF, SIP and Boardstock from Huntsman, and WALLTITE and Elastospray from BASF, and Eurowall®+ insulation from Recticel BiOH® and Agrol® soybean oil-based polyols for foams from Cargill, Elmira's ExaPhen Polyols based on Cardanol (cashew nut seed liquid).
  - So far, these have found applications in construction (insulation), automotives (instrumental panels, headliners, hood-liners, front panels and

[48] Rokicki, G., P.G. Parzuchowski, and M. Mazurek, *Non-isocyanate polyurethanes: synthesis, properties, and applications.* Polymers for Advanced Technologies, 2015. **26**(7): p. 707-761.
[49] Blattmann, H., M. Lauth, and R. Mulhaupt, *Flexible and Bio-Based Nonisocyanate Polyurethane (NIPU) Foams.* Macromolecular Materials and Engineering, 2016. **301**(8): p. 944-952.
Weyand, S., H. Blattmann, V. Schimpf, et al., *Structure-property-glass transition relationships in non-isocyanate polyurethanes investigated by dynamic nanoindentation.* Materials Research Express, 2016. **3**(7).
Schmidt, S., N.E. Goppert, B. Bruchmann, et al., *Liquid sorbitol ether carbonate as intermediate for rigid and segmented non-isocyanate polyhydroxyurethane thermosets.* European Polymer Journal, 2017. **94**: p. 136-142.

interior door panels, as well as seating), furniture and bedding, and footwear (sports shoes)

- A list of key producers include:
    - BASF - *important producer for the semi-rigid/rigid foam market*
      BASF has been working on BPUs for a while. They have a number of patents, including on rigid BPU foams based on natural oils or natural carbohydrate feedstocks for polyols. They are also an OEM partner of Ford Motors', supplying them with castor oil based semi-rigid PU Foams (e.g for their 2012 Ford Focus and 2018 Ford Fusion instrumental panels); although the bio-content of this foam is around 10%. This product is under the tradename Elastoflex® E. They have ongoing collaborations (since 2009) with Corbian Purac to develop bio-based succinic acid (Succinity®) for PU foams, amongst other products.
    - Cargill (who also acquired Biobased Technologies) - *leading biobased polyol maker for the flexible foam market* produce BiOH® and Agrol® soybean oil-based polyols for flexible (and rigid) foams. These polyols have bio-content ranging between 80-100%, with the resulting foams having bio-content between 5 to 20%.
    - Elmira's ExaPhen Polyols
      Cardanol (cashew nut seed liquid) based aromatic and Mannich-based polyether polyols for rigid BPU foams. These can be sprayed or cast. Polyol bio-content ranges between 70-100%, and resulting foam bio-content between 10 and 30%.
    - The Dow Chemical Company
      Through their RENUVA™ Renewable Resource Technology, they produce natural oil based polyols, mainly soybean oil, which can be used for flexible and rigid foams, including as co-polyols.
    - Mitsui Chemicals (and SKC merger)
      They have held patents and developing BPU foams using castor oil based polyols
    - Rampf Ecosystems
      Are developing a rapeseed oil based polyol for rigid foams
    - Arkema
      Are developing Vikol 1/2 polyols for polyurethane foams, based on epoxidized soy oil
    - Huntsman
      Are developing JEFFADD™ Bio-Based Polyol for Polyurethanes foams (flexible and rigid)
    - Covestro (Bayer MaterialScience)
      Are developing BPU coatings (not foams). What is notable is that it is sourcing bio-succinic acid from a company called BioAmber; and this bio-succinic acid can also be used for polyols for foams.

- PLA-based foams
    - PLA biopolymers derived from sugars from corn or beetroot could be used to produce foams. Their density can be tailored to improve mechanical properties.

- Waste fibres from agriculture or fruit harvest (date palm leaf, pineapple/banana leaf)
    - Instead of energy intensive cotton and polyester for wadding, waste fibres from the agriculture, fruit harvest (banana/pineapple/date pal leaf) or food industries could be used a fluffy fillers.
    - Shredded textile waste (including cottons and polyesters amongst other fibres) could be used as fillers

Linings and Skins

Functional requirements
- Breathability
- Grip and comfort
- Moisture performance
- Abrasion performance and good wear properties

Current materials
- Leather (gloves)
    - While Pittard's leather palms are commonly used for batting gloves, it is noted that there appears to be a preference for chamois leather for wicket-keeper gloves.
    - Lower grade gloves may use sheepskin or bovine leather
- Breathable polyester meshes (gloves and pads)
- Cotton linings (pads)

