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# BEYOND CONVENTIONAL LEATHER: ENGINEERING SUSTAINABLE VEGAN LEATHER THROUGH BIO-BASED MATERIALS, NANOTECHNOLOGY, AND GREEN INNOVATION

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## ABSTRACT

As concerns about being made from animal hides continue to rise, vegan leather made from synthetic polymers and renewables like biological tissue has gained popularity. But while the solution to the use of conventional leather is still a solution that must do more than simply forego animal materials, other plant-derived options must be equally indispensable in terms of mechanical strength, flexibility, durability, resistance to water and moisture, as well as demonstrating improved surface properties and environmental impact. In this review, the bio-based vegan leather systems such as those derived from plants, bacterial cellulose, fungal mycelium, gel type materials and nanocellulose reinforcement polymer composites are discussed. They cover their material structures, fabrication routes, post-treatments and characterization methods, focusing on the relationships between composition, processing and end-performance. Special focus is placed on the reinforcing effect of cellulose nanofibres and cellulose nanocrystals, polymer matrices, proteins, plasticisers, surface coatings and interfacial compatibility. The review discusses the possibilities of these material classes in fashion accessories, the footwear, upholstery and functional applications. It also defines research priorities around balancing mechanical strength, flexibility, moisture responsiveness, surface uniformity and durability whilst manufacturing uniformity, scalability and comparison of characterization modalities are being improved. Biodegradability and reduced environmental impact can't be assumed by use of renewable or bio-based constituents alone, and usage of life cycle assessment

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and end of life evaluation are, in addition to that, necessary. Areas of opportunity for valorization of agricultural residues and for production of sustainable alternatives using bio- leather, include the advances of green chemistry, polymer science and nanotechnology. It will take time to transition to material design with repeatable material processing and material performance and environmental assessment.

**KEYWORDS**

Vegan leather, bio-based materials, nanocellulose, polymer composites, sustainable materials

## 1. INTRODUCTION

Leather is extremely robust, supple, tough and offers a specific feel; it is extensively employed in footwear, garments, bags and furniture. However, the traditional leather-making process involves tanning and finishing animal skins, which can result in the consumption of resources, use of chemicals, and waste. All of this has led to an increased interest in finding alternative materials which might have a less harmful environmental effect. Leather alternatives that are manufactured without animal-derived leather are known as vegan leather.[1]

Leather is among the most ancient textiles to have been employed by man, with animal hides being used for clothing, footwear and shelter from the elements. It is an old artifact, so its inventor cannot be identified, nor is any particular civilization responsible for its invention. Preserved animal hides were used almost as long as agri-past, with many examples existing in early archaeological sites, such as leather shoes found in the Areni-1 cave in Armenia that date from c. 5,500 years ago. Artificial leather substitutes, In contrast, it appeared much later. The use of an artificial leather that had the same recognition as the first artificial leather to be commercially exploited was the Leatherette, which Harrington & Co. of London patented in 1875. It was initially created with treated and embossed paper sheets that are obtained from felted paper, to look just like leather. Later, Presstoff, Rexine and then polymer coated textiles were used to make modern synthetic leather. With the advances in biotechnology and materials science in recent years, the production of bio-based vegan leather materials using plant based resources, bacterial cellulose and fungal mycelium has been promoted.

Commercially viable products have been produced using synthetic polymers such as polyurethane (PU) and polyvinyl chloride (PVC), and the new bio-based products are based on plant fibres, bacterial cellulose, fungal mycelium, and natural polymers.[2] While their synthetic options can offer surface properties and manufacturing flexibility, the use of synthetic materials and their limitations after production present sustainability concerns. Equally, bio-materials do not necessarily have to be biodegradable or environmentally friendly; their chemical structure, processing and

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disposal have to be considered. Bacterial cellulose (BC) is an attractive material because of the network structure of the nanofibers which allows producing leather-like flexible sheets. The physical and functional properties of BC can be modified with the introduction of various proteins and plasticizers, pigments and surface treatments. Another option is to use fungal mycelium, which are woven together to create a fungal network of hyphae with properties that are influenced by fungal species, growth conditions, processing methods and reinforcement. Besides, cellulose nanofibrils and nanocrystals could also be used as reinforcing materials in polymer composites provided they are dispersed and compatible with the other components of the polymer composite.[3] An alternative to leather should be both durable and flexible, be able to withstand water, endure wear and use, have mechanical strength and stability and be comfortable. They depend on the application and should be evaluated by proper structural, mechanical, surface and moisture characterization. Moreover, The sustainability of the environment is to be considered, not only due to renewable raw materials but also throughout the whole chain of value of materials production, manufacture, utilization, and disposal of materials.

