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Fabrication of Vegan Leather from Botanical Barren Extracts on Blended Fabric: A Vanillin-Enhanced Approach

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Abstract

Objectives: The textile industry is increasingly shifting towards sustainability, eco-friendly materials and innovation. In this study, we present a novel approach in developing plant-based vegan leather using *Solanum lycopersicum* (tomato plant), a crop highly cultivated for consumption in India, particularly in Tamil Nadu. The high value of post- consumption waste contributes significantly to the environment pollution and creates landfills. To address this issue, agro-barren was collected from local farmers and the markets in Coimbatore, Tamil Nadu. The processing of bio-solution typically employed in food industry. **Method:** The cleaned agro-barren material underwent a modification of leather fabrication process, including natural dyeing process using *Ceratonia siliqua* (Carob) extracts and overlayed with organic cotton to produce vegan leather sheet. **Finding:** The result material was characterized following ISO standards using Scanning Electron Microscopy (SEM), surface elemental analysis, colour strength evaluation, thickness measurement, tensile strength testing, and colour fastness assessment. **Novelty:** The study demonstrates the transformation of agriculture barren into a sustainable leather alternative, offering a viable, environment friendly solution for the textile and fashion industry, the finding contributes the border circular economy and waste valorisation in material science.

Keywords: Bio-degradable; *Solanum lycopersicum*; *Ceratonia siliqua* plan-based; Organic cotton; Natural dye; Waste valorization; Agriculture-barren

1 Introduction

In our environment, many food-based crops are cultivated to meet the consumer demands. However, large scale cultivation and consumption generates significant quantities of organic waste, which often ends in landfill, contribution towards environmental pollution and greenhouse gas emission. Conventional waste disposal method such as landfilling or composting are not always very effective, as not all parts of the fruits and vegetables are easily bio-degradable and uniformly used. Additionally, food processing industries generate substantial amount of unused plant matter, which in-adequately managed, poses serious threats to ecological health and public well-being[1]. Recycling and valorizing this agro-waste offer a promising solution to mitigate pollution. Recent studies have explored the potentials of fruits and vegetable waste as a source of natural phytochemicals for the use in food, cosmetics and pharmaceutics industries[2]. Extending this concept to the textile sector, converting agro-barren into functional materials- such as vegan leather- can reduce reliance on synthetic chemicals and lower production cost, many innovations in vegan leather production now focus on utilizing the agro-industry as raw material, offering sustainable alternative with diverse application[3]. Contemporary vegan leather has developed from sources such as mushroom, strawberry, apples etc., however these methods often involve high resource consumption and optimize for single purpose production, raising concerns about scalability and sustainability[4]. In this study context *Solanum lycopersicum* (tomato) was selected for our study due to its extensive cultivation and high consumption, especially cultivated and consumed especially in southern India. India ranks second globally in tomato production and export. The fruits soft, perishable nature, storage challenge results in large volumes of unsold or damaged produce that are discarded created agro-barren waste. Food industries that process tomatoes into production such as sauces, ketchups and jams typically discard the skin compounding the waste issue[1].

The present study explores the use of the use of *Solanum lycopersicum* agro-waste to develop a plant-based vegan leather. This material was chosen due to its local abundance and ease the collection from farmers, open markets and food processing units in Coimbatore, Tamin Nadu. To the best of our knowledge, there is a limited literature on the preparation and characterisation of vegan leather substitute using an environmentally sustainable process. The methodology involves collecting the agro-waste, cleaning it with a food-safe bio-solution and processing into leather sheets using *Ceratonia siliqua* (Carob) as a natural dye[4]. *Ceratonia siliqua*, commonly used as a chocolate substitute in India, possesses medicinal properties and is valued for its natural pigment. The dyed tomato waste was laminated over organic cotton to form the final vegan leather material. The prepared material sheet was then subjected into a series of characterization tests[5]. These include Scanning Electron Microscopy (SEM) for surface morphology analysis, Colourfastness (washing, rubbing- wet and dry, light exposure to evaluate the dye retention, thickness measurement, surface elemental analysis to assess dye penetration, and tensile strength testing to determine mechanical robustness. Eco-friendly vegan leather is defined as a biodegradable textile material with minimal environmental impact, improved functionality, and cost-effectiveness compared to natural leather[2]. While various alternative leather derived from cactus, cork, mushroom, tree bark, recycled rubber, apple skin and kombucha tea are available in the market, each has their own advantages and limitation, some are still under research and development[5].

This study presents a novel and sustainable method for producing vegan leather from *Solanum lycopersicum* agro-barren and evaluate its performance against existing alternatives.

1.1 *Ceratonia Siliqua* (Carob)- Natural dye source

The carob tree (*Ceratonia siliqua* L.), indigenous to the Mediterranean basin, yields pods that are abundant in dietary fibre, polyphenols, natural sugars, and essential minerals. These bioactive constituents contribute to the carob's well-documented health benefits, including improved digestion, glycaemic regulation, and mitigation of chronic diseases[6]. In agriculture and food industries, carob pods are widely utilized as a natural alternative to cocoa, with the seeds being the primary component of interest[3]. however, the outer pod skin- typically considered a byproduct remains underutilized. In this study, the carob pod skin was repurposed as a natural dye source in the preparation of the leather sheet. This approach not only supports sustainable material processing but also adds value to the study converting them into functional bio-resource[7].

