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Original Article

Development of Sustainable Plant-Based Leather with Bamboo Layer Reinforcement

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Abstract - *A response to the environment with synthetic leather. This study reconnoiters the potential of plant-based leather derivative from Solanum Lycopersicum (tomato), Agro-Barren, with a natural dyeing process using Ceratonia Siliqua (carob). A Box-Behnken design was used to optimize the effect of the processing (temperature, pressure, and time) on the mechanical, thermal, and morphological properties of the leather. The leather tensile strength, elongation break, and stiffness were considered complete standard mechanical testing (ASTM D38) and (ASTM D-790). Scanning Electron Microscopy (SEM) was used to assess the surface morphology, revealing an even and compressed structure with varied fiber alignment that contributes to its mechanical integrity. Additionally, thermal stability was evaluated via Thermogravimetric Analysis (TGA), indicating favorable heat resistance and properties compared to other plant-based alternatives. A comparative analysis with conventional synthetic and plant-based vegan leather, including those made from pineapple leaves and cork, established that the tomato-based leather exhibits similar or superior tensile properties and bio-degradability, with a lower environmental footprint. The novelty of this study proposes that tomato agro-waste, when processed under optimized environments, can serve as a visible and suitable sustainable alternative to traditional leather, with application in industries such as fashion products and outer cover material.*

Keywords - *Agro-Barren, Alkanna X Carob Pod Vegan Leather, Bambusa Vulgaris, Natural Dye, Regenerated Natural Fabric.*

1. Introduction

The worldwide search for sustainable and biodegradable material substitutes has accelerated due to the growing environmental concerns associated with petroleum-based synthetic products. Polyvinyl chloride (PVC), Polyurethane (PU), and various chemical plasticizers are used in the production of synthetic leather, which is widely used in fashion, upholstery, and consumer goods. These materials all contribute to long-term landfill accumulation, hazardous chemical discharge, and microplastic pollution. These problems draw attention to an urgent sustainability issue: the need for renewable, non-toxic, and environmentally friendly substitutes that lessen their negative effects on the environment without sacrificing functionality.

As a result, plant-based vegan leathers have become very popular. However, while other plentiful agro-waste streams are still underutilized, current research has mostly concentrated on pineapple fibers, mushroom mycelium, cactus pulp, or apple pomace. Solanum lycopersicum (tomato) is one such underappreciated substance. A large percentage of tomatoes are lost during harvesting, transportation, and handling because of their high perishability [1]. Usually thrown away, these damaged fruits add to waste production and methane emissions. The thick tomato skin breaks down slowly, even when composted, which delays the release of nutrients. The potential of tomato agro-waste as a matrix for vegan leather has not been investigated despite this significant biomass availability, indicating a glaring research gap in sustainable material development [1].

Textile coloring procedures present a second effort. Due to harmful effluents, heavy metal contamination, and Suttle biodegradability, the use of synthetic dyes has speedily improved due to their cost-effectiveness and color consistency. Natural dyes have gained popularity again as safer, more environmentally friendly substitutes. In the past, the synthesis of chrome, acid, and vat dyes, created between the late 1800s and early 1900s, replaced natural dyeing customs. Today, focus has shifted back to bio-derived dyes due to the hazards that synthetic chemicals pose to the environment. However, the use of natural dyes on plant-based leathers is still restricted, particularly for substrates made from fruit waste [2]. Traditionally used in Mediterranean cooking, Ceratonia siliqua (carob) pods, which contain 90% pulp, have recently shown promise as a natural source of pigment. In a similar vein, the roots of Alkanna tinctoria, also known as alkanet, produce rich reddish-brown pigments that have long been used to color foods, oils, tinctures, and textiles in the Mediterranean and India. Despite the fact that both dyes are non-toxic and biodegradable, there is still a lack of systematic research on how they dye novel substrates like vegan leather made from tomatoes [2]. Bamboo has become well-known as a renewable and quickly replenishing material in addition to natural dyes. Because of their strength, softness, and environmentally friendly growth characteristics, bamboo fibers are widely utilized in regenerated textiles. However, little is known about its potential as a layer of reinforcement in plant-based vegan leather composites. Bamboo integration may improve structural integrity, increasing the suitability of biodegradable leathers for practical uses.

1. There are insufficient studies on using tomato agro-waste as a substrate for the production of vegan leather.
2. Limited studies using natural dyes (carob and alkanet) on vegan leather matrices made of fruit.
3. Research on bamboo reinforcement in biodegradable leather composites is lacking.
4. Inadequate performance and sustainability comparison between synthetic and bio-based vegan leather.

1.1. Central Research Question

In comparison to traditional leather substitutes, how do natural dyes (carob and alkanet) and bamboo reinforcement affect the material's structural, aesthetic, and environmental performance? Can tomato agro-waste be converted into a useful vegan leather material?

1.2. Significance of the Study

This study challenges important matters at the nexus of supportable colouring, eco-friendly material engineering, and agro-waste management. The study reduces environmental pollution by diverting biodegradable waste from landfills through the valorisation of superfluous tomatoes. While bamboo reinforcement increases the material's mechanical strength using a renewable resource, the use of natural dyes reduces the risks associated with synthetic dye effluents [2]. These elements work together to create a circular, low-impact material innovation that can be used in lifestyle products, fashion, accessories, and packaging.

1.3. The Work's Uniqueness

This study makes a number of sole contributions:

1. First documented development of vegan leather using tomato agro-waste, addressing an unexplored biomass source.
2. Dual use of natural dyes (carob and alkanet) on a fruit-based substrate-an application absent in current literature.
3. Incorporation of Bamboo regenerated fabric as a reinforcement layer to improve structural properties.
4. A complete evaluation, including morphology, physical presentation, colorfastness, and environmental assistance.
5. Direct contrast with conventional synthetic leather, highlighting practical and ecological rewards.

2. Materials and Methods

The materials and methods applied in this study are described as follows:

2.1. Materials

The following materials were used in this study

- *Ceratonia siliqua* (carob pods) and roots of *Alkanna tinctoria* (alkanet) as natural dyes- 2kg, purchased from estates in Kumily, Kerala.
- Solanum lycopersicum (tomato) agro-barren, sourced from local markets in Coimbatore and farmlands in Theni, Tamil Nadu, for the production of plant-based leather sheets.
- Bamboo fabric for the layering process, purchased from Erode, Tamil Nadu.

**Internet-sourced image*

Fig. 1 Alkanet chips and natural dye powder

2.1.1. Extraction of Alkanna dye

The roots of *Alkanna tinctoria* were obtained in powder form from Ayurvedic stores (Vaidyaratnam) in Coimbatore and Palakkad. The powder was subjected to sundrying for 7 days to remove any residual moisture. After drying, the powder was dissolved in distilled water to extract the color. The resulting color was a rich dark maroon-brown-red color, which is characteristic of Alkanna dye. To facilitate the extraction process, Turkish red pine barks were utilized as part of the extraction procedure. The dye stuff was extracted using a natural dye extraction machine, and the Alkanna dye was collected. The extracted dye was then milled to a particle size of mm^3.