This trend towards sustainable leather substitutes is also evident in market forecasts and environmental impact evaluations. Commercial interest in the emerging bio-based leather materials has risen, as reported by Kefale et al. projecting the bio-based leather industry globally growth by region from 2018-2030 (Figure 1). They also analyzed conventional leather and alternative materials based on total environmental impacts, human toxicity, ecological damage, global warming potential, and carbon footprint of selected materials based on mycelium (Figure 3). Such comparisons can be of assistance in exploring environmental benefits of bio-based leather alternatives and emphasize the need to compare each material by employing the same LCA methodology. Thus, in this current review, emphasis will be placed on the physical properties, manufacturing techniques, drawbacks of bacterial cellulose, mycelium, nanocellulose-polymer composite and others biobased composite systems and their sustainability prospects.[4]

In this review, the material structures, fabrication processes and characterization methods, in addition to the performance of vegan leather alternatives using plant-derived materials, nanocellulose-reinforced composites, bacterial cellulose, and fungal mycelium are discussed. It emphasizes the connections between composition, processing, microstructure, and material properties as well as key issues of durability, moisture resistance, manufacturing consistency, scalability, and environmental sustainability.

## 2. CLASSIFICATION AND STRUCTURE OF VEGAN LEATHER

Vegan leather is in fact a diverse group of materials that may be used for creating the look, suppleness, and attributes of animal leather without the use of animal-derived leather. The materials are composed of different materials, have different internal structures, are manufactured in various ways, and have various surface treatments, which leads to different mechanical strength,

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moisture resistance, durability, and environmental performance. They can be grouped into synthetic leather, plant-based alternatives, bacterial cellulose, fungal mycelium, gel-based materials, and nanocellulose-reinforced polymer composites based on their main components and structure.[5]

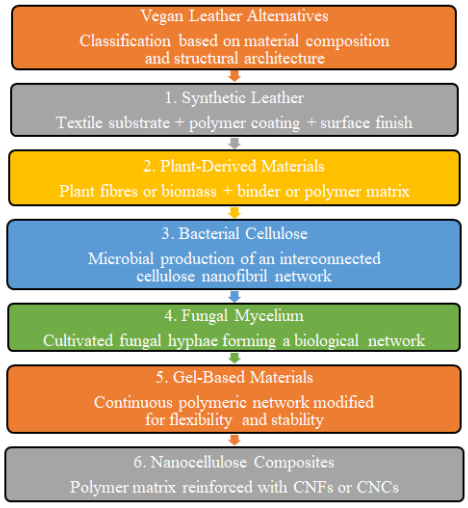



*Figure 1: Classification of vegan-leather alternatives according to their principal material composition and structural features. The categories may overlap because biological materials can also be incorporated into polymer composites.*

**2.1 Synthetic Leather** The most popular method of production of synthetic leather is to coat woven, knitted or nonwoven textile with polyurethane (PU) or polyvinyl chloride (PVC). It is typically composed of a textile base, polymer coating, and (optional) surface finishing. The textile is used to offer mechanical support, the polymer layer to give flexibility, surface texture, and liquid repellence. These materials have controllable surface and manufacturing properties but their sustainability is dependent on the polymer composition, manufacturing processes, service life, and end-of-life management.[6]

**2.2 Plant-Derived Leather** Alternatives Plant-derived Alternatives would be

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those made from plant fibers, agricultural residues or other plant-based biomass and appropriate binders, coatings or polymer matrices. The fibres give structure and reinforcement while the binder holds the elements together as a sheet. They are based on their properties of fibre distribution, matrix compatibility and moisture resistance. If the bonding is inadequate, it can cause cracking or delamination and cause damage when bent repeatedly. Renewable feedstocks are just one aspect of sustainability but also the performance of the processing and binder composition will influence the environmental performance of the final material.[7]