1.2 Use of Vanillin as a Natural Mordant

Vanillin is a naturally occurring aromatic compound, serves as an effective mordant in the natural dyeing process. It is primarily extracted from the seed pods of *Vanillin planifolia,* a tropical orchid species originally cultivated and remains one of the leading global procedures. The green vanilla pods contain vanillin predominantly in the form of glucose., an enzyme that helps in curing hydrolysis[8]. As a mordent, vanillin facilitates the fixation of natural dye on the bio-based material by forming strong interaction between the molecular and the fibre substance. This method enhances the dye intake and improves the colourfastness making it eco-friendly and non-toxic process in sustainable textile development.

1.3 Substrate material: Organic cotton blend linen

Organic cotton was used as the primary wrap fibre[3]. It is cultivated without chemical fertilizers or pesticides, supporting environmentally sustainable farming practice. India is among the top producer for organic cotton globally. Linen derived from the flax plant (*Linum usitatisimum)* was used as the weft fibre. They are known for their lightweight and breathable nature, linen blended with organic cotton in a structural way called plain weave. The plain weave technique was employed with a blend of 1:1 blend ratio (50:50) of organic cotton forming the base composite.

2 Methodology

2.1 Collection of Raw materials

Agro-barren derived from *Solanum lycopersicum* (tomato) was sourced from local farmers and open markets in Coimbatore, Tamil Nadu, India. The barren primarily consisted of tomatoes skin, pulp residues, over ripe and unsold fruits unsuitable for commercial sale. These materials were selected based on their abundance and repurposed into sustainable biomaterials [9].

2.2 Pre-treatment and cleaning process

The collected agro-barren was thoroughly cleaned using bio-solution commonly used in the food processing industries [8]. The solution ensured the removal of surface contaminants, pathogens and residues while preserving the structure of the plant fibre. After the cleaning process, the material was air-dried under the normal surrounding to prevent microbial growth and decomposition.

2.3 Preparation of Plant-based vegan leather

The pre-treated tomato waste was processed through a modification leather making procedure. The process includes mechanical churning and homogenization to break down the matter and help in facilitate the sheet formation [10]. A natural dye extraction from *Ceratonia siliqua* (Carob) was applied during this stage. The dried biomass was then overlayed on organic linen blend material, during this phase. The dyed biomass was then layered over the fabric for supportive substate to form the leather sheet. The prepared sheet was left to dry under controlled condition for uniform setting and boding later passed into the cabinet drier for baking.

2.4 Application of Natural Dye

Ceratonia siliqua, a leguminous plant commonly used in the food industry as a natural chocolate substitute, was selected as the dyeing agent due to its eco-friendly properties and pigment-rich composition [2]. The dye extracted was applied using aqueous method and uniformly blended into the churned tomato mass before sheeting step. This imparted both aesthetic and functional properties in the material [11].

2.5 Characterization and Testing

The prepared plant-based leather sheet was subjected to a series of standardized tests to evaluate their structure, mechanical and aesthetic properties:

- Surface morphological analysis: Scanning electron microscopy (SEM) was used to examine the surface microstructure and fibre distribution
- Colourfastness test: conducted under ISO standards including assessment for washing, rubbing (wet and dry), light exposure.
- Thickness measurement: thickness was measured using a digital micrometre to determine uniformity along the sample.
- Surface element analysis: Performed to assess dye penetration and chemical composition using energy using disperse X-ray spectroscopy (EDX)
- Tensile strength: Evaluated using a universal testing machine (UTM) to determine the material mechanical performance.

All tests remained conducted in accordance with relevant Indian ISO standards to ensure reliability and reproducibility. [9]

Table 1. Material used in the study

Dye material	*Ceratonia siliqua*
Mordant	*Vanillin*
Fabric	*Organic cotton* blend *Linen*
Fabric blend ratio	50:50 blend
Vegan material	*Solanum lycopersicum* (Tomato)

2.6 Material

2.7 Process of leather making

2.7.1. Material Collection

The study involves the use of *Solanum lycopersicum* (tomato) agro-waste, collected from local markets in Coimbatore and farmlands in Theni, Tamil Nadu. The *Ceratonia siliqua* (Carob pods) were sourced from estates in Kumily, Kerala. Organic/linen cotton fabric was purchased from Erode, Tamil Nadu. Vanillin, a natural mordant, was sourced from the local supplier.

2.7.2. Pre-treatment of materials

1. **Tomato agro-barren preparation:**

The tomato waste (mainly skin and pulp) was collected, separated from unusable parts, cleaned following as FSSAI- approved bio-chemicals method. The cleaned waste was then subjected to hot water treatment before being prepared for further processing.

1. 2.**Carob pod preparation:**

The carob pods were dried under partial sun exposure for several days, then crushed and powdered. The powdered carob was soaked in a mixture of distilled water (M:L) for 48 hours to extract the natural dye[2]. After soaking, the solution was filtered using litmus paper cones to obtain the dye.

2.7.3. Box-Behnken Design for Dyeing Process

A Box-Behnken experiment design was applied to optimize the three critical dyeing parameters: concentration of dye, concentration of mordant and temperature. The design aimed to identify the optimal conditions for producing vegan leather with enhanced qualities[12].

