



Original Article

Vegan Leather *Solanum lycopersicum* Pigment Dyeing with *Ceratonia siliqua* over Blended Fabric with Presence of Vanillin

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Abstract

Organic and linen blend fabric is among the most popular materials used in saree production and other textile applications, generating substantial market demand. This fabric supports various dyeing techniques, including traditional methods rooted in cultural heritage. Meanwhile, enormous quantities of agro-waste are generated annually in India from the vegetable, fruit, and food processing industries, as reported by national statistics. Among these, waste from tomato (*Solanum lycopersicum*) production is particularly high especially in the post-COVID era highlighting its potential for repurposing damaged or rejected fruit portions. Tomato is an affordable and widely cultivated crop in India, valued not only for its nutritional properties as a source of vitamins, fibre, and antioxidants but also as a renewable raw material. The dyeing process employed in the present study required comparatively less water and energy, thus addressing environmental concerns. For colouring, vegan leather samples were dyed using *Ceratonia siliqua* (carob) pigments, known for their distinctive ability to produce uniform colouration on both natural and synthetic substrates. The tomato-based substrate demonstrated excellent compatibility with natural dyes due to its intrinsic composition. This research established a novel technique for dyeing organic cotton and linen fabrics using pigments derived from tomato waste. The colour strength, evenness, and fastness properties of all dyed samples were evaluated. The results indicated uniform colouration, particularly at a dye concentration of 1% and a processing temperature of 100 °C.

Keywords: Availability; Antioxidants; Bio-Degradable; Dyeing; Natural Dye; Organic Cotton; Tomato Waste

Introduction

In recent years, there has been a growing focus on the utilisation of agrowaste in response to the numerous environmental issues arising from agro-industrial residues. Improper disposal of such waste has been linked to land contamination, soil degradation, and even human health problems, including cardiovascular diseases and atherosclerosis, resulting from pollution (Socaci *et al.*, 2017; Lu *et al.*, 2019). Consequently, research has expanded towards the use of fruit and vegetable by-products as alternative sources of natural phytochemicals, which hold significant potential for applications in the food, cosmetics, and pharmaceutical industries.

Tomato (*Solanum lycopersicum*) is among the most widely cultivated vegetable crops globally, with major production centres in India, particularly in Haryana and Telangana. In 2016, global production exceeded 168 million tonnes, of which over 40 million tonnes were processed into tomato paste, juice, sauces, purée, ketchup, and canned products (Anand Gowshal *et al.*, 2018). The principal by-product of tomato processing is tomato pomace, which comprises peel, seeds, fibrous material, and residual pulp. Depending on processing conditions and the quality of the raw material, pomace can account for

up to 7.5% of the raw tomato input, amounting to approximately 2 million tonnes of organic matter each year (Silva *et al.*, 2018).

Traditionally, tomato pomace has either been sent to landfills or used as a low-grade animal feed. However, its chemical composition presents significant potential for valuation. Tomato pomace is abundant in natural antioxidants, soluble dietary fibres, vitamins, and other bioactive compounds (Grassino *et al.*, 2016; Nour *et al.*, 2018). On a dry weight basis, it contains 59.03% neutral detergent fibre, 25.73% total sugars, 19.27% protein, 7.55% pectin, 5.85% lipids, and 3.92% minerals (Szabo *et al.*, 2018). It is also a rich source of carotenoids and phenolic compounds, particularly lycopene, which accounts for 80–90% of the total carotenoids. Lycopene, along with related compounds such as β -carotene, phytoene, and lutein, is recognised for its antioxidant properties and its beneficial effects on human health (Muruganandham *et al.*, 2025). Evidence indicates strong associations between dietary lycopene intake and reduced risks of prostate cancer and cardiovascular diseases (Socaci *et al.*, 2017; Song *et al.*, 2017).

In India, farmers frequently experience significant financial losses as tomatoes are highly perishable; their soft and fleshy texture makes them particularly susceptible to damage during harvesting, storage, and transportation. These challenges were exacerbated during the COVID-19 pandemic, when disruptions in supply chains and reduced consumer access to local markets resulted in unsold stock and large quantities of wasted tomatoes. Consequently, much of the crop was lost, underscoring the urgent need for sustainable approaches to utilise tomato waste in the production of value-added products.



Figure 1: Tomato Thrown Causing Pollution

The dyeing process examined in the present study introduces a novel method for treating blended textiles, specifically a linen–organic cotton blend. The cotton component was coloured using reactive dyes through the thermosol process. Unlike conventional bath dyeing, the thermosol method offers advantages such as improved dye fixation, reduced dye degradation, and compatibility with continuous processing, thereby enhancing the efficiency of cotton fabric colouration (Gupta *et al.*, 2025).