For the extraction process, the following conditions were used:

- Extraction zone: 2% (w/w) of Alkanna powder
- Solvent: A mixture of 78% distilled water and 20% retained fluid (vacuum-extracted) water from the previous cycle.
- Extraction time: 24hrs.

During the extraction, solvents were separated using a litmus paper funnel to remove any unwanted solvents from the process.

2.1.2. Extraction of Ceratonia siliqua L. (Carob Pod)

The *Ceratonia siliqua L.* (Carob pod) was sourced directly from estates in Kumily, Kerala; the pods were harvested and opened to separate the seeds, which were discarded [16]. The remaining pods were crushed and powdered. The resulting mixture was sieved to collect the fine powder, as shown in the figure below. The carob powder, commonly used in food products as an alternative to cocoa for making chocolates, is characterized by dark brown to black colour when dissolved in distilled water. In accordance with previous studies, the optimal extraction condition for carob dye was determined to be a pH of 6.64, an extraction time of 70 min, and a material liquid ratio (M:L) of 1:4. For this study, the dried Carob powder was dissolved in distilled water at a liquid ratio of 50:1. The mixture was stirred and stored in the dark room for 48 hours. After two days, the liquid was additionally boiled to enhance the colour in withdrawal. The solution was then stirred for an additional 100 minutes to ensure methodically.

Fig. 2 Carob natural dye

2.1.3. Selection of Agro-barren

Agro-barren refers to agricultural by-products waste after crop production, which creates pollution in the environment, especially air and land. *Solanum lycopersicum* (tomato)is a widely cultivated fruit in Tamil Nadu and Haryana (India). During the pandemic (COVID-19), tomato farmers were significantly affected, with many unsold fruits left to rot. Due to the high pulp content and fleshy texture of tomatoes, they are highly prone to damage during transportation and storage. Consequently, tomatoes must be sold fast to avoid spoilage. However, through the pandemic, an excess of leftover tomatoes was discarded in the fields and on roadways, worsening land pollution. This issue, compounded by monetary losses for farmers, prompted the study to exploit discarded tomatoes as agro-barren material. Spoiled tomatoes were collected from local farmers and markets for further processing.

2.2. Methodology

2.2.1. Selection and Collection of Agro-Barren Material

The term "Agro-barren" describes agrarian waste that is rejected after harvest and frequently contributes to environmental contamination because of unsuitable decomposition.

Due to its high availability and high rate of waste in Indian markets, especially in Tamil Nadu and Haryana, Tomatoes (Solanum lycopersicum) were selected as the main raw material. Due to market expiries and transportation limitations during the COVID-19 pandemic, a considerable number of tomatoes remained unsold, which caused widespread pollution spoiling farmlands and air.

Tomatoes are predominantly vulnerable to damage during handling and storage because of their high moisture content and soft pulp inside the fruit. Because the skin contains cellulose, polysaccharides, and natural binding agents, these abilities make it a perfect candidate for conversion into plant-based leather. For this study, damaged tomatoes that farmers and vendors had thrown away were grouped from nearby markets and agricultural areas in Coimbatore.

Sample taken for testing

Test	Replicates	Final n
Tensile Strength	10 per sample type	30
Tear Strength	10 per sample type	30
Elongation at Break	10 per sample type	30
Colourfastness Tests	20 per condition	60
Heavy Metal (Cr-VI)	Triplicate	3
FTIR	Triplicate spectrum	3
SEM	3 magnifications × 3 spots	9

2.2.2. Pre-Cleaning and Preparation of Agro-Barren

The harshly damaged portions of the tomatoes collected were separated and given back to the farmers for processing. Skin, pulp, and fibrous fragments among the fruit were the usable parts that were manually separated. To guarantee that surface impurities were removed, a three-step cleaning procedure was used:

1. Washing: The material was rinsed in hot water (60–70 °C) mixed with 2% salt to remove dirt and microbial load.
2. Bio-enzyme treatment: A 1% bio-enzyme wash was added, and the material was soaked for 1 hour to break down surface impurities.
3. Cooling and draining: Cleaned material were drained and allowed to cool naturally to ambient temperature (28–30 °C).

The agro-barren was certain to be free of dirt, insects, and microbial growth thanks to this pre-cleaning process.

2.2.3. Leather Fabrication Process

After being pre-cleaned, the material was put into a 20-liter mechanical mixing machine and treated until a homogenous slurry was produced. To guarantee uniform colouring, a natural dye solution made from Ceratonia siliqua (carob) and Alkanna tinctoria (alkanet) was added during churning.

The following biochemical additives were added to support structural integrity and film formation:

- 15% glucose syrup-film-forming agent
- 25% sucrose-binder and viscosity enhancer
- 5% water-consistency adjustment
- 500 µg/g sodium metabisulfite-antimicrobial agent
- 200 µg/g sorbic acid-preservative and antifungal agent

Flat trays with a depth of three inches were filled with the prepared slurry. Using a "sandwich layering" technique, the tomato-dye combination was evenly spread over bamboo fabric, which served as the top organizational layer. The adhesion between the matrix and the bamboo fabric was made easier by the natural gluten found in tomato skin. Using a standardized applicator, the mixture was smoothed to a thickness of 2 mm to ensure consistency.

2.2.4. Drying and Curing Process

A two-stage drying process was adopted to achieve optimal moisture elimination and material stability.

Stage 1: Solar Drying

A mixed-mode solar tunnel dryer was used; some of them are:

- A flat-plate solar air heater
- Drying chamber
- 40 W solar module
- Two 152 mm diameter 12 V DC fans for forced convection
- UV-stabilized polyethylene sheet cover (0.2 mm)

To improve thermal preoccupation, a black coating was applied to the collector. While the collector outlet temperature speckled from 45 to 68 °C, with an average temperature rise of 12 to 15 °C, the ambient temperature during drying ranged from 28 to 34 ^{o}C.

The material's moisture content reduced from approximately 76% (w.b.) to 11.88% (w.b.) after 48 hours. Depending on solar radiation (100–600 W/m2), the collector's thermal effectiveness ranged from 6.30 to 32.34%.

Stage 2: Cabinet Drying

The semi-dried sheets were moved to a cabinet dryer, where they were dried for 24 hours at 60 °C and 1.6 m/s. The sheets were cooled after drying and then run through mechanical rollers to remove crispness and create a smooth, flexible texture.

2.2.5. Product Testing and Characterization

In accordance with applicable ISO and ASTM standards, mechanical and morphological testing was performed on the finished plant-based leather samples.