Table 2. Parameters used for leather making

Parameter	**Levels**
Dye concentration	8%, 10%, 12%
Mordant concentration	0.5%, 1%, 1.5%
Temperature	70°C, 100°C, 130°C

The design matrix is shown in the Table 2. A detailed list of sample codes with corresponding conditions is provided in Table 2.

2.7.4. Leather preparation process

1. **Churning of Agro-barren:**

   The prepared tomato agro-barren was blended into a churner to form a smooth paste. The carob dye was then evenly mixed into a paste, along with vanillin, acting as a mordant to facilitate better dye absorption.

2. **Layering of fabric**

   A blend of 50:50 organic cotton and linen yarn plain weaved fabric was selected for layering. The fabric was bleached and then coated with the prepared agro-paste using a churner and spread using a spatula. The coated fabric was left to air-dry in the sun for 24hrs later passed into cabinet driers.

3. **Baking and pressing**

   After sun drying, the sheet was further dried in a cabinet dryer at 200°C for 2 hours. The dried sheet was then passed through rollers to remove creases and ensure uniform thickness. The final sheet was pressed using hot press at 30°C to bind the layers evenly (Table 2).

2.7.5. Characterization Studies

The prepared vegan leather samples were characterized for the following properties:

- SEM Analysis: To study the surface morphology of the leather[10].
- Colour Fastness Tests: Washing, rubbing (wet and dry) to evaluate dye retention.
- Colour Strength: Measured to analyse the depth of dye penetration.
- Thickness: Determined to check uniformity and flexibility[11].
- Tensile Strength: Assessed to evaluate mechanical properties[12].
- Surface Element Analysis: To examine the molecular and surface characteristics.

The tests followed standardized methods to ensure reproducibility.

Table 3. Based on Box-Behnken Design

Variables	Level		
	-1	**0**	**+1**
Concentration of Dye	8%	10%	12%
Concentration of Mordant	0.5%	1%	1.5%
Temperature for Dyeing	70	100	130

Table 4. Design with variables

Sl. No	Sample code	Concentration of dye (%)	Concentration of mordant (%)	Temperature of Dyeing
1	S1	8	0.5	70
2	S2	8	1	100
3	S3	8	1.5	130
4	S4	10	0.5	70
5	S5	10	1	100
6	S6	10	1.5	130
7	S7	12	0.5	70
8	S8	12	1	100
9	S9	12	1.5	130

Process mentioned under Figure 1 and 2.

Fig 1. Abstract images of materials

Fig 2. Process of plant-based vegan leather production

3 Result and Discussion

3.1 Characterization Studies

3.1.1. Colour Fastness Tests

Colourfastness tests were conducted to access the durability of the dyed textiles under various conditions, they include washing, light exposure and rubbing. These tests measure the ability of the dye to withstand external forces such as water, friction and light. The essential properties for evaluating the sustainability of dyed material.

The grey scale was used to determine colour change, rating 1 indicates the poorest fastness and 5 represents excellent fastness[13].

- **Wash colourfastness test (ISO 105-C06)**

The wash fastness of the dyed leather sample was evaluated using the Rota wash method, where a 100mm x 40mm test specimen was sewn on a 100mm x 40mm multi-fibre adjacent fabric. The samples were subjected to a washing solution containing 4g/L ECE detergent and if necessary 1g/L sodium perborate. The washing was performed at either 60° C or 40° C for six hours. After washing the samples were rinsed in cold water, air dried, and evaluated for colour change using the grey scale[14]. Table 5 presents the results, showing high fastness of the sample with minimum change observed.

Table 5. Properties of wash colourfastness test

Sl. no	Sample	Colour change	Staining
1	S1	5	5
2	S2	5	5
3	S3	4/5	5
4	S4	4/5	5
5	S5	5	5
6	S6	4/5	5

3.1.2. Wash fastness results

As shown in the Table 5, the wash fastness results for the pigment dyed sample indicates excellent durability. Most samples (S1, S2, and S5) exhibits no significant colour change after washing. A slight colour change was observed in sample S3 and S4 (4/5 rating), but no staining occurred demonstrating that the dyeing process effectively fixed the colour to the fabric without significant fading or transfer.

- **Rubbing colourfastness test (ISO 105-X12)**

The rubbing fastness, both wet and dry was performed using a crock meter, a device designed to rub a cotton cloth over the sample under controlled pressure. Each sample was rubbed 10 times dry and 10 times wet. The degree of staining on the rubbing cloth was then evaluated using the grey scale. Table 6 indicates moderate rubbing resistance with dry rub fastness and between 3 and 4 wet rub fastness between 4 and 5. This suggests a reasonable level of colour retention under friction, under wet condition particularly.

Table 6. Rub fastness of the dyed sample

Sl. No	Sample	Colour change	Staining	Change in colour	Staining
		Dry		Wet	
1	S1	3	4/5	4/5	4/5
2	S2	3	5	4/5	4
3	S3	4/5	4	3	4
4	S4	4/5	3	4	3
5	S5	4	4/5	5	4/5
6	S6	5	4/5	5	5

3.1.3. Rubbing Fastness Results

The results from the rubbing fastness test, presented in Table 6, show moderate colour retention when subjected to dry and wet rubbing. For dry rubbing, the samples typically scored between 3 and 4, while wet rubbing demonstrate slightly better performance, with rating between 4 and 5. These results indicates that the sample exhibit a reasonable resistance to colour degradation under friction, though additional modifications could improve durability.