Pigments, unlike fibre-specific dyes, are molecular substances capable of being applied to both organic and synthetic fibres. This versatility makes them a valuable choice for dyeing diverse substrates (Martínez-Ramos *et al.*, 2025). Pigment dyeing thus enables uniform colouration of blended fabrics while maintaining process simplicity. In the present research, the incorporation of vanillin into the dyeing process further strengthened pigmentation, improving both colour depth and fastness. Similar outcomes have been reported in studies where vanillin derivatives enhanced dye fixation and colour stability in polyester and cellulosic textiles (Ahmed *et al.*, 2023).

The focus of this study is the optimisation of pigment-based dye application on blended materials to achieve stronger colour intensity with reduced resource consumption. By combining bio-based pigments with functional agents such as vanillin, the process aims to deliver effective colouration while promoting sustainable practices in textile and leather finishing.

Types of Leather in the market

- Animal leather
- Plastic leather
- Vegan leather
- Microfibre leather

Animal Leather

Animal leather, also known as natural leather, is typically derived from the hides and skins of animals. While exotic varieties such as crocodile, pufferfish, and octopus leather are highly prized, more commonly used types include camel, buffalo, lambskin, and cowhide. The production of animal leather requires the slaughter of animals, thereby raising ethical concerns and contributing to sustainability challenges within the fashion industry (Zhou *et al.*, 2025).

Plastic Leather

Plastic leather, commonly known as pleather, is an informal term for synthetic, plastic-based leather. Pleather gained popularity in the 1970s as an affordable alternative to natural leather, making leather goods accessible to consumers who could not afford animal-derived products. It reduced the demand for animal hides and offered greater fashion versatility due to its wide colour range, flexibility, and ease of dyeing. Pleather has been used in the production of shoes, wallets, and seasonal fashion items, often featuring patterns that imitate animal skins such as ostrich or snake (Singh *et al.*, 2024).

Vegan Leather

Vegan leather is a more sustainable alternative to traditional animal leather, produced from plant-based or waste-derived materials. Recent advancements in vegan leather production utilise substrates made from mushrooms, fungi, cactus, pineapple, and apple waste, offering environmentally friendly alternatives that closely resemble animal leather in appearance (Pérez-Alonso *et al.*, 2025). These substitutes are gaining increasing popularity within sustainable fashion, as they support environmental conservation while meeting consumer demand for cruelty-free products.

Microfibre Leather

Microfibre leather is a man-made innovation that replicates the characteristics of natural leather but is at the same time more eco-friendly. Manufactured from homogeneous microfibres, microfibre leather is highly dense, strong, even in thickness, and long-lasting. Microfiber leather has been used for automotive interior components, footwear, gloves, handbags, and other synthetic apparel items because of its quality and uniformity (Martínez-Ramos *et al.*, 2025).

Dyeing

Organic linen and cotton are natural fibre textiles that are increasingly popular due to their environmental friendliness and versatility. These fibres can be dyed using various methods such as dip dyeing, hot bath processes, and bath-step modifications. Commonly employed techniques include the single-bath one-step and single-bath two-step processes. Double-bath approaches, however, tend to be energy- and water-intensive, highlighting the importance of resource-efficient methods (Kim *et al.*, 2021). In the present research, boiling was employed. The substrate was immersed in an ethanol-extracted dye solution at 75 °C for one hour, followed by washing with running water to remove excess dye. Previous studies have shown that cotton fibres can be enhanced with auxiliaries such as DBDCBS to improve dye absorption when using disperse dyes (Kim *et al.*, 2021). Pigments, unlike molecularly specific dyes, can be applied to both natural and synthetic fibres. Although pigments have traditionally been applied through pad-dry methods, exhaust dyeing techniques have recently gained attention, despite persistent challenges with uneven colouration (Gupta *et al.*, 2025). The addition of vanillin during pigment application increases dye fixation, resulting in deeper colouration and enabling lower-temperature processing with improved colour uniformity (Ahmed *et al.*, 2023). These methods were

developed in this study for dyeing blends of organic cotton and linen, which served as the substrate for the production of vegan leather.

Material and Methods

Materials Used

The present study utilized eco-friendly and naturally derived materials for the development of plant-based vegan leather composites. *Ceratonia siliqua* (carob) was employed as the natural dye due to its high tannin content, which contributes to rich coloration and enhanced dye affinity. *Vanillin* was used as a bio-mordant to promote dye fixation through non-toxic chemical interactions, ensuring sustainable colouration without reliance on metallic mordants. The reinforcement substrate consisted of an organic cotton and linen fabric blend in a 50:50 ratio; chosen for its balanced properties of tensile strength, flexibility and surface compatibility with the coating matrix. The base polymeric matrix of the vegan leather was derived from *Solanum lycopersicum* (Tomato), an agro-waste source rich in natural pectin and cellulose. This material provided the desired film-formation ability, flexibility and biodegradation essential for sustainable leather alternatives.

Following the selection of materials, the subsequent stages involved the preparation of the plant-based matrix, surface treatment of the fabric, dyeing process, and composite layer formation, as detailed in the following sections.