Example alternative materials to explore
- Alternative leathers
    - A number of alternative leathers were discussed in an earlier section on cricket ball casings – the discussion is also relevant here.
    - Synthetic chamois leathers
        - There are synthetic chamois leathers available, typically produced from PVA (polyvinyl alcohol) or viscose – both are biodegradable polymers; PVA is commonly used in the form of wood glue, while viscose is derived from wood celluloses. 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).
- Recycled polyesters (Bottle to Fabrics) – as discussed previously
- Semi-synthetic (e.g. Viscose) or Natural fibres – as discussed previously
- Upcycled materials
    - Upcycling: Gray Nicolls developed Off-Cut Batting Gloves in 2019
        - The batting gloves incorporate upcycled pieces of material to form a multi-coloured glove. To avoid substantial reprocessing (e.g. to remove colour) of the off-cuts, and therefore avoid embedding more

carbon and additional costs, the use of unsorted (by colour) off-cuts is critical – which leads to this multi-coloured product.

- Retailed for £45: cheaper than many comparable gloves[50]
- The gloves breached ICC *Clothing and Equipment Rules and Regulations* specifying that the colour of gloves should be more than 50% white and colour match the team's uniform[51] [52]. The gloves were banned from being issued in the professional level. However, the gloves are being sold for use in the recreational game. It is noteworthy that the gloves were banned for colour/broadcasting contraventions, not because they were upcycled.
- This example may also encourage end-of-1st-life product return schemes where players may return batting gloves to producers to re-use elements of their own gloves for future products, particularly as branding is likely to be retained.

4. Discussion

The author has explored the range of materials that go into producing cricket balls, gloves and pads – highlighting the complex, intricate, multi-material nature of cricket gear. Current and some alternative materials for balls, gloves and pads have also been mapped visually on the materials property (Ashby) chart (see below). This in part demonstrates the diverse property profiles of materials that are combined to offer the cricket ball its product properties.

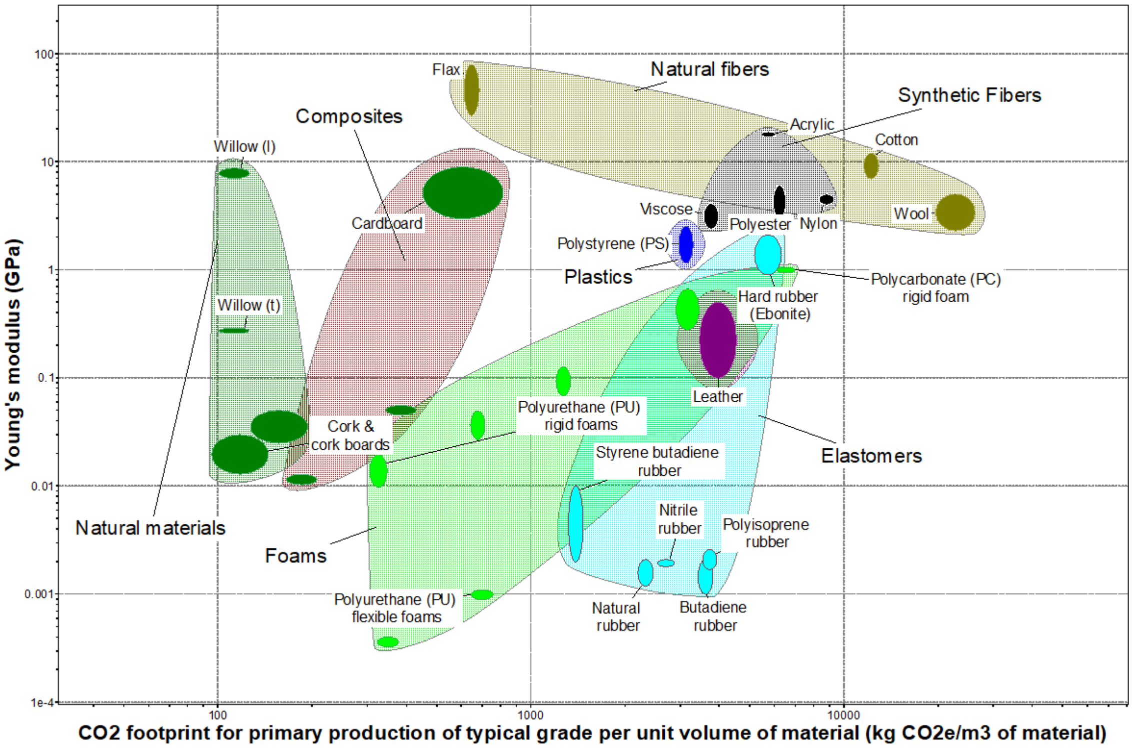
As per the author's knowledge, this is a scientific first, and helps illustrate the range of materials used, where opportunities might be, how they generally compare in performance. In this particular iteration of the materials property selection (Ashby) chart, we have added Young's modulus (a mechanical property representing stiffness or ability to resist deformation) on the y-axis, and added carbon footprint per unit volume of material on the x-axis. For example, one can use the chart to compare the performance of materials e.g. flax has a much higher Young's modulus but much lower environmental impact than cotton, wool, acrylic, polyester or nylon.