- **Light fastness test**

The light fastness of the sample was tested to determine of dye resistance fading under prolonged exposure to light. The results, summarized in the Table 7 shows the dyed fabric exhibits strong light fastness, with rating between 6 and 8 on the grey scale. These results suggests that the dye used in the study are suitable for applications requiring moderate to high light.

3.1.4. Light Fastness Results

As shown in the Table 7, the light fastness test results reveal that all the samples performed well, with most samples receiving a rating of 7 to 8, indicating a high resistance to fading under exposure to light. This suggests that the dyeing method employed in this study provide a durable and stable colourant for textile application.

Table 7. Lightfastness of the dyed sample

Sl. no	Sample	Lightfastness
1	S1	7/8
2	S2	7/8
3	S3	7
4	S4	6/7
5	S5	7
6	S6	7/8

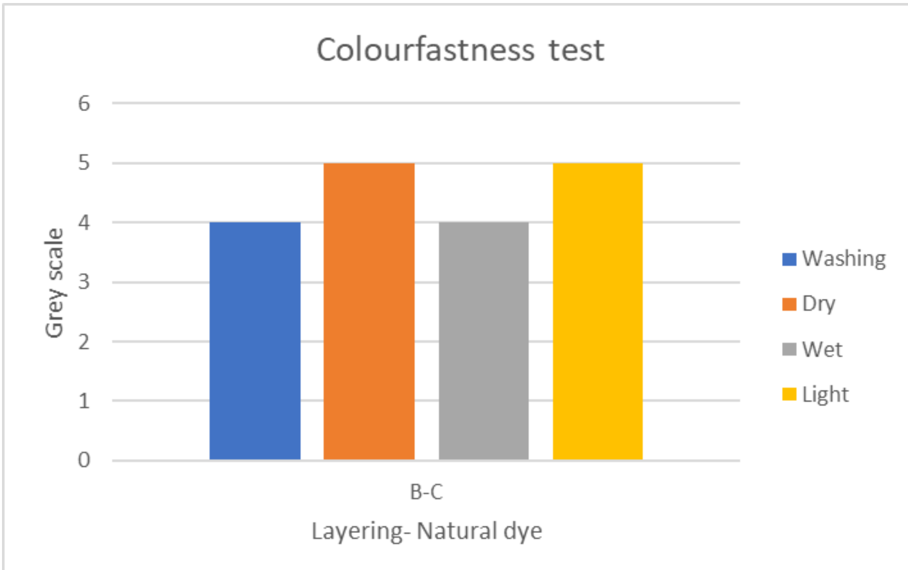

Fig 3. Colour fastness test report

3.1.5. Colour Strength

The colour strength of the dyed fabric was determined using the K/S value, which measures the absorption of light and is an indicator of the intensity of the colour. Figure 3 shows the highest colour strength was observed in Sample S2 and S4, while utilized an organic linen blend fabric dyed with Carob, a natural dye. These results highlight the effectiveness of the dyeing process and high colour intensity achieved with this natural method [15].

3.1.6. Fabric Characteristics of Vegan Leather

The fabric composition and dyeing results are presented in Table 8, which highlights the properties of the blended organic cotton and linen fabric. This combination of materials provided the best colour retention and strength characteristics. The fabric weight and cover factor are ideal for use in vegan leather applications, offering both durability and flexibility.

Table 8. Fabric particulars of leather sample

Material	EPI	Count	Material	PPI	Count	Total cover factor
Organic cotton	70	72	Linen	64	82	15.20

3.1.7. Surface Element Analysis

Surface element analysis was conducted on the fabric using SEM to evaluate the effects of vanillin treatment and pigment dyeing [16]. The results, summarized in Table 9, shows that the treatment with vanillin and pigment dye results in the attachment of specific surface elements (carbon and oxygen) to the fabric, which enhance the fabrics colour retention and durability.

Table 9. Surface element analysis of the sample

Sl. No	Sample	Composition (%)			
		Carbon	Oxygen	Nitrogen	Chlorine
1	Blended fabric	44	55	-	-
2	Vanillin treated	36	63	-	-
3	Dye pigment	40	58	-	-

3.1.8. Effect of Vanillin on Colour Strength

The impact of vanillin treatment on colour strength was evaluated and is shown in Figure 4. The result demonstrates that the optimal concentrate for pre-treatment in 10% by weight of the fabric, which yield the highest colour strength. This finding suggests that vanillin plays a crucial role in enhancing the dyeing process, contributing to better pigment fixation.

3.1.9. Effect of Dyeing Temperature on Colour Strength

The influence of dyeing temperature on the colour strength of the pigment is depicted in Figure 4. The results indicate that higher dyeing temperatures significantly increase the colour depth of the fabric, with the optimum temperature being around 100°C. this highlights the importance of temperature control in the dyeing process for achieving the desired colour intensity [13].

3.1.10. Statistical Analysis (ANOVA)

To evaluvate the effect of dyeing temperature and vanillin concentrate on the colour strength of the pigment-dyed samples, a two-way Analysis of Variance (ANOVA) was performed. The results are presented in Table 10.