**2.3 Bacterial Cellulose-Based Leather** The microorganisms that synthesize cellulose produce the product known as bacterial cellulose (BC) in the fermentation process. The cellulose fibres create a network together which may be able to form a hydrated pellicle and then worked up to leather like flakes. It can be made fibrous and can serve as the foundation for incorporating proteins, plasticizers, dyes and surface coatings. The hydroxyl groups in cellulose, however, are very susceptible to water, making dimensional instability and swelling possible. The incorporation of protein, plasticization, reconstruction of the sheets and modification of the surfaces are therefore examined for increased flexibility, durability and moisture resistance.[5]

**2.4 Fungal Mycelium-Based Leather** Mycelium is a network of fungal hyphae that are interconnected in a three-dimensional pattern. Biomass of fungi collected and processed or mycelium cultured directly on textile or fibre reinforcement may be used to manufacture leather like products. These are structural depending on various factors such as different species of fungi, growth conditions, substrate composition, and processing conditions. It has some advantages when fibres are used as reinforcement, but weak adhesion between the fungal matrix and the reinforcing fibre can lead to separation between the two. Hence, it is important to have cultivation control and composite architecture for consistent material properties.

**2.5 Gel-Based Leather** Gel-based materials are made up of continuous polymeric networks which can be prepared using biopolymers, other polymers, plasticizers, and reinforcing agents. They are composed of and their network structure affects softness, flexibility and deformation resistance. They can become over-swollen, lack tensile strength, suffer abrasion and undergo changes during long-term use, however. As such, Tests need to be conducted in terms of mechanics, moisture resistance, and aging to find out whether they are suitable for use or not.[3]

**2.6 Nanocellulose-Reinforced Polymer Composites** Nanocellulose-reinforced composites are composites made up of a polymer matrix and cellulose nanocrystals (CNCs) or cellulose nanofibrils (CNFs). The typical CNFs are elongated fibrillar particles while CNCs are shorter particles with a crystalline structure. The nanomaterials, depending

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on their distribution and interaction with the matrix, can enhance the integrity and resistance to deformation of the structure. They are effective if they are concentrated, dispersed, chemically compatible with the surface, and are compatible at the interface. But the reinforcement benefits reported for general polymer composites do not necessarily correlate with the finished product, vegan-leather, and direct testing of the intended formulation is required.

*Table 1 Classification and Structural Characteristics of Vegan Leather Alternatives*

| **Material Category** | **Principal Structure** | **Potential Advantage** | **Major Limitation** |
|---|---|---|---|
| Synthetic leather | Polymer coating on a textile substrate | Flexibility and tunable surface appearance | Fossil-derived polymers and end-of-life concerns |
| Plant-derived materials | Plant fibres bonded within a binder or polymer matrix | Potential use of renewable resources | Moisture sensitivity and weak bonding |
| Bacterial cellulose | Interconnected cellulose nanofibril network | Continuous, flexible sheet formation | Water absorption and dimensional instability |
| Fungal mycelium | Interconnected fungal hyphal network | Biological growth and reinforcement potential | Growth variability and weak interfaces |
| Gel-based materials | Continuous polymeric network | Adjustable softness and flexibility | Swelling and limited long-term durability |
| Nanocellulose composites | CNFs or CNCs incorporated into a polymer matrix | Potential mechanical reinforcement | Poor dispersion and matrix incompatibility |

## 3. APPLICATIONS OF VEGAN LEATHER

The properties of vegan leather, such as its strength, flexibility, surface, moisture resistance and durability, are used in various applications. Bio-materials have the capability of being used in the laboratory, but it is up to each individual application for that specific bio-material to be proven suitable.

