Toward Biodegradable and Cost-Effective Vegan Leather: Alginate Composites with Natural Fillers for Eco-Friendly Textile Applications

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ABSTRACT

The environmental and ethical concerns associated with traditional leather production have intensified the demand for sustainable alternatives. This study investigates the development of plant-based vegan leather using sodium alginate combined with beetroot, coffee, and charcoal—aiming to provide a biodegradable, cost-effective, and cruelty-free material for Bangladesh's fashion industry. Sodium alginate, cross-linked with calcium chloride, served as the base polymer, while natural fillers enhanced texture, color, and functionality. The samples, developed under academic supervision, underwent water resistance, fire resistance, flexibility, and durability testing, with each test repeated three times to ensure reliability. Results revealed that beeswax treatment significantly improved water resistance, and charcoal-based samples exhibited the highest fire resistance, averaging 6 minutes before ignition. Fabric-backed variants demonstrated better structural integrity. Compared to commercial vegan leathers like Piñatex and apple leather, the developed material offers full biodegradability and greater cost efficiency. However, challenges such as scalability, long-term durability, and advanced mechanical validation remain. This research highlights the viability of sodium alginate-based vegan leather and emphasizes the need for industry collaboration, consumer awareness, and policy support to facilitate its adoption in Bangladesh's textile sector.

1. Introduction

The global fashion industry, one of the largest contributors to environmental degradation, faces mounting criticism for its reliance on conventional leather production, which involves deforestation, animal exploitation, and toxic chemical use (Ro, 2022). Traditional leather tanning processes, particularly chromium-based methods, release hazardous pollutants into ecosystems, endangering both environmental and human health (Alternative Leathers, n.d.). As consumer awareness of sustainability grows, the demand for ethical and eco-friendly alternatives has spurred innovation in plant-based vegan leathers (Watson & Wolfe, 2020).

Vegan leather, derived from agricultural by-products and biopolymers, offers a promising solution. Materials such as pineapple leaves (Piñatex), apple peels (Frumat), and mushroom mycelium (Mylo) have gained traction for their reduced carbon footprint and biodegradability (Panaprium, n.d.; Oliver Co. London, n.d.; Watson & Wolfe, 2020). However, many commercial vegan leathers rely on synthetic coatings like polyurethane (PU) to enhance durability, compromising their environmental benefits (Melina Bucher, n.d.). This underscores the need for fully biodegradable alternatives that balance performance and sustainability.

In Bangladesh, a hub for textile and leather exports, the shift toward sustainable materials aligns with global trends and local agricultural potential. The country's abundance of underutilized resources, such as beetroot, coffee grounds, and charcoal, presents opportunities for innovative material development (University of Colorado Boulder, 2021). Sodium alginate, a seaweed-derived biopolymer, has emerged as a viable binding agent due to its flexibility, low cost, and compatibility with natural additives (Reef, n.d.). Yet, limited research exists on its application in vegan leather, particularly in combination with locally sourced pigments and fillers.

This study addresses this gap by developing sodium alginate-based vegan leather infused with beetroot, coffee, and charcoal. By leveraging Bangladesh's agricultural waste, the research aims to create a cruelty-free, biodegradable material that outperforms existing synthetic and plant-based alternatives in cost and sustainability. The findings contribute to advancing eco-conscious fashion practices while addressing challenges such as scalability and consumer acceptance in emerging markets.

2. Literature Review

The rising global concern over the environmental and ethical implications of traditional leather production has spurred the development of plant-based alternatives. Vegan leather—produced from biodegradable, renewable resources—has emerged as a promising sustainable solution, particularly within the fashion industry (Ro, 2022).

This review critically examines the scientific foundations, sustainability metrics, and global trends in vegan leather, while identifying research gaps that justify the exploration of novel materials such as beetroot, coffee, and charcoal in combination with sodium alginate.