Table 10. Two-way ANOVA for the effect of vanillin concentration and dyeing temperature on color strength

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Sample	0.106667	1	0.106667	5.647059	0.028789	4.413873
Columns	0.063333	2	0.031667	1.676471	0.214948	3.554557
Interaction	0.063333	2	0.031667	1.676471	0.214948	3.554557
Within	0.34	18	0.018889			
Total	0.573333	23				

The ANOVA results indicate that vanillin concentrate has a statistically significant effect on the colour strength of the dyed samples ($p = 0.0288$, $F = 5.65$), while the dyeing temperature ($p = 0.2150$) and the interaction between temperature and vanillin ($p = 0.2150$) do not show significant influence within the experimental range. This suggests that vanillin acts as a key mordanting agent, enhancing the colour fixation on the fabric. The optimal vanillin concentration was identified as 1% which correlates with the highest K/S values in the corresponding experimental samples Figure 4. Though dyeing temperature alone was not statistically significant, results from pigment intensity measurement suggest a practical optimal temperature near 100°C, which complements the mordanting effect of vanillin. These findings support the hypothesis that natural addictive like vanillin can significantly influence dye uptake in bio-based leather alternative, offering a sustainable and effective approach for natural dyeing processes.

The results of the ANOVA (Analysis of variance) presented in Table 10, indicate that vanillin concentrate significantly influences the colour strength of the dyed fabric. The statistical analysis also shows that temperature has a liner relationship with the colour intensity of the final product. The two-way ANOVA demonstrate that both physical test parameters and sample characteristics, including weight and dye concentrate, are significant contributes to the final outcome.

3.1.11. Statistical Analysis: One-Way ANOVA

To evaluate the effect of the material thickness on the mechanical properties of the SL(C) based leather, a one-way ANOVA was performed. The analysis investigated between the thickness and key performance indicates the tensile strength, elongation and tear strength. The result is summarized in the Table 11.

Note: SL = *Solanum lycopersicum*; CS = *Ceratonia siliqua*. P-values < 0.05 indicate statistically significant differences.

Table 11. One-way ANOVA results evaluating the effect of material thickness on mechanical properties

Characteristics	**f-count**	**p-count**	**F table**	**Conclusion**
Material thickness and tear strength	13540.27	1.9E	4.007	Material thickness affects tear strength (f count>F table)
Solanum lycopersicum with *Ceratonia siliqua* material thickness and tensile strength	10571.38	2.9E	4.0068	Material thickness greatly influences tensile strength (F count > F table)
Material thickness and elongation	88094.06	5.01E	4.0068	Material thickness greatly influences elongation (F count > F table)
Tensile strength with elongation	341327.8	4.9E	4.00687	Tensile strength affects elongation (f count > F table)
Material thickness and tear strength	10785.7	1.38E	4.0069	Material thickness affects tear strength (F count> F table)

The **ANOVA test** statistically influences material thickness and all tested mechanical properties. Specifically tensile strength and elongation are highly dependent on the fabric structure density and biomaterial matrix. These findings validate the mechanical property of SL(C) vegan leather showing better mechanical performance in commercial vegan leather.

3.1.12. Effect of Vanillin on Colour Strength

The impact of vanillin treatment on colour strength is shown in Figure 4. The result demonstrates that the optimal concentration for pre-treatment is 10% by weight of the fabric, which yield the highest colour strength. This finding suggests that vanillin plays a crucial role in enhancing the dyeing process, contributing to better pigment fixation.

Combined Effect of Vanillin and Dyeing Temperature

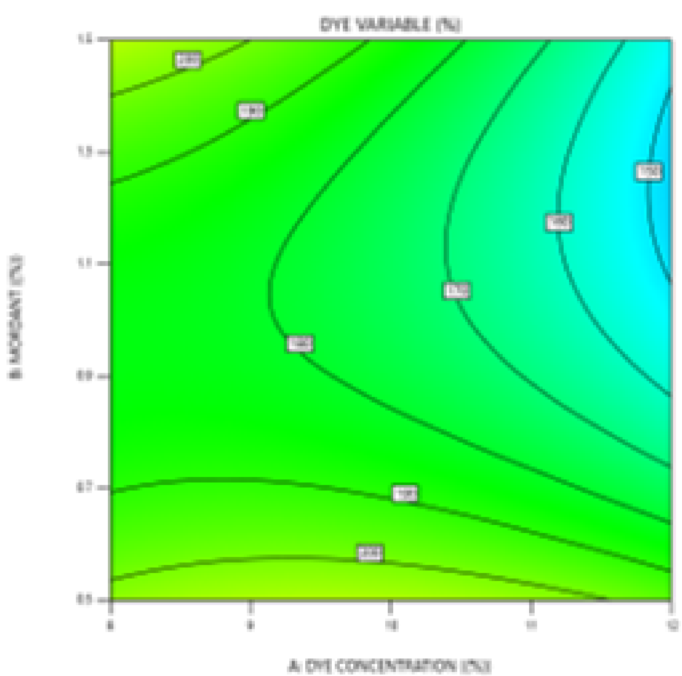

Fig 4. Interactive effect of vanillin concentration and dyeing temperature on colour strength

Visual Suggestions:

- X-axis: *Vanillin concentration (% owf).*

- Y-axis: *Colour strength (K/S value).*
- Use a line chart or bar graph with clearly distinguishable markers and include error bars.
- Include a legend if multiple dye types or fabric blends are shown.