Methods

Ceratonia siliqua, commonly known as the carob tree, produces pods that are extensively cultivated for their seeds, which are often used as a natural substitute for cocoa. While the seeds are highly valued, the pod skins are seldom utilised; in this study, however, the skins were employed as a natural dye source (Gupta *et al.*, 2025).

Vanillin, used as a natural mordant, was extracted from the seed pods of *Vanilla planifolia*. Traditionally, Madagascar has been the largest producer of this plant, although it is now cultivated globally. The green pods contain vanillin in glucoside forms, which aid in dye fixation and enhance both the intensity and durability of the colouration (Ahmed *et al.*, 2023).

Organic cotton, cultivated without synthetic pesticides or fertilisers, was selected as one of the base materials. India is a leading producer of organic cotton, and the crop thrives under diverse climatic conditions (Singh *et al.*, 2024). Linen derived from hemp plants was chosen as the second base material, being lightweight, breathable, and suitable for summer apparel (Martínez-Ramos *et al.*, 2025). For blending, a simple weave method was employed, using organic cotton as the warp and linen as the weft in a 50:50 ratio.

The vegan leather was produced from *Solanum lycopersicum* agro-waste (tomato). Spoiled tomatoes were collected locally from farmers in Erode, Tamil Nadu. Edible portions, such as the skins, were separated, blended, and mixed with the extracted dye to achieve uniform colouration (Nour *et al.*, 2018; Pérez-Alonso *et al.*, 2025). Glycol syrup and alum were added as binding agents. The prepared mixture was cast into trays to form sheets, which were initially sun-dried for 24 hours and subsequently dried in a UV oven. The dried sheets were then rolled, applying gentle heat and pressure to achieve the desired flexibility and surface finish (Sharma, V., & Ali, S. W. (2023).

Dyeing method- Blended fabric

The blended cotton–linen fabric was first bleached and then dyed using pigment dyes, with vanillin serving as a mordant. Three key parameters were varied during the dyeing process: dye concentration, vanillin concentration, and temperature (Kim *et al.*, 2021).

Pigments, unlike fibre-specific dyes, can be applied to both natural and synthetic fibres. The addition of vanillin enhanced pigment fixation, intensified colour depth, and enabled lower-temperature processing with more uniform colour distribution (Ahmed *et al.*, 2023). This approach was adopted to optimise

colour strength, uniformity, and fixation while reducing water and energy consumption compared to conventional dyeing methods.

Table 1: Based of 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 2: Design with Variables

Sl. No	Sample Code	Concentration of Dye (%)	Concentration of Mordant (%)	Temperature of Dyeing °C
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

Pre-treatment of Dyeing

The blended fabric was collected and boiled in a water bath at a temperature of 80 °C for 30 minutes, with baking soda and white vinegar added to the water to facilitate the natural bleaching of the fabric. The treated fabric was then dried at 80 °C until completely dry.

The pigments were prepared according to the concentrations and temperatures specified in the table above, and the corresponding samples were collected and preserved for subsequent testing (Singleton, V. L., *et.al* (1999).

Colour strength evaluation

The colour strength of the fabric was expressed using the UV Spectrometer and pigment dye sample. The KS value was calculated using the formula (Kubelka-Munk equation).

$$R = \text{max measurement}$$

$$K/S = (1-R)^2 / 2R$$

Results

The study demonstrated that tomato waste, which is otherwise a source of land pollution, can be processed into a reliable bioactive compound for application in vegan leather development. The pigment dye derived from carob was successfully applied to the leather, showing good evenness and uniformity in the colour. Analytical results confirmed the presence of vanillin, which contributes to the strength of the dye and the dyed leather sheet was exhibited.

Colour Fastness Test

The colourfastness test was done using the AATCC test method, the crocking test, the perspiration test and the light test. The fastness result was determined using the grey scale.

The above material prepared was given for testing and the results are defined below:

Fabric Particulars of Vegan Leather

The dye result of the natural fabric dyed in Carob and are depicted in the table and figure

The fabric construction property, such as weight (g/m²), is presented in the table, which depicts the dyeing results of the fabric. The highest fabric combination was obtained from the organic cotton and linen blend.