2.1 Material Science of Vegan Leather

The formulation of vegan leather is rooted in material science, particularly the use of biopolymers such as cellulose, alginate, lignin, and pectin. These substances emulate the fibrous collagen network found in animal hide, thereby offering structural integrity and flexibility (Watson & Wolfe, 2020). Reinforcement is often achieved through cross-linking agents like calcium chloride, while plasticizers such as glycerin enhance elasticity. Surface coatings derived from nanotechnology and natural waxes contribute to water resistance and durability (University of Colorado Boulder, 2021).

Compared to conventional leather, which relies on toxic chrome tanning, plant-based alternatives offer safer, more biodegradable solutions. However, their thermal stability and tensile strength vary depending on source materials and processing methods (Panaprium, n.d.). For instance, banana fiber demonstrates tensile strengths near 800 MPa, whereas cowhide averages 25–30 MPa.

2.2 Sources and Types of Vegan Leather

A variety of raw materials have been utilized for vegan leather production. These include pineapple leaves (Piñatex), cactus pulp (Desserto), apple peel (Frumat), mushroom mycelium (Mylo), and kombucha SCOBY (Suzanne Lee's BioCouture) (Melina Bucher, n.d.; Reef, n.d.). These plant-based materials are often derived from agricultural waste, offering dual environmental benefits: waste valorization and reduced reliance on synthetic or animal-based components.

Nevertheless, many commercial vegan leathers still incorporate polyurethane (PU) or polyvinyl chloride (PVC) coatings to enhance durability, which undermines their overall sustainability (Ro, 2022). Despite their eco-labeling, such synthetic components pose long-term environmental hazards due to poor biodegradability.

2.3 Vegan Leather in Bangladesh and Global Context

Bangladesh, with its rich agricultural base and textile expertise, offers significant potential for localized vegan leather production. Locally available materials such as banana fiber, jute, coconut husk, and beetroot can be leveraged to reduce dependency on imports (Israt, 2025). However, current initiatives remain fragmented due to limited infrastructure, high production costs, and low consumer awareness.

Globally, sustainable leather initiatives are expanding rapidly. Countries like Germany, the Netherlands, and Italy are leading efforts through green manufacturing policies, carbon footprint reduction, and ethical fashion campaigns (Watson & Wolfe, 2020). Simultaneously, leading brands are investing in alternative materials as part of broader corporate sustainability strategies.

2.4 Research Gaps and Opportunities

Most current research focuses on materials such as Piñatex, apple peel leather, and Mylo, often neglecting other regionally abundant bio-resources like coffee grounds and charcoal. Furthermore, many studies emphasize laboratory-scale material properties while ignoring field performance, scalability, and life-cycle impact assessments (Israt, 2025). The lack of real-world durability tests, consumer market research, and economic viability studies underscores the need for more integrated research frameworks.

2.5 Sustainability and Performance Metrics

Key performance metrics for vegan leather include carbon footprint, biodegradability, durability, and cost-effectiveness. Compared to synthetic vegan leather (e.g., PU or PVC), plant-based options tend to offer superior environmental profiles but may lack consistency in mechanical properties. Coffee-based composites, for instance, introduce natural oils and antioxidants that enhance texture but reduce fire resistance (Israt, 2025). Conversely, charcoal-based formulations exhibit excellent fire resistance but may require conditioning agents to prevent brittleness.

3. Research Objectives

This study aims to explore sustainable alternatives to conventional leather by developing plant-based vegan leather using locally available materials in Bangladesh. The specific objectives are

- to develop biodegradable vegan leather using beetroot, coffee, and charcoal as primary raw materials combined with sodium alginate as a natural binding agent.
- to evaluate the physical and functional properties of the developed vegan leather, focusing on flexibility, durability, water resistance, and fire resistance.
- to compare the performance of the developed materials against both traditional animal leather and commercial vegan leather products.

- to assess the feasibility and cost-effectiveness of producing alginate-based vegan leather using indigenous resources within the context of Bangladesh's fashion industry.
- to identify potential applications of the developed leather in sustainable fashion products such as accessories, footwear, and apparel.
- to contribute to the broader discourse on sustainable fashion, offering eco-friendly material innovation grounded in circular economy principles and agricultural waste utilization.