**3.1 Fashion Accessories and Garments**. Vegan leather can be used to make fashion accessories or for clothing panels like bags, wallets, belts and clothing panels. The appropriate flexibility, even surface, abrasion resistance and repeated

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handling resistance are required in these products. The bacterial cellulose (BC) and miyelium based materials can be formed into sheet form, and the surface can be modified for different properties. Da Silva Junior, et al. showed the feasibility of the use of reconstituted BC for coloured and surface treated leather-like materials. The performance specifications are dependent on the product. Wallets need to be bend resistant, garment soft and repeatedly flexible, and belts need to be strong and dimensionally stable. The following test items must be subjected to testing before it can be used commercially: Colour stability, Coating adhesion and Perspiration resistance.[8]

**3.2 Footwear Components** of footwear are subjected to many flexings, abrasion, moisture, pressure and temperature changes. They have to satisfy performance criteria for tensile and tear resistance, dimensional stability, moisture resistance and adhesion between layers. Fungal mycelium-based composites are potential candidates as they can be mixed with reinforcing substrates. [9] Kniep et al. have shown that the mechanical response and structural integrity of these composites depends on the type of fungi and the reinforcement used. But, the appropriateness of mycelium materials for footwear depends upon the component and needs to be tested under representative service conditions.

**3.3 Interior and upholstery** uses Furniture coverings and furniture interior surfaces must be wear resistant, be dimensionally stable, be relatively easy to clean, and be resistant to ageing and exposure to the environment. Bio-based polymer composites and reinforced cellulose materials present possibilities to adjust the surface and mechanical properties. Adequately dispersed and compatible nanocellulose can be helpful in providing reinforcement.[10] However, suitability for upholstery must be confirmed under repeated loading, abrasion, cleaning, humid and climatic conditions and under prolonged use. As such, these applications are still reliant on the properties of the final formulation of the material.

**3.4 Biofabricated and Customized Materials** There are biological pathways to create leather-like sheets having varying structural properties, such as bacterial cellulose, fungal mycelium. The extraction and processing of BC can take place by reconstitution, incorporation into proteins and surface modification while mycelium can be processed as pulp or grown with reinforcing substrates. These methods provide options for thickness, texture and reinforcement. However, the variations in cultivation, processing and material structure should be controlled in order to ensure the reproducibility and reliable, large-scale production.[11]

**3.5 Functional and Specialty Materials** Vegan leather-like materials may also be developed with additional functions, including improved wet strength, modified surface wetting, and UV-blocking properties. Kriechbaum and Bergström demonstrated antioxidant and

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UV-blocking functionality in leather-inspired nanocellulose films with high wet strength. This research shows the viability of functionalized nanocellulose-based materials but does not provide evidence for equal functionality in manufactured vegan leather products. Likewise, the surface treatment of regenerated BC will affect its interactions with water.[12] Such treatments must be evaluated for their effects on flexibility, adhesion, durability, processability, and environmental performance.

*Table 2 Potential Applications and Principal Performance Requirements of Vegan Leather*

| **Potential Application** | **Important Performance Requirements** | **Relevant Material-Development Directions** |
|---|---|---|
| Bags, wallets, and accessories | Flexibility, tensile and tear resistance, abrasion resistance, and surface appearance | Reconstituted BC, protein-modified BC, and mycelium composites |
| Garments and clothing panels | Drape, repeated-flexing endurance, comfort, and colour stability | Flexible cellulose-based materials and surface-modified bio-based sheets |
| Footwear components | Tensile and tear resistance, abrasion resistance, moisture resistance, and flexing endurance | Reinforced mycelium, modified BC, and bio-based composites |
| Upholstery and interior surfaces | Wear resistance, dimensional stability, cleanability, and ageing resistance | Reinforced polymer composites and modified bio-based materials |
| Customized biofabricated sheets | Structural uniformity, controllable thickness, and reproducibility | BC cultivation and reconstitution, and mycelium cultivation |
| Functional specialty films and surfaces | Wet strength, surface functionality, and stability under use conditions | Nanocellulose-based films and appropriately modified composites |

## 4. SYNTHESIS METHODS

The studies reviewed in this article indicate that vegan leather should not be considered a single material category. Its performance depends on the raw materials, fabrication route, internal structure, surface treatment and intended application. Bacterial cellulose, fungal mycelium, plant-derived composites, nanocellulose-reinforced polymers and gel-based systems offer different combinations of mechanical performance, flexibility, moisture response and processing requirements.[5] Consequently, selecting a suitable alternative requires evaluating the

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complete material system rather than relying solely on its biological origin.