Table 3: Fabric Particulars

Material	EPI	Count	Material	PPI	Count	Total Cover Factor
Organic cotton	70	72	Linen	64	82	15.20

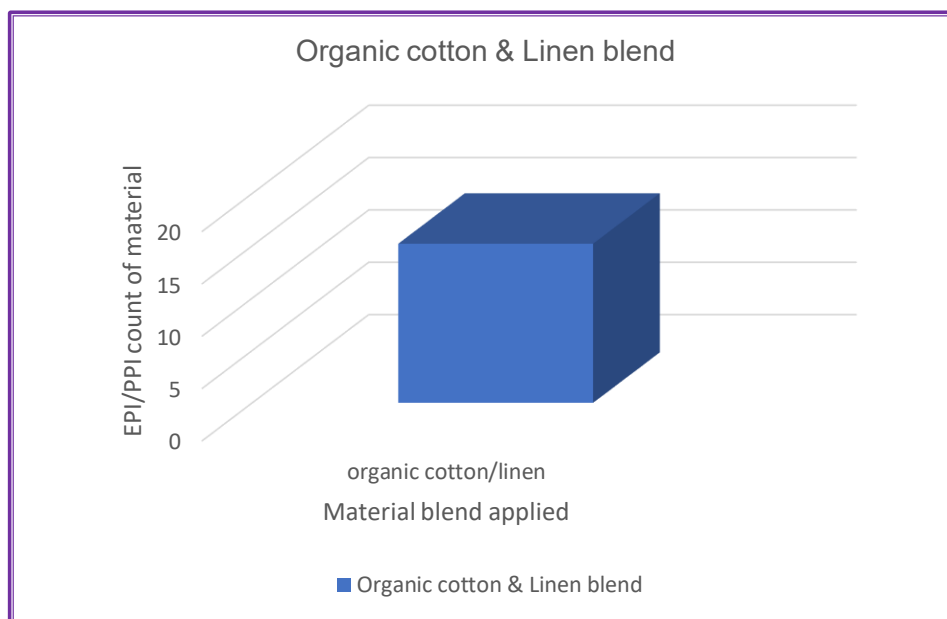


Figure 2: Fabric Cover Factor of Carob Treatment

Woven fabrics are produced by the interlacing method using two sets of yarns arranged vertically and horizontally, forming a plain weave structure with a binary system.

Surface Element Analysis of Base Fabric

The elements of blended fabric of organic cotton and linen with treatment of sample and pigment dye was obtained. The presence of surface elements, vanillin and the cationic agents are attached in the surface of the blended fabric.

Table 4: 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	-	-

The Table 4 shows the surface element analysis of the samples that are blended, treated and pigmented

Colour strength of the dyed sample

Table 5: Colour Strength of Dyed Sample

Sl. No	Sample Code	K/S Value	Strength (%)	L*	a*	b*
1	S1	1.88	221	65.55	-14.55	-31.22
2	S2	1.44	174	63.51	-13.05	-32.56
3	S3	1.57	180	59.12	-14.01	-30.51
4	S4	1.29	153	58.21	-12.08	-29.31
5	S5	2.12	250	59.30	-19.30	-39.44
6	S6	1.03	120	55.02	-13.02	-26.21

Explanations:

The parameters L^* , a^* and b^* represents the coordinates in the CIELAB colour space:

- L^* indicates the lightness of the colour, ranging from 0 (black) to 100 (white).
- a^* represents the red–green axis, where positive values indicate redness and negative values indicate greenness.
- b^* represents the yellow–blue axis, where positive values indicate yellowness and negative values indicate blueness.

The data presented in Table 5 show the K/S values, which represent the relative colour strength of the dyed samples. Among these, samples S1, S3, and S5 exhibited higher colour strength when dyed on organic fabric using natural dye. In addition to the K/S values, the CIELAB colour parameters provide further insight into the shade characteristics: L^* indicates lightness (0 = black, 100 = white), a^* denotes the red–green axis (positive = red, negative = green), and b^* represents the yellow–blue axis (positive = yellow, negative = blue). The negative a^* and b^* values observed across the samples confirm that the dyed fabrics tended towards greenish-blue shades, with S5 displaying the deepest colour intensity due to its higher negative values and maximum K/S.

Effect of dye and vanillin on colour strength

The figure shows the effect of *vanillin* in colour strength of pigment dyed fabric.