4. Methodology

A systematic experimental design was followed, covering material preparation, sample development, and property evaluation. All property tests were repeated in triplicate for data reliability. The methodology comprised the following key steps:

4.1. Material Selection and Preparation

- Sodium alginate was selected as the primary biopolymer due to its gel-forming and biodegradable properties.
- Beetroot, coffee grounds, and charcoal powder were used as natural fillers and colorants.
- Glycerin and soybean oil were incorporated as plasticizers and conditioners.
- Calcium chloride ($CaCl_2$) served as a crosslinking agent to enhance structural integrity.

Each raw material was sun-dried, ground into powder or paste, and then blended with sodium alginate solution to form a homogenous bio-composite. The entire experimental process was supervised and reviewed by Tanzil Hasnain Moin Roneet, Associate Professor, Department of Textile and Fashion, RPSU, ensuring academic oversight of the home-based laboratory setup.

4.2. Sample Development

Two types of samples were developed

- Standalone vegan leather sheets
- Fabric-backed composite leather

The mixture was poured into molds and allowed to set for 12 hours before crosslinking with $CaCl_2$ solution. The samples were air-dried for 3–4 days at room temperature. Beeswax was applied post-drying for waterproofing.

4.3. Testing and Evaluation

The prepared samples were evaluated through home-based tests for the following properties: The tests were conducted between March 15–20, 2025, under the supervision of Tanzil Hasnain Moin Roneet, Associate Professor, Department of Textile and Fashion, RPSU.

Each performance test (water, fire, flexibility, and bending strength) was conducted in triplicate across different days to account for consistency and reduce observational bias.

- Water resistance (via spray and droplet test)
- Fire resistance (measured time to ignition using a controlled flame)
- Texture and flexibility (qualitative observation)
- Bending strength and structural integrity (manual stress testing)

4. 4. Comparative Analysis

Results from the developed samples were compared with the physical attributes of traditional animal leather and commercially available vegan leathers (e.g., Piñatex, apple leather, cactus leather), referencing both laboratory data and published studies.

5. Results and Discussion

This section presents the experimental outcomes of developing alginate-based vegan leather using beetroot, coffee, and charcoal. The materials were tested for their water resistance, fire resistance, texture, flexibility, and structural integrity. Comparative analysis was also conducted against conventional and commercial vegan leather products.

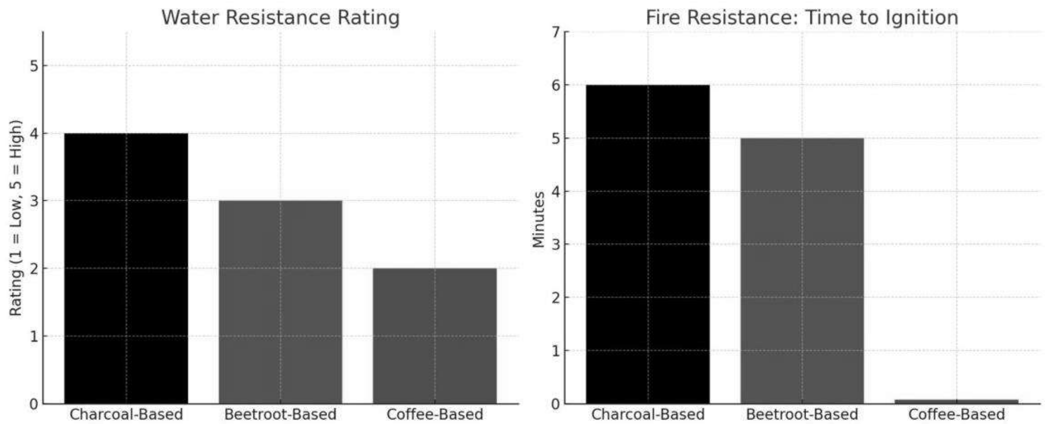

Figure 1. Water resistance ratings (left) and fire resistance performance (right) of vegan leather samples.

All test results were averaged over three trials conducted under controlled home-lab conditions.

Future work will incorporate statistical variance and standard deviation analysis to validate result robustness.