**4.1 Bacterial Cellulose and Protein-Modified Systems.** BC (bacterial cellulose) is a potential choice since the formation of nanofibers of cellulose takes place through microorganisms. This structure can provide a useful foundation for developing thin, flexible, leather-like sheets. Nevertheless, the material's strong interaction with water can limit dimensional stability and performance during wet exposure. Absharina et al. discussed the potential of bacterial cellulose in sustainable fashion while identifying production consistency and material quality as important considerations. Protein modification serves as another possible way of altering the characteristics of BC. Kim et al. studied the incorporation of soy and mushroom proteins into bacterial cellulose and their effect on mechanical properties. Their work demonstrates that the performance of BC can be modified through composite formation rather than depending exclusively on the characteristics of the unconditioned cellulose network.[11] However, the effects of protein incorporation are dependent on the formula and processing conditions. Results from individual formulations should therefore not be interpreted as universal performance values for all BC-based materials. Reconstituted cellulose offers another fabrication strategy. In this approach, existing BC material is processed and re-formed into sheets, allowing greater control over the resulting geometry and appearance. da Silva Junior et al. demonstrated a route combining reconstituted cellulose, natural dyes and surface treatments. Their study supports the feasibility of tailoring colour and surface characteristics, although additional evidence is needed to establish long-term resistance to moisture, abrasion and repeated use under practical conditions.

**4.2 Mycelium-Based Materials,** Mycelium-based leather alternatives are formed from interconnected fungal hyphae, either through direct cultivation on a supporting structure or by processing fungal biomass into a composite. This biological network offers opportunities to use renewable feedstocks and develop material structures through controlled growth. However, fungal species, cultivation conditions, reinforcement selection and post-processing can substantially affect the resulting properties. Kniep et al. compared several fungal species and reinforcement configurations using different fabrication approaches. Their findings indicate that the mechanical performance of a mycelium material cannot be predicted from the fungus alone. The presence and arrangement of reinforcement, together with the quality of the interface between the fungal network and reinforcing fibres, also influence the final composite. This observation is important when designing materials intended to withstand tensile loading, folding and repeated handling. Although mycelium materials have potential for fashion and product applications, they still require systematic evaluation of surface quality, thickness uniformity, durability and production

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repeatability.[9] The most appropriate formulation may therefore differ between lightweight accessories, footwear components and products exposed to frequent mechanical stress.

**4.3 Nanocellulose-Reinforced Composites,** Cellulose nanofibres (CNF) and cellulose nanocrystals (CNC) offer a complementary approach to improving the performance of bio-based leather-like materials. Rather than acting as the primary material in every formulation, these nanomaterials can serve as reinforcing phases within polymeric or other bio-based matrices. Their contribution depends on dispersion, compatibility with the matrix and the effectiveness of stress transfer across the interface. Choi et al. highlighted the potential of nanocellulose reinforcement for addressing mechanical weakness and structural instability in leather-like composites, while also noting the limited availability of direct studies and long-term durability data for these applications. Therefore, improvements demonstrated in general nanocellulose–polymer composites should be treated as a basis for material development, not as automatic proof of performance in finished vegan leather.The importance of matrix selection is also evident in the broader literature on nanocellulose composites.[7] [6] Chakrabarty and Teramoto and Aigaje et al. discussed how processing methods, polymer compatibility and composite structure affect performance. In leather-like applications, these considerations must be balanced against flexibility, surface appearance and resistance to moisture. Excessive reinforcement or poor dispersion may fail to deliver the desired combination of properties.