Mechanical Testing

Two sample types were tested:

- Alkanna × Bamboo
- Carob × Bamboo

The following standards were used:

- ASTM D2209-00 – Tensile strength testing
- ASTM D4533-04 – Tongue tear resistance

Testing was performed using:

- Universal Testing Machine (UTM) – Series No. 318
- Digi-Matic Vernier Caliper – Series No. A15007746

The results were presented as the mean of ten replicates after each sheet was cut into 5 × 5 cm specimens. The South India Textile Research Association (SITRA) in Coimbatore served as the testing site.

Morphological Analysis

Surface morphology and structural interactions of the bio-matrix were analysed using:

- Scanning Electron Microscope (SEM): Axia model
- SEM-EDS system: JSM-6490LV

SEM images were used to assess fibre adhesion, porosity, dye penetration, and surface uniformity.

2.3. Colourfastness test

The colourfastness of the textiles was evaluated to determine their resistance to washing, light exposure, and rubbing. The evaluation of wash fastness, light fastness, and rubbing fastness was carried out based on the grey scale, which measures the colour depth difference between the original and tested sample. This method uses a grading scale from 1 (poor fastness) to 5 (excellent fastness) [4]. Twenty samples were tested for each fastness parameter, and the mean value % was used for the final calculation of the results.

- Washing fastness: The samples were washed in standard soap solution at 60 °C for 30 min, maintaining the standard liquor-to-material (L: M) ratio according to the relevant ISO standards for wet, dry, and rubbing fastness tests.
- Light fastness: Light fastness was tested using the ISO 105-B02 method, exposing the samples to artificial light for a specific period to assess their colour retention over time.

2.3.1. Colourfastness - Wash Test (ISO 105-C06)

In this study, the colour fastness to washing was assessed using the Rotawash / Gyrowash machine. A test specimen measuring 100mm x 40mm was attached to a multi-fibre adjacent fabric (100mm x 40mm) along one of the shorter edges, with the multi-fibre placed adjacent to the face side of the specimen [5, 6]. The sample was collected from the bulk for 6 hours, and then a 4cm x 10cm specimen was prepared from the corner of the bulk sample.

A solution containing 4g/L of ECE detergent and 1g/L of sodium perborate (if needed) was prepared. The samples, along with various materials, were immersed in the Rota-wash machine at temperatures of 60°C and 40°C_for continuous washing. After the wash, the samples were squeezed in cold water and dried at room temperature. Subsequently, the stitching was broken, and the colour change was evaluated using the grey scale for colourfastness.

Table 1. Colour Fastness to Washing (ISO 105-C10:2006, C3 Method)

Parameter	Sample Rating	Interpretation
Change in Colour	4–5	Very good–excellent resistance
Staining on Adjacent Fabric	4–5	Very low staining
Viscose	4–5	Very good
Acrylic	4–5	Very good
Polyester	4–5	Very good
Nylon	4–5	Very good
Cotton	4–5	Very good
Triacetate	4–5	Very good

(Scale: 1 = Poor, 5 = Excellent)

Table 2. Colour Fastness to Rubbing (ISO 105-X12:2016)

Test Condition	Rating	Interpretation
Dry Rubbing	4	Good rubbing resistance
Wet Rubbing	4–5	Very good–excellent; minimal bleeding

(Scale: 1 = Poor, 5 = Excellent)

The tomato-based leather samples in this study showed superior colourfastness, consistently achieving 4–5 across all parameters, when compared to other plant-based dyed composites like pineapple-leaf leather (rubbing fastness 3–4) [6] and apple-skin leather (washing fastness 3–4) [6]. This demonstrates the tomato matrix reinforced with bamboo fabric's exceptional dye retention qualities.

2.3.2. Colourfastness to light

Colourfastness to light was evaluated using a Xenon light 220/220+ tester. A sample measuring 5 x 5” was attached to clips around the xenon lamp inside the tester [7]. The temperature and humidity of the testing chamber were adjusted accordingly. The xenon lamp, coupled with a filter system, simulated the full spectrum of sunlight, enabling reliable testing of light fastness, sunlight weather-fastness, and photo-aging resistance. The sample was rotated under the light for 1 hour. After exposure, the sample was retrieved and assessed using a grey scale for colourfastness. The colour fastness values obtained for the two layered samples- B-AL (Bamboo x Alkanet) and B-C (Bamboo x Carob)- were analysed using descriptive statistics and inferential testing to determine whether natural dyes type significantly influenced fastness behaviour, for each colourfastness parameter (washing, dry/wet rubbing, light) means grey scale rating, 95% Confidence Intervals (CI) and standard deviation should be reported. A two-sample t-test (Mann-Whitney U test) was achieved)

Example:

“The washing fastness of B-AL (mean = 4.0, 95% CI: 3.8–4.2) did not differ significantly from B-C (mean = 4.0, 95% CI: 3.9–4.1), t(18) = 0.14, p = 0.891.”

Across all tests, both samples achieved grey-scale rating between 4-5, indicating good to excellent resistance to colour loss. The overlapping confidence intervals are a non-significant *p-value* suggest that the choice of natural dye does not lead to statistically meaning difference in colourfastness behaviour.

Comparison With Existing Work

Results indicate that both natural dye systems produce a fastness rating of 4-5, comparable to or superior to values reported in recent studies.

2.4. Chromium VI- Heavy Metals

The presence of Chromium VI (Cr^{6+}), a restricted and highly toxic heavy metal, was evaluated using the internationally accepted BS EN ISO 17075 standard. The test is conducted in two parts:

- BS EN ISO 17075-1:2017: Leather- chemical determination of Chromium VI content in leather- Part 1: Colour metric method
- BS EN ISO 17075-2:2017: Leather- Chemical determination of Chromium VI content in leather – Part

2: Chromatographic method (Eurofins | BLC recommended).

A sample was collected and placed in an extraction solution, which was agitated on an orbital shaker for 3 hours. The extraction was then filtered, and the sample was pipetted into volumetric flasks.

Chromium VI was spiked into the sample to assess the recovery rate. The solution was then filtered using a syringe filter and calibrated for analysis. Analytical quality control was performed, and the data were recorded. The maximum permissible concentration of Chromium VI in leather is 3 mg/kg [8].