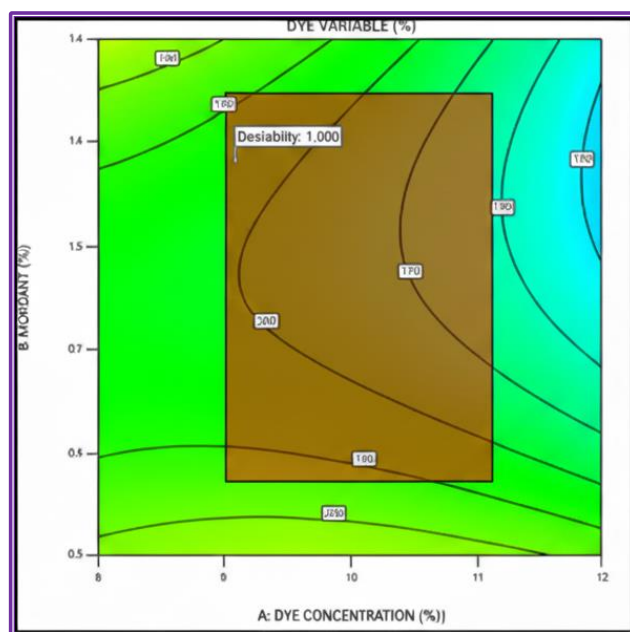


Figure 3: Effect of Vanillin on Colour Strength

The figure 3 illustrates the interactive effect of dye concentration (A) and vanillin mordant concentration (B) on the colour strength (K/S) values of the pigment-dyed blended fabric. The contour plot indicates that an increase in dye concentration significantly enhances colour strength up to an optimum level, beyond which the effect becomes less pronounced. Similarly, a moderate concentration of vanillin improves dye fixation by forming stable dye-mordant fibre complexes, resulting in higher colour intensity. The optimum colour strength was observed at approximately 10% dye concentration with 1% vanillin mordant, showing the max K/S value for the treated sample.

The desirability plot further confirms this optimized condition, where a desirable value of 1.0 also represents the ideal combination of variable yielding maximum colour strength. This result signifies that under these optimized parameter, the dye uptake and colour intensity of the fabric are at their most efficient level.

Short comparison with Recent Natural-Dye studies

Recent research aligns well with the present findings, particularly regarding how K/S values and CIELAB coordinates (L^* , a^* , and b^*) vary depending on dye source, mordanting process, and dyeing duration.

- Hassan *et al.* (2024) found that when pomegranate peel, marigold flower and turmeric were applied to hybrid fabrics, increasing the mordant flowers concentration or extending dyeing time led to higher colour strength (K/S). Simultaneously L^* value decreased (indicating darker shades), while shifts in a^* and b^* corresponded to greater colour strength saturation.
- Demir and Karadağ (2023) investigated Merino wool fibre dyed with natural dye from horse-chestnut shell and similarly confirmed that increasing mordant concentration and dyeing duration enhanced colour strength. Correspondingly, L^* values decreased and variations in a^* and b^* indicated shifts towards red/green or yellow/blue tones, depending on the dye chemistry.
- Uddin *et al.* (2023) optimised a green dyeing process using Corchorus olitorius extract and observed comparable pattern: optimal dyeing conditions (eg. Correct temperature and duration) resulted in stronger K/S values, lower L^* values and measurable shifts in a^* and b^* based on the dye extract used.
- Zahid *et al.* (2024) explored the use of Rhus Coriaria L. on wool, cotton and linen fabrics treated with various mordants: they reported L^* values for linen in the range of ~74-78 under certain mordanting conditions, accompanied by shifts in a^* and b^* depending on mordanting and dye type.

Result comparison

- From the discussed papers, we observe that the samples with higher K/S (S1, S3 and S5) also tend to have lower L^* compared to ones with lower K/S- indicating a darker, more intense coloured sample
- The negative values from a^* and b^* in the above table are considered the dye lean towards green-blue shades (or blue/green/blue-violet), which is different from many studies and b^* dominated (yellow shifts) shows your dye-fibre system producing cooler tones.
- Strength (%) roughly corresponds to those in other studies with optimal mordanting/dyeing parameters producing K/S values significantly above more weakly treated samples.

Effect of vanillin and dyeing temperature colour strength

The effect of vanillin and dyeing temperature on pigment colour strength is illustrated in the sample figure below.

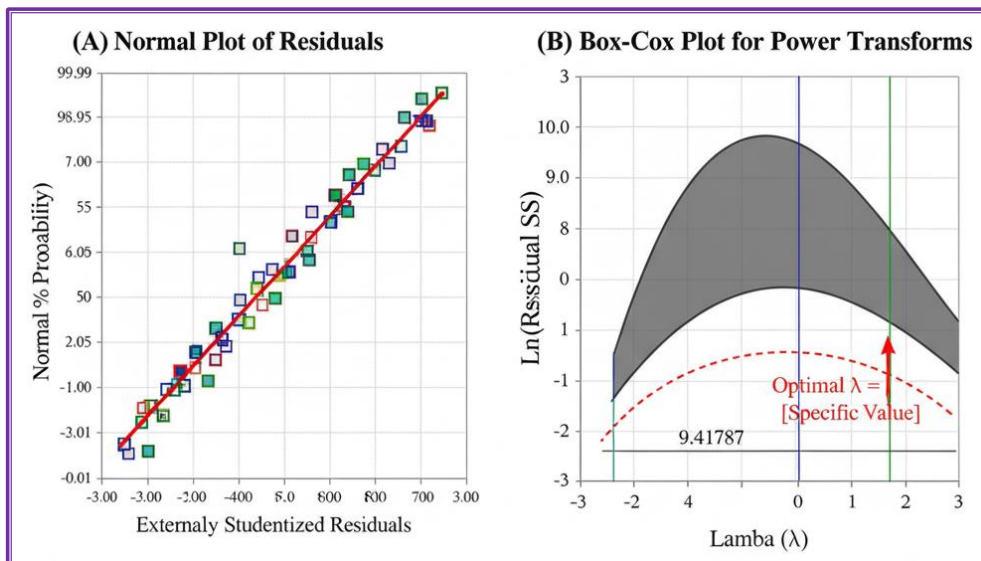


Figure 4: Effect of Vanillin In Colour Strength Pigment

Purpose: To determine if a power transformation (like log, square root, or inverse) should be applied to the Colour Strength data to improve the model's assumptions (primarily to stabilize the variance and improve normality, especially if the Normal Plot was poor).