Figure 4 demonstrates the interactive effect of varying vanillin concentration and dyeing temperature on the colour strength to treat the sample. The highest K/S value were recorded at 1% vanillin concentration and dyeing temperature of approx. 100º C, indicating an optimal synergy between mordant concentration and thermal diffusion. The influence of temperature lone was not statistically significant (Table 11) suggesting that vanillin plays an important role in the dye material. These results further support the use of bio-derived mordant such as vanillin in eco-textile dyeing[17]. The finding also demonstrates the effect of Box-Behnken experiment for identifying key variables for optimizing natural dyeing in vegan leather development.

The plot Figure 4 above shows the optimum concentration for the pre-treatment and the color strength found on the blended fabric. The colour strength maximum is 10% according to the weight of the fabric.

The results in the Figure 4 illustrate the relationship between vanillin concentration and the colour strength (K/S value) of the pigment dyed sample. An increasing trend in colour strength is observed with vanillin concentration up to 1% (fabric weight), beyond which no significant improvement is noted. This suggests that 1% vanillin is the optimum concentration for achieving maximum dye uptake likely due to its ability to enhance dye-fibre interaction through hydrogen bonding or electrostatic attraction. These observations are consisted with the statistical finding in the ANOVA (Table 11) which confirms the significant effect of vanillin as natural mordant for plant base leather application using pigment dye derived from agro-barren.

3.1.13. Effect of Dyeing Temperature on Colour Strength

The influence of dyeing temperature on the colour strength of the pigment is depicted in Figure 5. The results indicate that higher dyeing temperature significantly increase the colour depth of the fabric, with the optimum temperature being around 100º C. This highlights the importance of temperature control in the dyeing process for achieving the desired colour intensity.

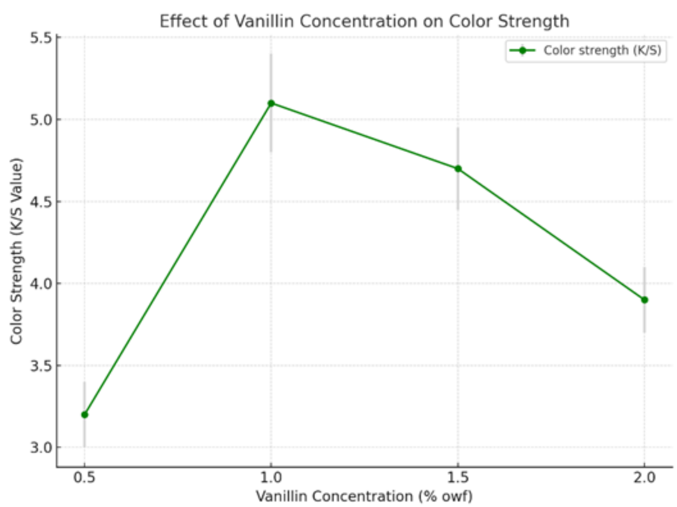

Fig 5. Effect of Vanillin concentration on colour strength of vegan leather

Figure 5 shows interaction effect of vanillin concentration and dyeing temperature on the colour strength (K/S value) of vegan leather. The maximum colour strength was observed at 1% vanillin and 100°C. statistical interaction was analysed using two-way ANOVA, showing vanillin as the dominant factor influencing dye uptake ($p < 0.05$).

Visual Suggestions:

- Consider a 3D surface plot or grouped baar graph with dyeing temperature on one axis, vanillin concentration on another and K/S value as output.
- X-axis: *Vanillin concentration (% owf)*
- Y- axis: *Dyeing temperature (°C)*
- Colour gradients can be used to show K/S variation if using surface plots.

Figure 5 shows colour strength (K/S value) of pigment dyed vegan leather samples at different vanillin concentration (0.5%-2% based fabric weight). Result indicates optimum dye up to 1% vanillin, error bars represent $\pm$ standard deviation (n = 3). Statistical significance was confirmed via two-way ANOVA ($p < 0.05$).

3.1.14. Thickness of the Prepared Vegan Leather

The thickness of the fabricated plant-based leather sample was evaluvated using a standard thickness gauge, as per the relevant ISO guidelines. The result is summarized in the Table 12.

Table 12. Thickness of the SL(C)-based vegan leather sample

Thickness parameter	Leather sample
Fabric thickness	
Thickness ($\pm$0.01)	0.77

The measured thickness of 0.77mm aligns with the general industry standards for lightweight leather as specified by leather Indian ISO guidelines[16] , typically ranging from 0.6 to 1.0mm. this confirms that the developed material falls within the acceptable dimensional profile for potential use in soft leather goods and outer cover products like diary and acessories.

Compared to the commercail synthetic leathers (0.8-1.2mm), the slightly lower thickness of the SL(C) based sheet may contribute to improved flwxibility and reduced weight yet depends on the end-use application.

3.1.15. Tensile Strength and Elongation Behavior

The mechnical properties of the SL(C)-based plant-derived vegan leather were evaluated using a Zwick/Roell universal testing machine follwing ISO 70162-2 standards. Rectangular specimens of dimension 200mm x 50mm were tested at a traverse rate of 100mm/min. the measurement includes both tensile strength and elongtaion in the warp and weft direction. The result is discussed in the Table 13.