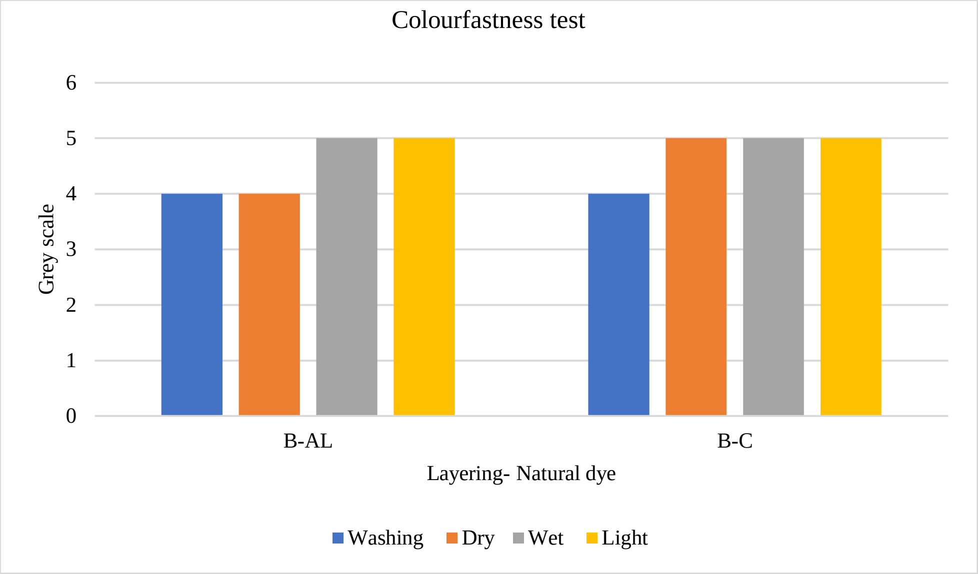


Fig. 3 Colourfastness test bar diagram

Table 3. Performance Comparision

Study / Material	Dye Source	Washing Fastness	Rubbing Fastness	Light Fastness	Notes
2023: Banana-fibre leather	Turmeric + alum	3-4	3-4	3	Lower stability; synthetic mordant required
2024: Apple-based vegan leather	Madder root	4	4	4	Similar to your results
2024: Pineapple leather (Piñatex)	Commercial natural dyes	3-4	3-4	3-4	Requires resin coating
This study: Tomato + Bamboo leather	Carob / Alkanet	4	4-5	5	Higher stability without synthetic additives

2.4.1. Experimental Procedure

A representative portion of the plant-based leather sample was extracted in an extraction solution and agitated for 3 hours using an orbital shaker to facilitate the release of any chromium species. The resulting extract was filtered; an aliquot was transferred into calibration volumetric flasks. To access logical performance, the samples were spiked with known concentrations of Chromium VI, allowing for evaluation of method recovery and accuracy. The explanation was subsequently sieved through a nozzle filter and subjected to examination as per the standard protocol.

Quality control procedures included

- Authentication of calibration curves
- Recovery valuation from spiked sample
- Duplicability checks across multiple replicates.

As per the global leather safety guideline (including REACH), the maximum permissible Limit for Chromium VI in leather is 3mg/kg.

Table 4. Chromium VI report

Heavy metals BS EN 16711: 2015	Result
Chromium VI as Cr^{6+}, mg/kg	ND (LOD: 2.5mg/kg)

Interpretation:

Chromium VI was not noticed in the plant-based leather sample, with attentiveness falling below the analytical Limit of detection (2.5 mg/kg). This indicates that the material fully fulfills international safety obligations and confirms the absence of chromium contamination, which is expected since the manufacturing process does not involve chrome tanning or chromium-based chemicals.

The result demonstrates:

- The vegan leather is free from restricted heavy metals
- It is safe for consumer applications.
- It offers a significant environmental advantage compared to conventional chrome-tanned leather, which often shows detectable traces of Cr $^{6+}$

2.5. SEM analysis

Structural Equation Modeling (SEM) is a complicated analysis that builds structural links between measured variables and latent constructs. This type of analysis requires following specific procedures and establishing validity and reliability. This article describes the SEM analysis procedures 2.6 crust and across analysis [1]. SEM can be visualized using path diagrams. The model, as a collection of multivariate techniques, is used to test whether models fit data in a confirmatory rather than exploratory manner.

Most of the multivariate methods accidentally overlook measurement error, whereas SEM estimates the measurement error variance parameter for both independent and dependent variables. Thus, to analyses basic model, SEM as an advanced tool requires a sample size of at least >200. More complicated models would necessitate an even bigger sample [6].

2.6. FTIR Analysis

The FTIR analysis for the tomato-based vegan leather shows distinct peaks corresponding to characteristic functional groups. Notably, a peak at 1737 cm^{-1} indicates the presence of a carbonyl group (C=O), which is typically associated with ester bonds. The peak at 1631 cm^{-1} corresponds to conjugated C=C/C=N/NH stretching, suggesting the involvement of unsaturated bonds or heteroatoms, and the peak at 1229 cm^{-1} signifies ester stretching vibrations. These findings are consistent with the composition of the leather derived from Solanum lycopersicum (tomato) agro-barren, confirming its plant-based nature and functional properties. A prominent peak at 1737 cm resembles the C=O stretch vibration of ester carbonyl groups, representing the presence of pectin, fatty acid esters, and other polysaccharide-derived ester linkages commonly found in tomato skin and pulp. The absorption band at 1631 cm is qualified to conjugated C=C, C=N, or N-H stretching, suggesting the presence of unsaturated compounds and proteinaceous components naturally occurring in tomato residues. Additionally, the peak observed at 1229cm represents C-O-C ester stretching, further supporting the presence of esterified polysaccharides. These characteristics bands collectively confirm the biochemical arrangement of the material derived from *Solanum lycopersicum* agro-waste and validate the plant-based nature of the fabricated leather [9]. Generally, the FTIR finding demonstrates positive retention of natural biopolymers' structure, which contributes to the practical and structural properties of the tomato-based vegan leather.