Interpretation:

- The plot shows a range of possible power transformations (λ) on the x-axis versus a measure of normality/goodness of fit on the y-axis.
- The plot identifies an "Optimal" (the best-fit power) and a 95% Confidence Interval (the two curved red lines).

Key Values to Look For:

- Current : This is $\lambda = 1$. It represents using the original Colour Strength data.
- Optimal: The value that yields the best model fit.

Inference:

- If the confidence interval includes, then no transformation is statistically necessary.
- If the confidence interval does not include, a transformation is recommended. You would choose a common, rounded value for square root, that falls within the confidence interval and is closest to the optimal

Table 6: ANOVA for The Depth of Colour

Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Model	21506.28	9	2389.59	2.80	0.0625	Not significant
A – Dye concentration	2626.93	1	2626.93	3.07	0.1101	–
B – Mordant	1560.83	1	1560.83	1.83	0.2064	–
C – Dye temperature	5267.99	1	5267.99	6.16	0.0324	Significant*
AB	1200.50	1	1200.50	1.40	0.2634	–
AC	1300.50	1	1300.50	1.52	0.2456	–
BC	882.00	1	882.00	1.03	0.3337	–
A ²	702.91	1	702.91	0.82	0.3858	–
B ²	7320.26	1	7320.26	8.56	0.0151	Significant*
C ²	25.38	1	25.38	0.03	0.8666	–
Residual	8547.52	10	854.75	–	–	–
Lack of Fit	5614.19	5	1122.84	1.91	0.2467	Not significant
Pure Error	2933.33	5	586.67	–	–	–
Total	30053.80	19	–	–	–	–

*Significant at $p < 0.05$

Explanation for ANOVA results (Table6)

The quadratic ANOVA model for the dye variable yielded an overall F-value of 2.80 with a p-value of 0.063, indicating that the model was not statistically significant at the 95% confidence level. Among the individual factors, dye temperature ($^{\circ}\text{C}$) was found to be significant ($p = 0.033$), suggesting that temperature plays a crucial role in influencing the dyeing process. The quadratic term of mordant concentration (B^2) was also significant ($p = 0.0151$), indicating that non-linear effects of mordant usage have a strong impact on the dye variable. Other factors, including dye concentration (A), mordant (B), and their interactions (AB, AC, BC), were not statistically significant.

The lack of fit was found to be non-significant ($p = 0.2467$), confirming that the model adequately fits the experimental data. Therefore, optimising dye temperatures and mordant levels may enhance dye uptake and colour strength in the plant-based leather substrate.

Colour Fastness Properties of the Dyed Fabric

The colourfastness properties were evaluated using the standard test procedure involving a greyscale assessment for changes in colour, staining, and overall performance. The grey scale was used to rate the extent of change in sample properties under conditions such as washing, perspiration, water exposure, and rubbing. On the grey scale, a rating of 1 indicates the poorest performance, while 5 represents the best.

Table 7: Properties for Dyed Fabric

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

Table 7 shows that the wash fastness of the pigment-dyed samples is very good. The washing properties of the dyed samples are comparable to those of natural dyes. A slight variation was observed in samples 4 and 6, with minor colour changes appearing in certain areas of the fabric; however, no staining was detected, owing to the use of pigment dyeing.

Table 8 presents the rub fastness of the pigment-dyed samples. The fastness of the pigmented samples is rated as average, which may be attributed to the application of the dye on a blended fabric.

Table 8: 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

The Table 9 below shows the light fastness property of fabric sample. The dyed fabric shows good properties to light; they are similar to the other fastness test.