**4.4 Gel-Based Materials and Functional Films,** Gel-based systems have much potential for regulation of their softness, composition, and structure. These structures can be designed using different types of polymers and additives, and hybrid systems might provide better performance than simple ones with only one component. However, the lack of tensile strength, abrasion resistance, swelling, and stability is still an issue that needs to be addressed. Nanocellulose films have the potential that goes far beyond mechanical reinforcement of structures. Kriechbaum and Bergström researched leather-like films based on nanocellulose that have wet strength, antioxidant properties, and UV protection. However, a functional film should not automatically be treated as a complete leather substitute: its performance must be evaluated within the context of the intended product, substrate and service environment.[1] [10]

## 5. PROPERTIES OF CONVENTIONAL AND VEGAN LEATHER

### 5.1 Properties of Animal-Derived (Conventional) Leather

Regular leather is a natural material which has been in use since ancient times derived from the skin of animals using different tanning, dyeing, and finishing techniques. Regular leather is mainly made up of collagen which is a fibrous protein consisting of interlinked fibers in

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a 3D matrix form. The properties of regular leather due to the arrangement of collagen fibers make it useful for making shoes, clothing, car upholstery, handbags and furniture.

*Chemical composition and physical structure*:

- Made up primarily of collagen proteins.
- Has moisture and natural fats among other organic compounds.
- The fibrous structure is formed by interlinked collagen fibers arranged in a 3D matrix form.
- Tanning agents react with collagen to stabilize the structure and enhance its durability.

*The significant features of natural leather include the following*:

- **Tensile and tear strength**: The leather material has tensile strength due to its fibrous nature.
- **Flexibility and softness**: The material can be bent, folded, deformed and still retain its structure.
- **Abrasion resistance**: This feature is provided by the fibrous nature of leather along with suitable finish.
- **Moisture transfer**: The material has a porous fibrous structure that provides the capacity to absorb moisture and water vapor.
- **Durability**: The combination of the leather's strength, flexibility and resistance to deformation provides long-term usability.
- **Thermal insulation**: The material's fibrous and porous nature allows for thermal insulation and comfort.
- The material's grain, texture, and ability to dye and finish create unique surface properties.

### 5.2 Properties of Synthetic Leather

Synthetic leather is a man-made leather substitute created via application of polymeric coatings onto a textile substrate. The construction of synthetic leather consists of chemical components, rather than being made of collagen proteins like in the case of natural leather. Usually, polymeric components that are used to create synthetic leather include polyurethane (PU) and polyvinyl chloride (PVC).

*Chemical components and structure*:

- Polyurethane (PU): A polymer that contains urethane linkages that have been formed during reactions between polyols and isocyanates.
- Polyvinyl chloride (PVC): A thermoplastic polymer, whose monomers contain repeating units of vinyl chloride.
- Textile base: Usually made from woven, knit or non-woven polyester and other types of textile fibers.

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- Additional components: Plasticizers, colorants, stabilizers, extenders and finish agents.

*Synthetic leather typically is constructed with three layers:*

- Textile substrate: Structure and mechanical strength
- Polymer coating: Surface, flexibility and cohesion of material
- Surface finishing: Texture, colour and surface properties.

*The material systems, however, offer several desirable properties:*

- **Mechanical properties**: Textile backing offers the structure while polymer coating offers tensile strength and surface cohesion.
- **Flexibility and softness**: Polymer used and amount of plasticizer can be varied to obtain varying degrees of flexibility and softness.
- **Resistance to abrasion**: Finishing and surface coatings offer resistance to surface wear due to friction and contact.
- **Moisture resistance**: PU and PVC coatings offer protection against water penetration, dependent on coating and its structure.
- **Uniformity**: Controlled manufacturing process provides consistent thickness, colour and texture of the surface.
- **Aesthetics**: Embossing, pigmentation and surface finishing enable reproduction of different leather textures and appearance.
- **Processability**: Polymer coating and textile processing allow large scale production and production of specific application materials.

### 5.3 Properties of Bio-Based Vegan Leather

Plant leather is one of the emerging products under leather substitutes that are produced from renewable biological resources and bio-based or natural polymer materials. The materials are produced through the use of plant biomass, bacterial cellulose, fungal mycelium, natural polymers, and other biological elements, unlike synthetic leather that uses predominantly polymers from petrochemicals. The chemistry and structure of the materials depend on the type of biological resource and process involved.