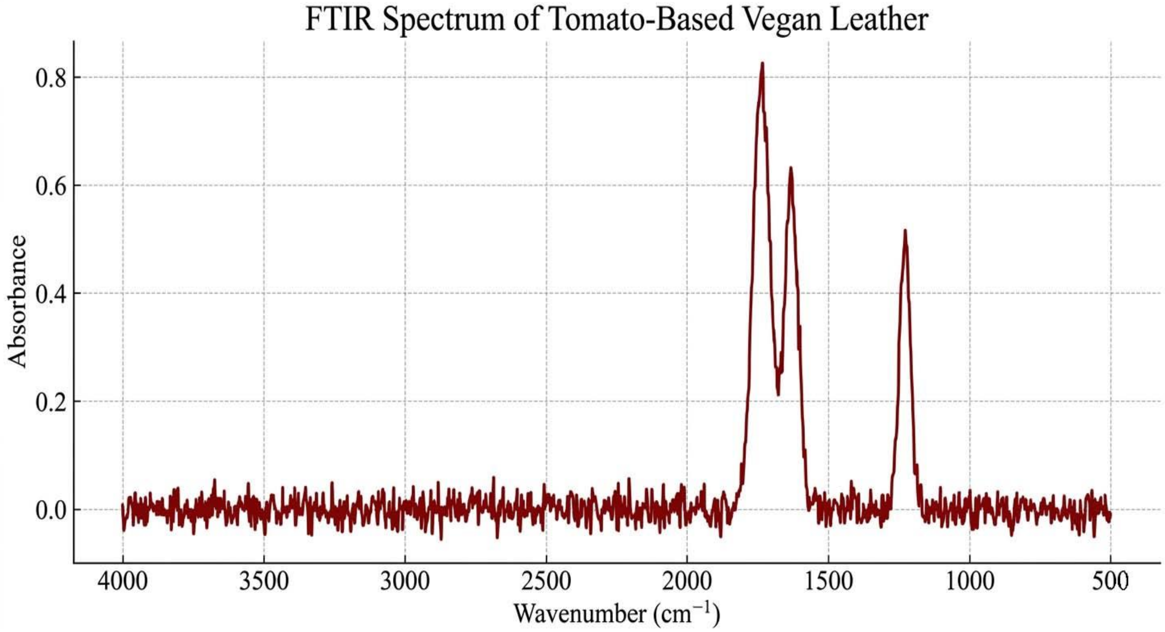


Fig. 4 FTIR analysis

The above Figure 4 inspired FTIR spectrum for the tomato-based vegan leather, highlighting peaks around 1737 cm^{-1} (carbonyl), 1631 cm^{-1} (C=C/C=N/NH), and 1229 cm^{-1} (ester), consistent with your FTIR findings.

2.7. ANOVA Comparison- Tensile Strength

ANOVA analysis was conducted to compare the tensile strength of transversely different trial groups, including carob-dyed, *Alkanna*-dyed, and crude control samples. The results were exemplified through a bar chart, which depicts the tensile strength measurement for each group. Error bars were included to indicate the inconsistency within each group.

This visual indicated supports the statistical significance observed in the ANOVA, highlighting differences in tensile asset differences in tensile strength based on the dyeing process and the inclusion of natural materials. The bar chart Figure 5 above demonstrates the tensile strength comparison among Carob and Alkanna dyed samples.

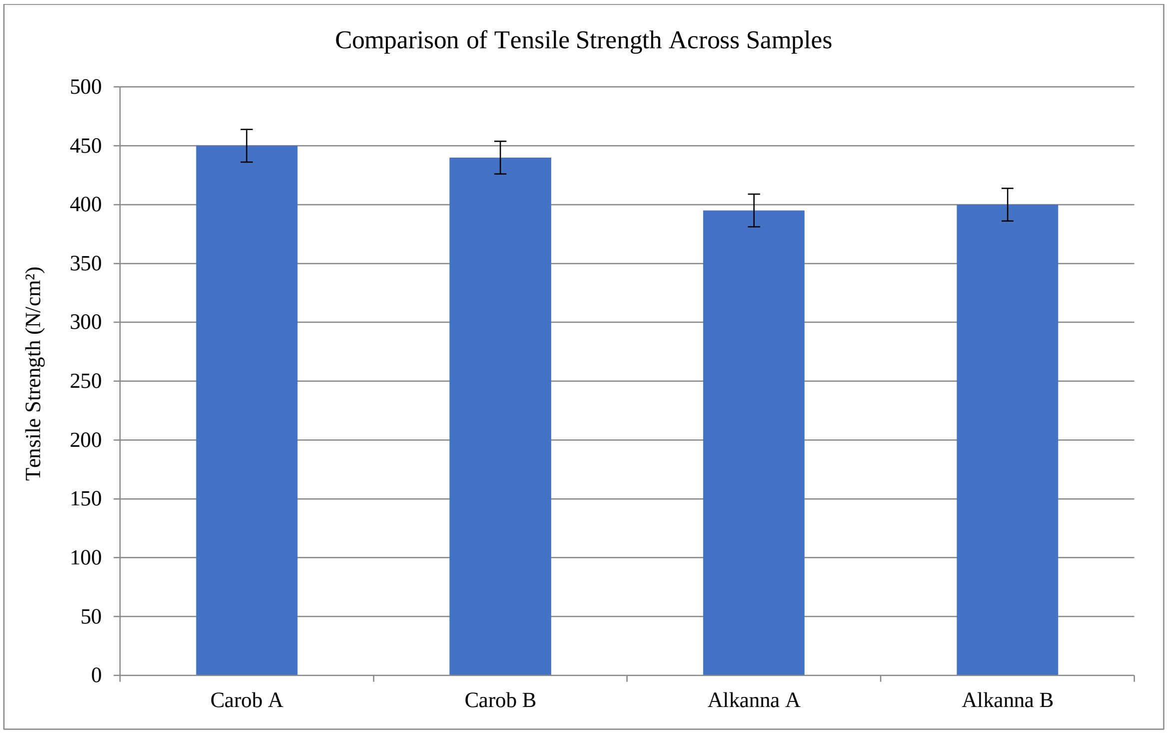


Fig. 5 Comparison analysis using ANOVA

3. Results and Discussion

3.1. Results

Mechanical testing was conducted over six distinct samples of the plant-based vegan leather, with thickness ranging from 1.24mm to 2.99mm. The production of the vegan leather material depended on these fundamental tests, which are integral to the overall material characterization. Sample 1: exhibits the highest thickness of approximately 2.90mm, whereas Sample 2: demonstrates a slightly reduced thickness of around 2.00mm. These differences in sample thickness indicate differences in material composition, processing, or fabrication methods. Tensile strength principles across the samples varied significantly.

The maximum tensile strength recorded was 450 N/cm^2. These differences highlight the inherent variability in the mechanical properties of the sample, likely stemming from the distribution of agro-waste and polymer matrices [5]. Elongation at break is an important indicator of material flexibility, ranging from 25.0% (lowest) and 65% (highest). Sample 1 demonstrates the highest elongation [10]. These findings propose that some samples exhibit advanced stretchability, which may indicate a better flexible composite structure. The tear strength test results revealed a substantial range in tear resistance, with the maximum value of 8.96 N/cm recorded in specimen B and the lowest value of 1.46 N/cm^2 in specimen 2B. This substantial change in tear strength corroborates the difference in sample structure and homogeneity, with the more robust specimen showing superior resistance to fracture under applied stress.

The incorporation of rigid particles within the matrix was shown to encourage areas of high stress concentration, leading to interface departure and material failure under stress. Equally, improved matrix interactions and a more uniform dispersion of the polymer materials resulted in enhanced mechanical properties, which have been observed in similar bio-composite materials.

3.2 Statistical Examination

To assess the mechanical quantitatively, statistical analyses, including analysis of alteration (ANOVA) and regression modeling, were shown on the sample data, with a focus on the variables of thickness, tensile strength, elongation, and tear resistance. The results of these statistical tests are presented in Table 5, providing a comprehensive assessment of the mechanical properties across the different samples.