Table 9: Light Fastness of the Dyed Sample

Sl. No	Sample	Light fastness
1	S1	7/8
2	S2	7/8
3	S3	7
4	S4	6/7
5	S5	7
6	S6	7/8

Surface of the Vegan leather

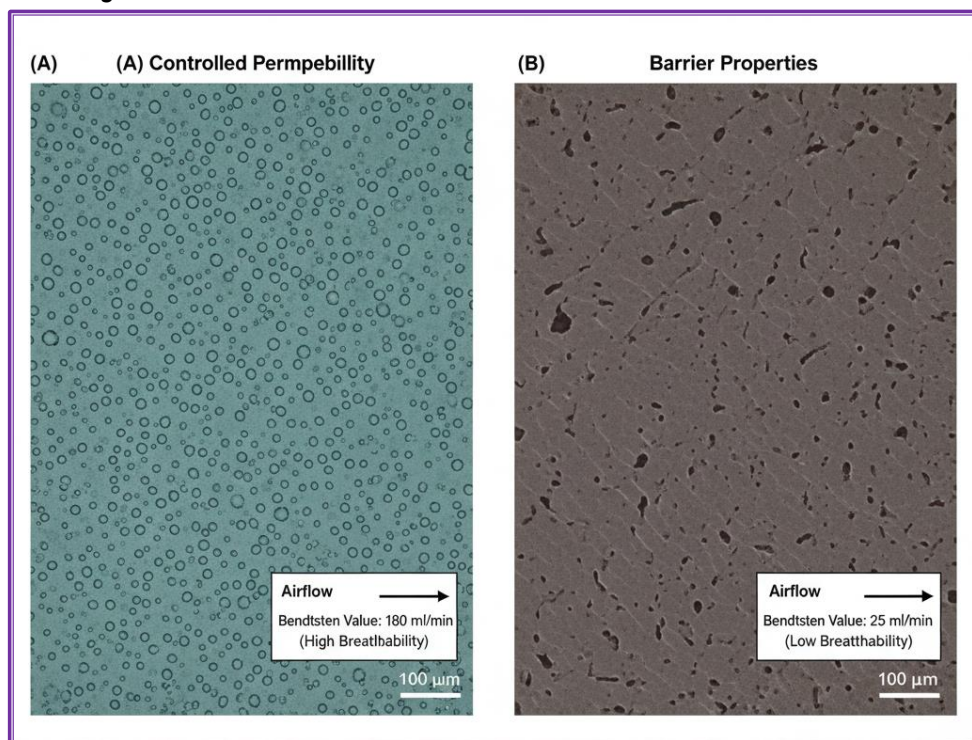


Figure 5: Microstructure and Airflow Analysis of Vegan Leather Surface. The Porous Structure of the Polymeric Matrix was Observed Using an Optical Microscope at [Insert Magnification, E.G., 100×] (A, B). Airflow Through the Material Was Quantified Using a Bendtsen Tester Apparatus (N3500), Indicating Pore Distribution and Breathability of the Sample. Uniform Pore Formation Suggests Consistent Material Processing and Potential for Controlled Permeability.

The microstructural surface of the vegan leather was examined to analyse its pore distribution and airflow characteristics. The images (Figures 6A and 6B) were captured using an optical microscope at a magnification of [insert magnification, e.g., 100×], illustrating the porous structure of the polymeric matrix. The test samples were further analysed using a Bendtsen test apparatus (N3500) to quantify airflow through the material. The measured airflow indicates the level of porosity, which directly influences the breathability and functional performance of the vegan leather. The uniform pore distribution observed in Figure 6 suggests consistent material processing and potential for controlled permeability in practical applications.

Discussion

The findings of this study confirm the potential of tomato waste as a sustainable raw material for the development of vegan leather (Singh *et al.*, 2024). This aligns with current trends emphasising the valorisation of agro-waste for eco-friendly material production. For example, sustainable leather alternatives derived from fungal chitin and tannic acid have demonstrated superior performance and dyeability, providing a benchmark for comparing the colour strength achieved in our pigment-dyed fabrics (Zhou *et al.*, 2025). The utilisation of tomato waste in this research contributes to the expanding field of sustainable materials by creating value from waste streams.

The uniformity of pigment application observed in our samples indicates strong compatibility between the substrate and the bio-based pigment. Similar results have been reported in studies where novel plant sources were optimised for natural pigment extraction and textile dyeing, confirming that underexplored plant by-products can produce uniform colouration and stable shades (Martínez-Ramos *et al.*, 2025). The incorporation of vanillin detected in our samples is particularly significant. Vanillin and

its derivatives are known to improve dye fixation and colour stability, as evidenced by functionalisation studies on cellulosic and polyester textiles (Ahmed *et al.*, 2023). The results further suggest that the naturally occurring vanillin in tomato waste pigments enhances colour strength and durability.

The observed colour strength corresponds with compositional analyses of tomato waste, which have identified substantial levels of carotenoids and phenolic compounds. Comparative extraction studies have demonstrated that these compounds can be effectively recovered from tomato processing residues, contributing to pigment quality (Pérez-Alonso *et al.*, 2025). Furthermore, recent reviews highlight that fruit and vegetable by-products are rich in bioactive compounds with strong industrial potential, supporting our approach of using tomato waste as both a functional dye source and a step towards waste reduction (Singh *et al.*, 2024).

Beyond aesthetic outcomes, the functional attributes of bio-based dyes are attracting increasing attention. For instance, studies on natural dyeing using *Bixa orellana* seeds have shown not only effective colouration of cotton, silk, and leather but also additional antibacterial properties (Gupta *et al.*, 2025). Such multifunctionality suggests that bio-derived pigments, including those obtained from tomato waste, could be further optimised for advanced textile and leather applications within the sustainable fashion industry (Ahmed *et al.*, 2023).