*Chemical composition and structural characteristics*:

*Table 3 Chemical Composition and Structural Characteristics of Bio-Based Vegan Leather*

| Material category | Principal chemical composition | Structural characteristics |
|---|---|---|
| Plant-derived | Cellulose, hemicellulose, lignin and | Plant fibre or biomass-reinforced |

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| Material category | Principal chemical composition | Structural characteristics |
|---|---|---|
| materials | natural polymeric binders | composite structure |
| Bacterial cellulose | β-1,4-linked glucose units forming cellulose | Interconnected nanofibrillar network |
| Fungal mycelium | Chitin, glucans, proteins and other fungal cell-wall constituents | Interconnected network of fungal hyphae |
| Gel-based materials | Natural or synthetic hydrophilic polymers, depending on formulation | Three-dimensional polymeric network |
| Nanocellulose composites | Cellulose nanofibres (CNFs), cellulose nanocrystals (CNCs) and polymer matrices | Reinforced polymer composite structure |

*The important properties of Bio-Based Vegan Leather include*

- **Mechanical properties**: Plant fibres, cellulose networks and fungal structures provide reinforcement and contribute to the mechanical integrity of bio-based materials.
- **Flexibility and softness**: Polymer matrices, plasticizers and gel formulations can be adjusted to obtain different flexibility and softness characteristics.
- **Structural characteristics**: Bacterial cellulose provides a fine interconnected nanofibrillar structure, whereas fungal mycelium develops a biological network through interconnected hyphae.
- **Surface properties**: Natural dyes, pigments, waxes and polymer coatings can be incorporated to modify colour, texture and surface appearance.
- **Moisture-related properties**: Protein incorporation, glycerol treatment and surface modifications can influence water interaction and dimensional behaviour. Kim et al. [6] investigated protein-modified bacterial cellulose, while da Silva Junior et al. [7] studied naturally dyed and surface-treated reconstituted cellulose.
- **Functional properties**: Selected bio-based films and composites can provide additional functionalities. Kriechbaum and Bergström [11], for example, investigated nanocellulose-based films exhibiting wet strength, antioxidant activity and UV-blocking properties.

### 5.4 Limitations of Vegan Leather

Vegan leather alternatives have good potential to replace conventional leather in various applications, but their material characteristics also significantly depend on the chemical composition, production

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process and post-processing procedures. Some of the issues that have to be tackled are those that concern mechanical performance, flexibility, and durability.

*The main constraints are*:

1. **Mechanical strength and durability**: There are some biopolymer materials that need further development in terms of their tensile strength, tear strength, abrasion resistance, and repeated flex.
2. **Moisture sensitivity**: Some biopolymers contain hydrophilic components such as bacterial cellulose and nanocellulose that can take up moisture leading to swelling. It is important for maintaining their wet strength and structural integrity.
3. **Flexibility and structural integrity**: Finding a right balance in stiffness, flexibility, and strength is also a key factor in designing of these materials, especially for polymers and gels.
4. **Interfacial compatibility**: In composites, the insufficiency of interface bonding of reinforcing fibers with the polymer matrix affects stress transfer and performance.
5. **Manufacturing repeatability**: Biological growth conditions, raw materials composition and manufacturing process influence thickness, homogeneity, and properties of the biopolymer material.
6. **Environmental performance**: Renewable or bio-based components do not necessarily provide biodegradability and less negative impact on environment. Composition of polymers, processing chemicals, coatings and disposal of the biopolymers should be taken into account.

### 5.5 Enhancement of Vegan Leather Properties through Nanomaterials

Nanomaterials can be used to improve the properties of the vegan leather. The most promising nanomaterials for such purpose are cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs), as they are known to have the reinforcing properties and compatibility with polymer matrix.

*The use of nanomaterials may help improve the following properties:*

1. **Improved mechanical strength:** Nanocellulose may serve as reinforcement for polymer matrices. Small sizes and high aspect ratio of nanocellulose can provide stress transfer between reinforcement and matrix, which can increase tensile strength.
2. **Improved structural stability:** Nanocellulose network may increase cohesion and structural stability of the composite. Proper dispersion and compatibility of the reinforcement are crucial for proper reinforcement.
3. **Controlled mechanical properties:** The amount and distribution of nanomaterials can be controlled in order to get proper balance between stiffness, strength and flexibility. Selection of proper polymer matrix

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and amount of reinforcement is needed to reach proper mechanical properties.