5.1. Texture, Flexibility, and Appearance

- Beetroot-based leather exhibited a smooth and pliable surface, with rich natural pigmentation. The sample was moderately elastic and had a leather-like feel.
- Coffee-based leather had a slightly coarse texture due to fine coffee granules and showed moderate flexibility. Its dark color mimicked conventional leather.
- Charcoal-based leather produced the firmest structure with high surface uniformity. It demonstrated superior dimensional stability but required conditioning for softness.

5.2. Water Resistance Performance

A five-minute water droplet test was conducted. The rating scale ranged from 1 (low resistance) to 5 (excellent resistance):

A five-minute water droplet test was conducted. The rating scale ranged from 1 (low resistance) to 5 (excellent resistance):

Table 1. Water Resistance Ratings of Vegan Leather Samples

Material	Water Resistance Rating (1–5)	Observation
Charcoal-Based	4	Surface beading, minimal absorption
Beetroot-Based	3	Minor dampness, slight water penetration
Coffee-Based	2	Noticeable absorption, required beeswax coating

5.3. Fire Resistance Test

Fire tests measured the time to ignition under direct flame (1 cm distance). The results were:

Table 2. Fire Resistance (Time to Ignition) of Vegan Leather Samples

Material	Time to Ignition	Observation
Charcoal-Based	6.0 minutes	High resistance; flame extinguished naturally
Beetroot-Based	5.0 minutes	Moderate resistance; slow combustion
Coffee-Based	0.075 minutes (4.5s)	Quick ignition; fast flame spread

5.4. Structural Integrity and Bending Strength

- Fabric-backed versions outperformed standalone leather in strength, offering higher resistance to cracking during bending.
- Charcoal-based leather, in particular, maintained structural integrity under repeated folds.
- The beetroot-based variant was more elastic but showed slight softening under stress.
- Coffee-based leather was least durable under bending, requiring reinforcement.

5.5. Comparison with Existing Alternatives

Table 3. Comparison of Developed Vegan Leather with Animal and Commercial Alternatives

Criteria	Animal Leather	Piñatex / Apple Peel	Developed Leather
Material Source	Animal hide	Agricultural waste (PU coated)	Beetroot/Coffee/ Charcoal + Alginate

Biodegradability	Low (due to tanning)	Moderate	High
Water Resistance	Naturally high	Moderate (needs coating)	High with beeswax treatment
Fire Resistance	Moderate	Low to moderate	High (Charcoal), Moderate (Beetroot)
Cost	High	High	Low (locally sourced)
Sustainability	Low	Moderate	High

5.6. Texture and Flexibility Evaluation

Samples were scored based on visual and tactile inspection using a 5-point scale (1 = poor, 5 = excellent):

Table 4. Texture and Flexibility Scores of Vegan Leather Samples

Material	**Texture Score (1–5)**	**Flexibility Score (1–5)**
Charcoal-Based	4	3
Beetroot-Based	5	4
Coffee-Based	3	2

Beetroot-based leather received the highest texture and flexibility scores, making it ideal for flexible fashion items.

Charcoal-based leather scored well in texture but was slightly stiffer.

Coffee-based leather had moderate texture but lower flexibility, requiring improvement for wearable applications.