Table 13. Tensile strength and elongation of the SL(C)-based vegan leather

Sl. No	Fabric – Tensile strength (Zwick/Roell)	Leather sample
1	Warp strength (N)	1161.12
2	Warp elongation (%)	19.53
3	Weft strength (N)	457.93
4	Weft elongation (%)	14.29

Note: Test conducted using Zwick/Roell apparatus; specimen size 200 mm $\times$ 50 mm, traverse rate: 100 mm/min (IS 70162-2 standard).

The results indicate that the developed vegan leather processes tensile property, particularly along the warp direction. The increased warp strength to the fibre and weave organic cotton linen blend fabric. Elongation values fall within acceptable ranges for flexable sheet materials, suggested that the material is mechanically suitable for practical application.

3.1.16. Surface of the Vegan Leather

3.1.17. Surface Morphology and Air Permeability of the Vegan Leather

Figure 6 presents the surface morphology of the developed plant-based vegan leather, captured from two perspectives: (A) straight view and (B) angled (slide) view. The surface structure reveals a relatively compact matrix with minimal pore openings, indicating low porosity.

To qualify the air permeability, the sample was evaluated using **Bendtsen Tester Apparatus (Model N3500),** standard instrument for assessing airflow resistance in fibrous material. The results demonstrate the leather exhibits low air permeability, pore size and tight polymeric matrix formation makes it beneficial application using less moisture or reduced breathability. The observation indicates that the polymers of the vegan leather from *Solanum lycopersicum* waste and natural dye uniformly produces limited air passage.

3.1.18. SEM analysis

3.1.19. SEM Analysis of Plant-Based Vegan Leather

Figure 7 (**A and B**) shows the SEM image of the SL(C) based leather sample at magnification of 20,000x and 1000x respectively. The SEM micrograph provides insight into the surface morphology and topographical characteristics of the polymers.

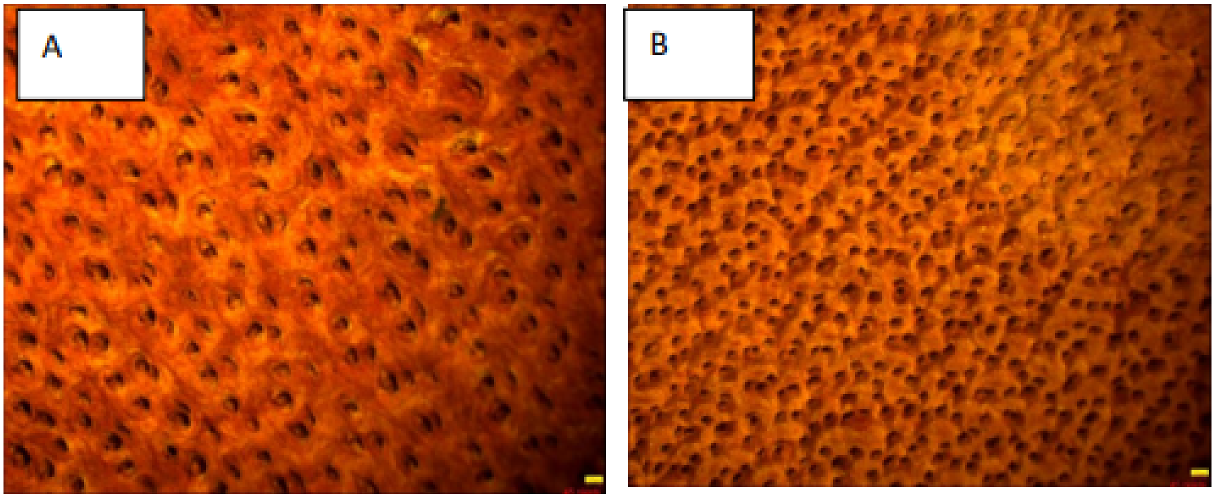

Fig 6. Airflow through the surface of the vegan leather (A) straight view (B) slide view