4. **Improved moisture performance:** Nanocellulose surface modification, hydrophobic coating and proper polymer matrix can be tested in order to control the interaction with moisture. It may increase wet stability and control of dimensions.
5. **Increased abrasion resistance and improved surface properties:** Nanomaterials addition and surface modification can be used in order to improve coating properties and resistance to wear. It should be proved experimentally.
6. **Multifunctionality:** In addition to their reinforcing capabilities, nanomaterials have potential applications that go far beyond mechanical reinforcement. For instance, Kriechbaum and Bergström explored leather-like films made of nanocellulose, which have wet strength, antioxidative properties, and ultraviolet protection properties.

On the whole, reinforcing vegan leather with nanomaterials is a potentially viable method of endowing it with desirable mechanical and structural properties. However, the efficiency of such improvements will be dependent on various factors including choice of nanomaterials, their dispersion, etc.

## 6. REASEARCH GAP

Mechanical strength, water-resistant and compatible interface, and production consistency at scale and low cost are some of the important issues to address. There is also a need for standardized testing, life cycle assessment, and end-of-life analysis to establish performance and sustainability of vegan leather in the long term.

## 7. FUTURE PERSPECTIVE

**7.1 Design of Hybrid and Multiphase Materials**, Future researches may be carried out on hybrid composites such as BC with protein/nanocellulose, mycelium with textile, and gel with biofiller. Research should optimise composition and interfacial interactions while balancing strength, flexibility, swelling, and processability.[11]

**7.2 Improved Moisture Resistance**, Research should focus on reducing water absorption in BC-, nanocellulose-, and gel-based materials through surface modification and composite design. Treatments should preserve flexibility and sustainability while avoiding persistent or difficult-to-separate additives.

**7.3 Process Optimisation and Reproducibility**, Optimising cultivation, thickness control, reinforcement, and post-processing is essential for consistent material quality. Scale-up studies should assess production yield, batch variation, processing time, and resource consumption.[8]

**7.4 Standardised Testing and Long-Term Performance**, A common testing framework should include tensile and tear strength, flex endurance, abrasion resistance, water absorption, dimensional stability, and ageing.[9] Long-term performance under humidity changes,

cleaning, and repeated wear also requires investigation.

**7.5 Life-Cycle Assessment and Circular Design**, Life-cycle assessment should evaluate energy and water use, chemical inputs, product lifetime, and waste management.[10] Future materials should prioritise repair, reuse, recycling, and verified biodegradability wherever feasible.

**7.6 Functional and Application-Specific Development**, Future research may explore functional properties such as wet strength, antioxidant activity, and UV protection. Material development should target specific applications, considering flexibility for accessories, flex endurance for footwear, and dimensional stability for upholstery, rather than seeking a single universal formulation.[12]

**7.7 Nanomaterial-Based Enhancement,** The use of suitable nanomaterials, such as cellulose nanofibres (CNFs) and cellulose nanocrystals (CNCs) with the aim of increasing mechanical strength, the moisture resistance and the structural stability of vegan leather, as well as functional properties, should be investigated in the future. Optimization of dispersion, concentration, and adhesion at the interfaces of nanomaterials and composites will be very important for high performance and sustainability of composites.

## 8. CONCLUSION

Bio-based vegan leather is one of the most interesting classes of alternatives to leather: bacterial cellulose, fungi mycelium, vegetable materials, nanocellulose composites and gels. Properties of these materials are defined by the kind of material and its processing and post-processing. Moreover, there is the possibility of further enhancement of these properties using reinforcement with nanomaterials. However, there are certain aspects, which require more investigation with respect to durability, water repellency, consistency of the material production and scalability.

Future research needs to focus on material design optimization and standardization of tests and life-cycle assessment to evaluate the technical properties and environmental sustainability of these alternatives. Utilizing advanced fabrication methods, renewable raw materials and agricultural wastes would help in developing sustainable materials.

Overall, bio-based vegan leather has a lot of perspectives for use in fashion, footwear, interior automotive and upholstery. Commercialization of the technology would depend on the balance between material properties, cost, scale and environmental impact. Further research is needed in order to create sustainable alternative to leather.

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