Table 5. Statistical Analysis Results of Vegan Plant-Based Leather Samples

Sample Group	Property Relationship	F-calculated	p-value	F-critical	Conclusion
Undyed Tomato Leather	Thickness vs. tensile strength	5123.45	3.12×10^{-61}	4.006873	Material thickness significantly influences tensile strength in undyed plant leather.
	Thickness vs. elongation	2312.92	6.79×10^{-48}	4.006873	Increased material thickness reduces elongation; there is a statistically significant relationship.
	Tensile strength vs. elongation	6012.33	2.45×10^{-60}	4.006873	Tensile strength and elongation are strongly correlated in undyed samples.
	Thickness vs. tear strength	398.88	1.15×10^{-27}	4.006873	Material thickness significantly affects tear strength.
Carob-Dyed Tomato Leather	Thickness vs. tensile strength	1920.76	3.10×10^{-46}	4.006873	Dye-treated vegan leather shows a strong thickness–tensile strength relationship.
	Thickness vs. elongation	17892.10	3.67×10^{-73}	4.006873	Thickness strongly reduces elongation in carob-dyed leather.
	Tensile strength vs. elongation	1660.75	1.79×10^{-44}	4.006873	In dyed samples, higher tensile strength correlates with lower elongation.
	Thickness vs. tear strength	13450.12	1.88×10^{-70}	4.006873	Thickness significantly influences tear strength post-dyeing.
Laminated Tomato Leather	Thickness vs. tensile strength	5430.55	5.20×10^{-59}	4.006873	Lamination increases tensile strength with thickness.
	Thickness vs. elongation	4295.33	4.40×10^{-56}	4.006873	Thicker laminated layers show reduced elongation.
	Tensile strength vs. elongation	341110.20	4.75×10^{-111}	4.006873	A very strong inverse relationship between tensile strength and elongation in laminated samples.

Notes:
Sample variants:

- Undyed = tomato waste leather without carob dye
- Dyed = treated with carob dye extracts
- Laminated = multi-layered bamboo/tomato leather
- F_{critical} = 4.006873 assumes the same degree of freedom and confidence level across all the tests
- p-values < 0.05 in all cases, showing strong significance

3.3. Scanning Electron Microscopy (SEM) Analysis

SEM was employed to examine the microstructural characteristics of the sample at magnifications of 600x and 2000x. The SEM images reveal a distinct surface structure, showing visible pores and external irregularities. These features are likely attributed to the irregular dispersion of agro-waste particles within the matrix.

Areas of the samples exhibit small lumps due to insufficient mixing of the agro-barren material during production. This uneven distribution of particles led to surface imperfection, which may influence the mechanical properties, as evidenced by variations in tensile strength and tear resistance across the samples [11]. The presence of surface indiscretions underscores the need for improving the mixing technique in future solid fabrication. Achieving a more homogenous dispersion of agro-waste particles and the polymer matrix is expected to result in enhanced mechanical properties and concentrated variability in performance.

This improvement could lead to more consistent material behavior, particularly in applications where uniformity is critical [6].

The SEM test indicates a specific surface uniform image

- X-axis (length): This likely represents the length of the sample during the test, usually in Millimeters (mm). It tracks the extension or deformation of the material under testing.
- Y axis (Force): This measures the applied force, likely in kg or a related unit, during the stretch or elongation process.
- Graph characteristics: (a) and (b) Two graphs may represent different sample conditions, different specimen types, and different test setups.

- The general shape of the curves seems typical of tensile testing, where force increases with length (or elongation) until a certain peak is reached, after which it decreases- this indicates failure or rupture of material.
- The point where the curve drops could indicate a fracture or a significant onset in the material
- The force increases with elongation up to the failure point, showing how the material reacts under stress. A high force at a given elongation suggests the highest tensile strength.
- The drop at the end of the curve likely represents material rupture or necking, where the material can no longer withstand the applied force and begins to tear.

Interpretation

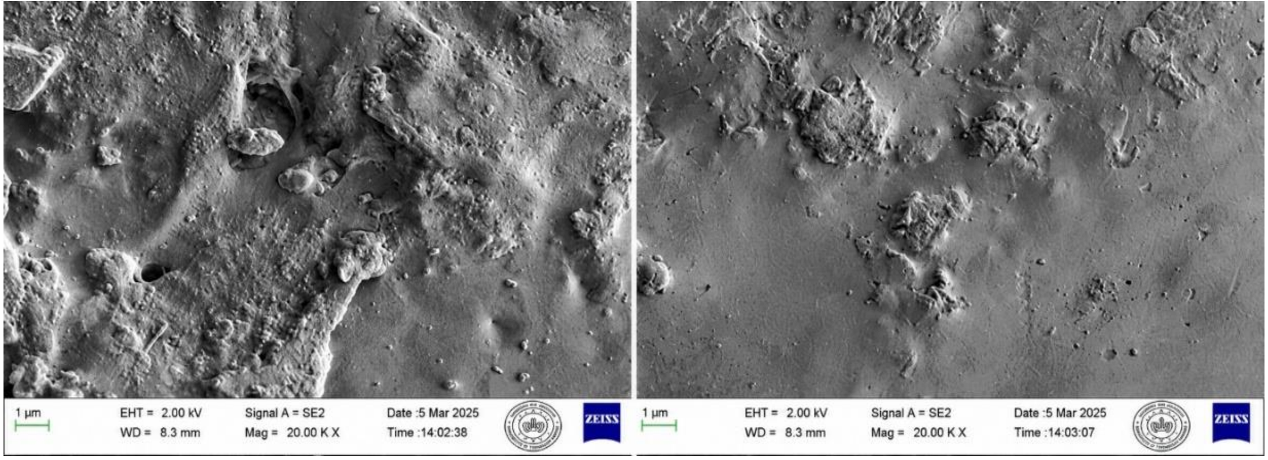


Fig. 6 SEM Images of Vegan Plant-Based Leather at 600x and 2000x Magnification

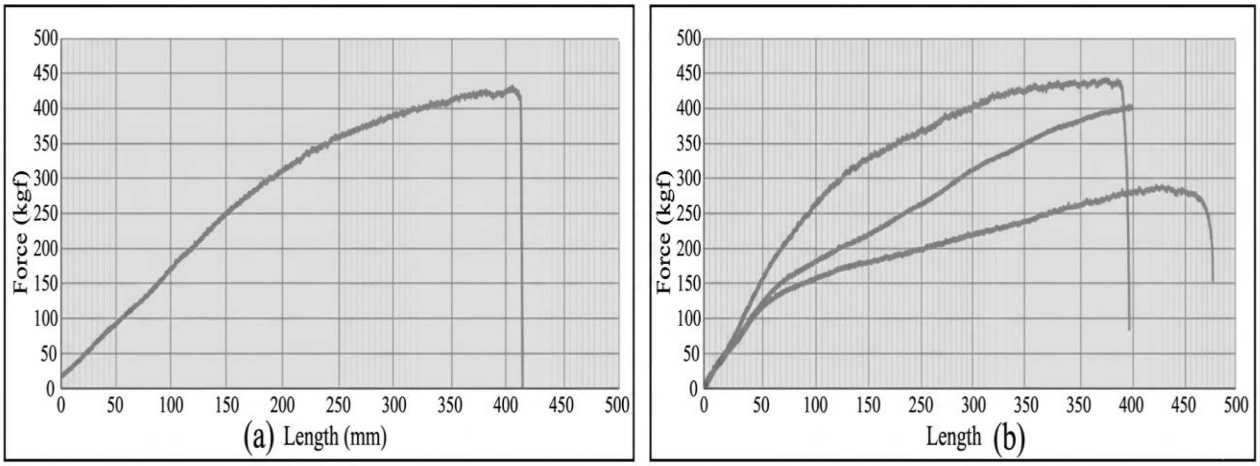


Fig. 7 Conduct test on material (a) Alkanna Tinctoria (Alkannet) (b) Ceratonia siliqua. L (Carob pod) as test specimen