The author has also shown groupings of materials - such as foams, composites, natural materials, elastomers (rubbers) and natural and synthetic fibres. An interesting observation is that all materials are polymeric/composites in nature, and consequently lightweight. Lightweighting is therefore clearly a property that is prioritised for cricket gear. Secondly, we find an interesting binary: most materials used in cricket gear are completely natural (c. 100% renewable content), such as leather, cork, wool, flax linen, or completely synthetic (ca 100% fossil-fuel derived), such as polyester (PE) and polyurethane (PU). The only exceptions

[50] https://www.gray-nicolls.co.uk/products/off-cuts-pro-batting-gloves
[51] https://www.cricket365.com/gear/is-this-the-worst-thing-the-icc-has-ever-done/
[52] https://icc-live.s3.amazonaws.com/cms/media/about_docs/57d2c4c0b2222-19_Clothing%20Regulations_22%20Sep_2016.pdf

of materials that lie in between this continuum are rubber for the core (which combine natural rubber and synthetic rubber) and paperboard (which include some glue content).

The categories of the forms of the materials is also interesting. The materials are typically in the form of foams (padding), fibres and textiles, sheets (leather casing) for wrapping, or bulk materials (blade of bat, core of ball, kneecap) when a specific defined shape is needed.



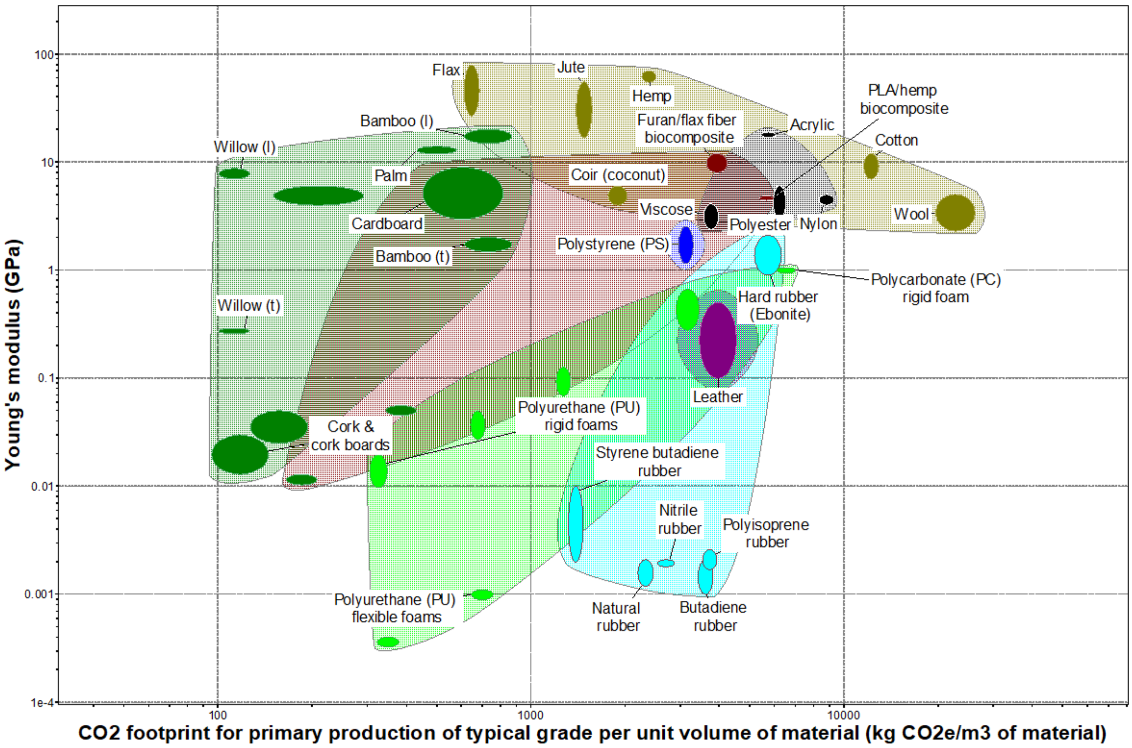


Figure 7. Materials property charts (Ashby charts) illustrating the range of conventional materials used in cricket balls, gloves and pads (TOP). In the BOTTOM graph, alternative materials are also included.