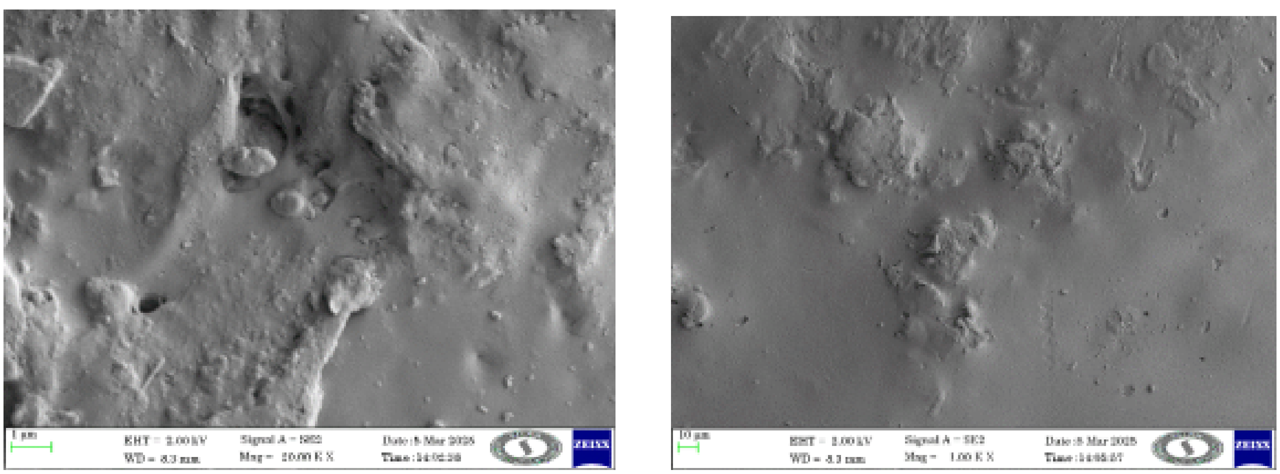

Fig 7. SEM analysis of SL(C) based sample

Figure 7A (20,000x magnification) reveals a relatively compact surface with irregular distribution of pores and granules like structure. The presence of micropores and uneven surface morphology suggests the heterogeneous dispersion of the bio-based material and indicates partial between the polymer matrix pigment particles.

Figure 7B (1,000x magnification) displays a border view of the surface structure, highlighting regions of roughness and surface agglomeration. The features can be attributing natural additives (vanillin pigment particles)

The SEM result confirms that the developed material exhibits porous surface, benefits in less breathability in the application. These features make the surface free from moisture capture and gives a smooth enhance surface uniformly finished.

Note:

- Magnification level: used (eg: 100x, 500x, 1000x)
- Key observation: from the SEM image (eg: smooth surface, presence of small cracks, dye evenness)
- Notable structure: (eg: fibre bonding, layering, uniformity)

3.1.20. Comparative Analysis with Other Vegan Leathers

The surface texture observed in the SL(C) based material differs significantly from the synthetic leather such as such as polyurethane and PVC-based composites, which typically exhibit smooth, homogeneous surfaces. In contrast the developed bio-based sample demonstrates a non-uniform, microporous surface with evidence of particle dispersion due to incorporation of vanillin and natural fillers in the process of forming.

Compared to other bio-based leather alternatives:

- Pineapple leaf leather (Piñatex) often displays denser fibre packing with visible directional alignment.
- Mycelium-based leathers (e.g., Mylo™) exhibit porous, sponge-like morphologies, similar to the void observed in this study in SEM (A).
- Apple waste-based leathers (AppleSkin™) tend to have smoother finish due to additional surface treatment and coating.

The cluster in the SL(C) based sample may contribute to improve breathable and bio-degradable surface uniformly. The visible SEM (A) (B) samples result in compatibility between the polymer matrix and reinforcement agents.

Future enhancing mixing techniques, cross-linkers or surface finishes improve the homogeneity and mechanical behaviour, when competing with commercial leather.

Statistical analysis tests using one-way ANOVA and Regression were conducted to assess mechanical properties variations between vegan leather specimens. This statistical test will also examine differences in thickness, tensile strength, elongation, and tear strength of each vegan leather sample report.

Table 14. Comparative Benchmarking of Vegan Leathers

Material	Tensile Strength (MPa)	Thickness (mm)	Color Fastness (Washing/Rubbing/Light)	Surface Properties	Environmental Impact
Apple-based Leather [4]	20 - 45	0.3 - 1.0	Moderate to high	Smooth, uniform, flexible	Biodegradable, low resource use
Mushroom-based Leather (e.g., Mycelium) [5]	30 - 50	0.5 - 2.0	High	Smooth to slightly textured	Biodegradable, minimal water use
Cork-based Leather	25 - 60	0.7 - 1.5	Moderate	Soft, porous, flexible	Biodegradable, renewable resource
Tomato-based Leather (*Solanum lycopersicum*) [11]	10 - 25	0.5 - 1.2	Moderate to high	Smooth with fiber structure visible	Biodegradable, sustainable, uses waste material

4 Conclusion

This study successfully developed and evaluated a sustainable, plant-based leather derived from *Solanum lycopersicum* (tomato) agro-waste. The primary aim was to offer an eco-friendly alternative to the leather industry, by minimising the environmentally harm and reducing industrial pollution. The selected biomass, abundantly cultivated and consumed in Tamil Nadu. Cleaned and processed layering technique on organic cotton blend linen fabric was used. The incorporation of natural dye extract from *Ceratonia siliqua* (carob) contributes to the environment friendly material, avoiding the use of synthetic dyes, the presence of vanillin and structure quality of the resulting leather sheet. SEM surface analysis, mechanical testing., revealed that the prepared sample exhibits favourable characteristics including flexibility, low moisture absorbency and reduced breathability. The production method requires minimal water input and involves no chemical processing making it bio-based leather as superior in sustainability compared to other alternatives such as mushroom, strawberry, corn, grapes leather etc. Since the leather was produced from agro-barren rather than the whole fruit, environment footprint is negligible. For large scale production, the process can adapt treated effluent water in ecological impact.

Compared to traditional animal leather and synthetic leather, the *S. lycopersicum*-based leather offers clear environmental advantages. Animal leather processing typically requires high water and chemical input, were as this method uses agriculture by products and food safe natural dye like *C. siliqua*. The physical and chemical analysis confirms the development material meets the essential leather quality benchmark, making it a promising candidate for application in leather products and cover.

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6 Authors contribution

- Experimental study, data, and report analysis, an original article written: Fiona Paulson. T.
- Research guidance, editing, and reviewing: Dr. J. Banu priya

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