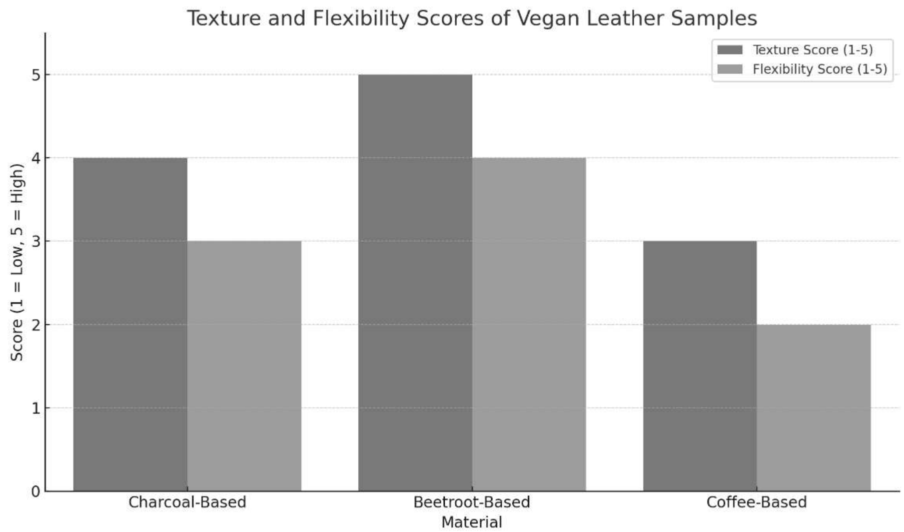

Figure 2: Texture and Flexibility Scores of Vegan Leather Samples

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- **Charcoal-based leather** scored well in texture but was slightly stiffer.
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5.7. Bending Strength and Cost Comparison

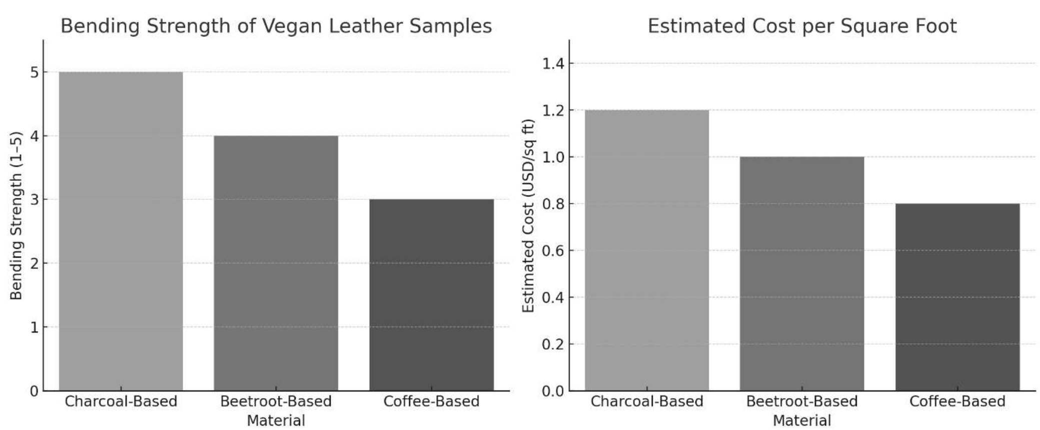

Figure 3: Bending Strength and Cost Comparison

Bending strength was rated based on resistance to cracking and structural retention during repeated folds. Estimated production costs per square foot were calculated based on material inputs and local resource availability.

Table 5. Bending Strength and Estimated Cost of Vegan Leather Samples

Material	Bending Strength (1–5)	Estimated Cost (USD/sq ft)
Charcoal-Based	5	1.20
Beetroot-Based	4	1.00
Coffee-Based	3	0.80

- **Charcoal-based leather** demonstrated the highest bending durability but was the most costly due to processing and conditioning needs.
- **Beetroot-based leather** struck a balance between strength and affordability.
- **Coffee-based leather** was the most cost-efficient but showed lower structural resilience.

6. Summary of All Performance Metrics

Table 6. Summary of All Performance Metrics of Vegan Leather Samples

Performance Metric	Charcoal-Based	Beetroot-Based	Coffee-Based
Water Resistance (1–5)	4	3	2
Fire Resistance (min)	6.0	5.0	0.075
Texture Score (1–5)	4	5	3
Flexibility Score (1–5)	3	4	2
Bending Strength (1–5)	5	4	3
Cost (USD/sq ft)	1.20	1.00	0.80

The results confirm that alginate-based vegan leather has the potential to serve as an eco-friendly, functional substitute for both animal and synthetic vegan leathers. Notably:

- **Charcoal-based leather** excels in fire resistance and structural stability, making it suitable for footwear and accessories.

- **Beetroot-based leather** combines color vibrancy and flexibility, ideal for fashion applications like bags and chokers.
- **Coffee-based leather**, while aesthetically pleasing, requires further optimization to improve fire and water resistance.