- **Further research – analysis, (re)design and testing**
  Following this initial exploratory research, it is evident that more dedicated research into the substitution of each component material for the various products can and needs to be carried out. This includes a feasibility analysis which would consider cost, manufacturing, supply-chain and environmental impact implications, but also the technical possibilities and specifications/performance levels that can be met.

  There is a need to promote materials development that reduces environmental impact, in particular the substitution of fossil-fuel derived plastics. This report highlights that a lot of key materials used in the manufacture of cricket equipment are oil-derived and/or plastic based. For example, materials such as high-density foam (HDF), synthetic rubber, polyurethane (PU) and polyvinyl chlorides (PVC), polyester (PE) lining are all derived from petroleum by-products. For example, there been a transition away from the use of leather to various polymers in batting and wicket keepers pads

- **Further investment in R&D needed to explore sustainable alternatives to traditional materials**
  - There are conservative attitudes towards innovation within cricket that have contributed to the preservation of traditional materials. Stakeholder attitudes needs further research – and exploration of how these attitudes can be changed.
  - There is a need for further research into the overall embedded carbon associated with the production of various cricket gear that is produced generally speaking in Northern India and Northern Pakistan and a widescale review across manufacturers, as well as sharing of best-practices
  - More industry-academic partnerships can enable exploration of material and design innovations through active experimentation.

- **Need to evaluate regulatory and standards that may be acting as a barrier to innovation.**
  - The current standards for cricket gear and laws of cricket may be acting as barriers to the initiation of sustainable innovation in cricket equipment e.g. gloves, despite the gloves passing performance requirements and still be sold for use in the recreational game.
  - The nature of various cricket gear being PPE adds further complexity/challenges to consideration of circularity

5. Conclusions

This report documents conventional materials used in cricket gear, with a focus on balls, gloves and batting pads. Following an assessment of some of the functional, technical, manufacturing and performance requirements required by existing standards and manufacturer specifications from these component materials, sustainable alternatives are explored and identified. Emerging material innovation opportunities are also flagged.

A range of sustainable alternatives are identified, many of which are plant derived – although they may need some mechanical or chemical processing – and some of these alternative materials may also have their own end-of-life challenges.

There are a number of challenges that sustainable materials face in terms of their applicability for the specific cricket gear. Firstly, many of these materials may be 'new', or at least 'new' to current manufacturers. The cricket gear manufacturing sector is innovation-averse, and perhaps restricted by the stringent standards and laws of the games. Consequently, manufacturers may be hesitant to adopt 'new' materials. Being an established cottage industry, it may also be hesitant to change supply-chain dynamics and explore new sources of materials. Secondly, the 'sustainability' of these potential alternative materials needs to be demonstrated through LCAs and more holistic analysis, including consideration of which impact indicators ought to be prioritised. Finally, scale and scalability and supply-chain considerations are critical to their successful deployment in the sector. It is likely that current manufacturers have a long and established relationship with their raw materials suppliers to produce their products.

While the exploration of sustainable alternative materials to conventional materials is an important and much-need task, particularly to fuel innovation in this sector, it is important to recognise that for truly circular cricket gear a number of other material and design aspects need consideration. For example, simply using a renewably-resourced/bio-based alternative material will not directly imply ease of disassembly or ability to be recovered/recycled – these will require careful redesign of some products. Avoiding glues and stitching may be a challenge in meeting this. In some cases (e.g. for shoes) a move towards single-material products is a route, but this is not suitable for complex cricket gear.

In some discussions 'material cost' of these new sustainable materials in comparison to the conventional materials has been raised as a point. However, in many ways the author thinks that reducing 'production time and cost' may need to be the priority. For example, a worker may require 3-4 hours to hand-stitch a cricket ball, and a worker may only be able to produce 1.5 pairs of cricket gloves or pads in a single day. The material costs are unlikely to be the primary driver of cost. The use of second-life materials, recycled materials or waste precursors to materials may in any case enable material costs to remain low.

Finally, it is evident that standards and the regulatory bodies of the sport need to actively get behind incorporating sustainability criteria as part of specifications and performance criteria to really enable change-making in this sector.