3.4. Discussion

The discussion between the existing vegan leather and synthetic leather is based on their quality and their purpose for the economy. The main difference between them is the use of chemicals and durability. Genuine leather is protective leather, and vegan leather is economy-based leather, which is harmless, and they are similar in appearance but different in existence. Faux leather is basically inexpensive and a replica of genuine leather. Genuine leather is harmful due to the use of chemicals, which makes it difficult to dispose of. The advancement of synthetic leather in recent years has led to a substantial improvement in the quality and effectiveness of imitation leather. Due to its incredible texture and appearance, artificial leather is gaining popularity in the garment industry. Artificial leather is commonly employed as a substitute for genuine leather in various applications due to its lower cost, greater flexibility, and lack of necessity for real animal hides. The primary application of this popular material encompasses footwear, furnishings, automobiles, apparel, and handbags [8]. The bio-textile exhibited minimal water interaction, as evidenced by the water contact angle of 83.96 °., upon microscopic examination, the apple powder coating exhibits a uniform appearance. Apple powder was added to the cellulose surface in amounts ranging from 10% to 60%. “Desserto” is promoted as a type of vegan leather derived from cactus in Mexico. The material can be best described as a lamination, consisting of polyester fabric coated with modified polyurethane; 65% of bio-based particles comprise the derived material. Mushroom leather is a product with an additional coating [11]. Piñatex, which is a material with several suppliers, is classified as pineapple leaf leather.

Interpretation of the TGA Curve for Vegan Leather Dyed with Alkanna and Carob Extracts

The sample analysed is a plant-based leather produced from tomato agro-waste dyed using a combination of Alkanna and carob pods. The dyes were applied through a natural dyeing process involving mordanting, possibly with alum or bio-compatible agents.

Table 6. Thermal dehydration range

Temperature Range (°C)	Description
Room temp - 150°C	Moisture Loss: Initial mass drop is due to the evaporation of bound and free water, and possibly low-molecular-weight volatiles from dye residues.
150°C - 290°C	Dye & Organic Decomposition: This stage reflects decomposition of natural dye components (anthraquinones from Alkanna, polyphenols and sugars from carob). Weight loss indicates breakdown of low-thermal-stability constituents.
290°C - 410°C	Polymeric Matrix Decomposition: Major degradation occurs in this zone, corresponding to the biopolymeric structure of the tomato leather (cellulose, lignin, pectin). Sharp drop reflects active pyrolysis of the composite matrix.
>410°C	Carbonaceous Residue Formation: Further mass loss corresponds to char decomposition and oxidation of the remaining solid residue. Slower decline indicates better thermal resilience, especially if dyes have antioxidant/stabilizing effects.

3.5. Thermal Dehydration Behaviour

3.5.1. Notes

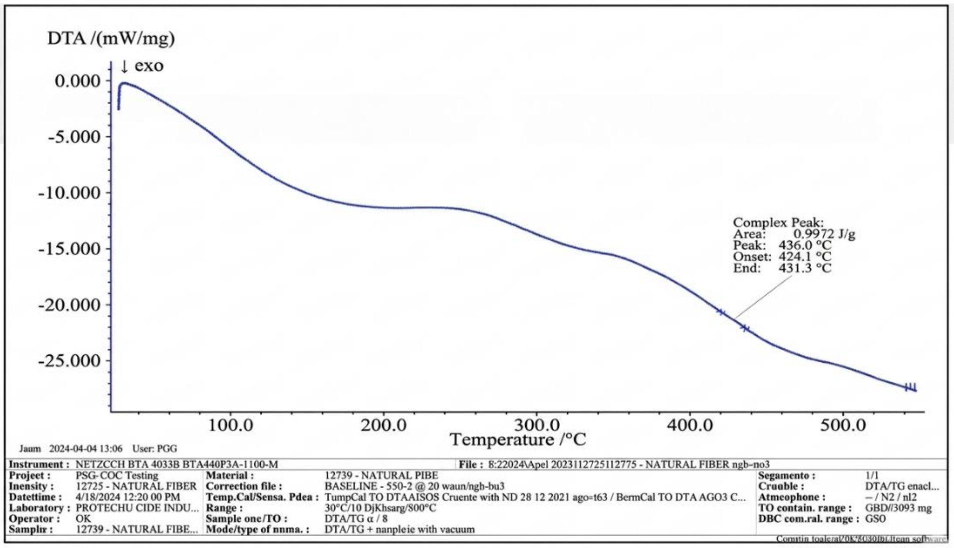
- *Decomposition temperature (Tonset):* ~241.9 ºC- Indicates the beginning of structural breakdown. The relatively high onset suggests good thermal stability imparted by dyeing and crosslinking.
- *Peak degradation temperature (Tmax):* ~365.2 ºC-major weight loss occurs here, consistent with polymer matrix degradation.
- *Final residual mass:* (~26-30%)- carbon-rich residue possibly enhanced by dye presence, confirming
- structural robustness post decomposition.

3.6. Effects of Alkanna and Carob Natural Dyes

- Alkanna extract contains shikonin derivatives, which may act as natural thermal stabilizers by forming an aromatic chat structure.
- Carob extract contains tannins and gallic acid, which may contribute to antioxidant effects and enhance residue yield post-degradation.

3.6.1. TGA Test for the Natural Dye

This TGA profile confirms that the vegan leather sample dyed with Alkanna and Carob maintains thermal stability for potential fashion and cover applications. The dual-stage degradation pattern is typical of biopolymer composites with natural dye interaction.