7. Conclusion and Future Recommendations

Conclusion

This study developed three types of biodegradable vegan leather using sodium alginate combined with beetroot, coffee, and charcoal—leveraging locally available resources in Bangladesh. Charcoal-based leather showed superior fire resistance and durability; beetroot-based variants were most flexible and visually appealing; coffee-based leather was cost-effective but less robust. The materials proved more affordable and environmentally friendly than commercial vegan leathers like Piñatex or apple leather. While results confirm the potential of alginate-based composites for sustainable fashion, challenges remain in scalability and mechanical validation. Pilot production, quality control, and industry collaboration are essential next steps. Overall, the study demonstrates a viable path toward cruelty-free, cost-effective, and eco-friendly leather alternatives suitable for fashion, accessories, and footwear.

Future Recommendations

Despite the promising results, several areas require further exploration:

Advanced Mechanical Testing

Future studies should incorporate lab-based tensile strength, tear resistance, and abrasion testing to validate the materials' usability for commercial applications.

Fireproofing Optimization

The integration of natural flame retardants (e.g., borax, kaolin clay, or wool protein) should be tested to enhance fire resistance without compromising biodegradability.

Waterproofing Enhancement

Although beeswax provided basic water resistance, other plant-based hydrophobic coatings should be explored for more effective moisture control.

Life-Cycle Assessment (LCA)

Comprehensive environmental impact assessments—including carbon emissions, water footprint, and end-of-life decomposition—should be conducted to quantify sustainability benefits.

Scalability and Industrial Production

Pilot-scale production trials are recommended to evaluate the feasibility of mass production, supply chain integration, and quality control.

Consumer Perception and Market Research

Surveys and focus groups with designers, retailers, and consumers could offer insights into acceptance, design preferences, and pricing tolerance.

Policy and Industry Collaboration

Partnerships with eco-conscious fashion brands and support from government bodies could accelerate mainstream adoption, especially through sustainability incentives or green certifications.

With proper research, industrial investment, and consumer education, plant-based vegan leather—particularly those developed in this study—can become a mainstream solution for a more ethical, affordable, and environmentally sustainable fashion industry.

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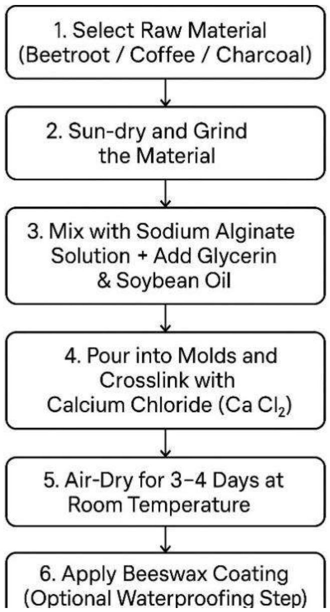
Appendix

Appendix A: Materials Used in Sample Preparation

Component	**Function**
Sodium Alginate	Biopolymer base; provides structure and flexibility
Calcium Chloride	Crosslinking agent; enhances strength
Glycerin	Plasticizer; improves softness
Soybean Oil	Conditioning agent; enhances durability
Beetroot	Natural colorant and fiber source
Coffee Grounds	Provides oil, texture, and color
Activated Charcoal	Adds strength, texture, and dark color
Distilled Water	Solvent; ensures purity
Beeswax	Natural waterproofing treatment

Appendix B: Flowchart of the Vegan Leather Development Process



Appendix C: Home-Based Test Protocols

C.1 Water Resistance Test Procedure

- Spray water lightly on sample surface.
- Observe surface beading, absorption, or penetration.
- Wipe with tissue after 5 minutes and record moisture level.

C.2 Fire Resistance Test Procedure

- Hold sample 1 cm from an open flame using tweezers.
- Record time until ignition.
- Observe burning behavior, smoke emission, and self-extinguishing capacity.

C.3 Flexibility and Bending Test

- Bend sample in multiple directions.
- Note any cracks, stiffness, or structural changes.

- Repeat test with both standalone and fabric-backed samples.