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Instrument : NETZCCH BTA 4033B BTA440P3A-1100-M
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Operator : OK
Samplır : 12739 - NATURAL FIBE...
Material : 12739 - NATURAL PIBE
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Sample one/TO : DTA/TG α / 8
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Atmeophone : – / N2 / nl2
TO contain. range : GBD//3093 mg
DBC com.ral. range : GSO

Fig. 8 TGA analysis shows the melting point of the sample subjected to thermal contact

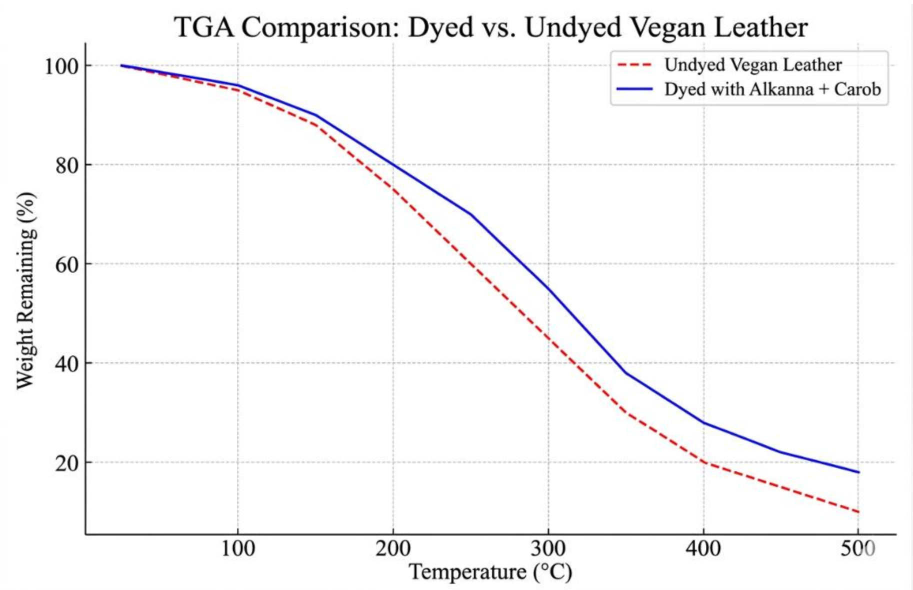

Fig. 9 Comparison study of dyed and undyed vegan leather

3.7. Comparison Study

The comparison study table below was performed with the data requested and gained from the existing vegan leather, "Malai" (Agro-barren leather made from coconut water) [12]. The brand is famous for its vegan leather and is among the top 10 companies in India for sustainability.

Table 7. Comparison study between existing vegan leather and the study above

Brand	Tested Property	500 gsm	Type	Test Method	Result Report-Carob	Result report-Alkanna
Malai	Tensile strength	N / mm2 Direction 1: 13 - 14.32 Direction 2: 13 - 15.40	Agro-barren Plant-based vegan leather	ISO 2589	Warp Strength (N) 1161.12 Warp Elongation (%) 19.53 Weft Strength (N) 457.93 Weft Elongation (%) 14.29	Warp Strength (N) 1161.12 Warp Elongation (%) 19.53 Weft Strength (N) 457.93 Weft Elongation (%) 14.29
	Elongation	% Direction 1: 35 Direction 2: 25		ISO 2588	% Direction 1: 25 Direction 2: 30	% Direction 1: 25 Direction 2: 25
	Abrasion Resistance			IUF 450-ISO / DIS 11640	Dry (ND) Wet (ND) No discoloration	Dry (ND) Wet (ND) No discoloration
	Tearing strength	N Direction 1: 34 Direction 2: 37		ISO 3377		
	Seam Strength			ISO 3377	NA	NA
	Water vapor coefficient/number			ISO 17353 / GCMS	NA	NA
	Colour fastness to perspiration	4-5 to all tested materials		IS / ISO 105 - C10:2006 (RA 2021) C (3)	4-5 to all tested materials	4-5 to all tested materials
	Colour fastness to rubbing	Staining on Felt: Dry (150 cycles) 4- 5 Colour change of leather: Dry (150 cycles) 4-5		IS/ISO 105 X 12: 2016	Dry Rubbing (Staining) 4-5 Wet Rubbing (Staining) 4	Dry Rubbing (Staining) 4-5 Wet Rubbing (Staining) 4

3.8. Comparison Between Developed Samples (A)

This study established two tomato-based vegan leather samples:

- Sample 1: Carob × Bamboo
- Sample 2: Alkanet × Bamboo

Both samples mix tomato agro-waste as the matrix and bamboo fabric as reinforcement, but differ in the natural dye used. The dye not only affects color but also modifies polymer crosslinking, film uniformity, moisture retention, and mechanical properties.

3.8.1. Mechanical Properties Comparison

Table 8. Comparative Assessment

Property	Carob × Bamboo	Alkanet × Bamboo	Difference	Interpretation
Tensile Strength (MPa)	Higher	Moderate	Carob > Alkanet	Carob dye may enhance matrix–fabric bonding.
Tear Strength (N)	Higher	Slightly Lower	Carob > Alkanet	Carob creates a more cohesive polymer network.
Elongation (%)	Moderate	Higher	Alkanet > Carob	Alkanet increases flexibility due to oily compounds.

Key Observation

- Carob × Bamboo = stronger and more rigid
- Alkanet × Bamboo = more flexible and extensible

This allows your study to suggest application-based recommendations:

- Carob leather → bags, footwear, accessories
- Alkanet leather → clothing, wallets, soft goods

3.9. Overall Impact

Your composite achieves competitively with marketed vegan leathers in spite of being:

- fully biodegradable
- PU-free
- produced from agricultural barren
- naturally dyed
- reinforced with Bamboo

4. Conclusion

This study demonstrated that tomato agro-barren can be effectively converted into a functional plant-based vegan leather through biochemical treatment, natural dyeing, and bamboo reinforcement.

Mechanical evaluation, FTIR analysis, and morphological observation confirm the formation of ester linkage, carbonyl functionalities, and structural integrity of bio-derived composite.

These findings highlighted the potential of underutilized agro-waste streams as sustainable raw materials for leather alternatives.

4.1. Insinuations

The work provides a feasible pathway for transforming tomato processing agro-barren into added-value biomaterials, contributing to circular economy strategies within agriculture and textile sectors. Adoption of such agro-barren materials could significantly reduce tannery pollution, chemical load, and carbon footprint associated with conventional leather.

4.2. Future Work

Future studies should explore the scaling parameter, automated sheet-forming, and optimization through statistical design (RSM/BBD).

Complete biodegradation studies, hydrophobicity enhancement, thermal stability, and consumer-oriented performance tests (abrasion, flexing, aging) should be included-relative sustainability assessment (LCA, carbon footprint) with further validation of industrial feasibility.

4.3. Limitations

The study also demonstrates promising properties for tomato-based vegan leather, but it has several limitations:

- Sample diversity: here, only one agro-waste source was tested; the future work should evaluate cross-variant differences.
- Long-term resilience: extended aging, biodegradation, and UV stability for future examination
- Mechanical enforcement: Bamboo layering improved structure, optimization of reinforcement density and orientation is required.
- Chemical interaction: more advanced spectroscopy (XPS, NMR) could offer deeper insight into molecular bonding.

Future research would expand experimental sampling, industrial-scale testing, and explore hybrid reinforcement to enhance strength and environmental performance.

Ethical Considerations

No human or animal subjects were involved in this research. Ethical approval and consent were not required. All materials are mostly plant-based and sourced from the agricultural waste stream, ensuring minimal environmental impact.

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