Overall, this study demonstrates that incorporating tomato waste into vegan leather production addresses both environmental challenges and market demand for sustainable alternatives. The results contribute to the broader framework of circular economy practices by transforming agro-waste into high-value, functional materials for eco-fashion applications.

Limitations

This study was restricted to laboratory-scale dyeing and characterisation; large-scale production and long-term durability assessments were not undertaken. Furthermore, only fundamental colour strength and pigment properties were examined, without an in-depth investigation of mechanical or environmental resistance.

Future Scope

Future research should aim to optimise large-scale processing of tomato waste pigments for industrial vegan leather applications. Further investigations into mechanical strength, biodegradability, and multifunctional properties (e.g., antimicrobial activity) will enhance their applicability within sustainable fashion.

Conclusion

The present research demonstrated the feasibility of utilising tomato waste, a readily available agro-residue and potential land pollutant, as a promising raw material for producing sustainable vegan leather. Through the extraction and incorporation of bioactive compounds, particularly pigment dyes derived from *Ceratonia siliqua* (carob), this study established that tomato waste can be repurposed to create functional and aesthetically appealing materials suitable for eco-fashion applications. The dyed vegan leather sheets exhibited good evenness and colour uniformity, with analytical confirmation of the presence of vanillin—a natural compound known to enhance dye fixation, colour fastness, and the overall strength of the dye–substrate interaction.

The results align with international trends that prioritise agro-waste valorisation and bio-based alternatives over traditional leather. The incorporation of natural pigments not only achieved satisfactory colouration but also highlighted the environmental value of recycling waste streams that would otherwise contribute to land degradation. When compared with currently utilised sustainable leather substitutes, such as fungal chitin–tannic acid composites and plant-based pigments, tomato waste demonstrates strong potential as a renewable resource within this industry.

By integrating material science, waste valorisation, and green design, this research underscores the effectiveness of circular economy approaches in reducing environmental impact and supporting the development of green innovation products. The utilisation of tomato waste in vegan leather production

has been successfully established as a valuable advancement for both the environment and industry, addressing consumer demand for sustainable alternatives. Overall, the study contributes to the growing body of knowledge on bio-derived dyes and positions tomato waste as a promising candidate for future large-scale sustainable leather production.

Conflict of Interest

Authors have declared no competing of interests.

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References

- Ahmed, M., El-Sayed, M., & Hassan, R. (2023). Functionalization of cellulosic and polyester textiles using reduced Schiff base (RSB) of eco-friendly vanillin. *Cellulose*, 30(6), 3785–3799. <https://doi.org/10.1007/s10570-023-05085-z>
- Demir, M., & Karadağ, R. (2023). Investigation of dyeing characteristics of Merino wool fibre dyed with natural dye from horse chestnut shell. *Journal of Natural Fibers*, 20(9), 13212–13226. <https://doi.org/10.1080/15440478.2023.2186115>
- Food and Agriculture Organization of the United Nations. (2019). *World Crops Production*. FAOSTAT. <http://www.fao.org/faostat/en/#data/QC/visualize/>
- Grassino, A. N., Halambek, J., Djaković, S., Brnčić, S. R., Dent, M., & Grabarić, Z. (2016). Utilization of tomato peel waste from canning factory as a potential source for pectin production and application as tin corrosion inhibitor. *Food hydrocolloids*, 52, 265-274. <https://doi.org/10.1016/j.foodhyd.2015.06.020>
- Hassan, M. N., Fariha, F. T., Zayee, Z., & Hasan, M. (2024). Analyzing different functional and dyeing performance of natural blended fabric utilizing natural dyes and quality prediction by fuzzy logic. *Heliyon*, 10(22), e40399. <https://doi.org/10.1016/j.heliyon.2024.e40399>
- Jamal, P., Akbar, I., Hashim, Y. Z. H., & Jaswir, I. (2016). Process development for maximum lycopene production from selected fruit waste and its antioxidant and antiradical activity. *Journal of Food Processing & Technology*, 7(4), 1–7. <http://dx.doi.org/10.4172/2157-7110.1000576>
- Lin, C. H., & Chen, B. H. (2003). Determination of carotenoids in tomato juice by liquid chromatography. *Journal of Chromatography A*, 1012(1), 103-109. [https://doi.org/10.1016/S0021-9673\(03\)01138-5](https://doi.org/10.1016/S0021-9673(03)01138-5)
- Lu, Z., Wang, J., Gao, R., Ye, F., & Zhao, G. (2019). Sustainable valorisation of tomato pomace: A comprehensive review. *Trends in Food Science & Technology*, 86, 172–187. <https://doi.org/10.1016/j.tifs.2019.02.020>
- Martínez-Ramos, J., López-Morales, D., & Hernández, P. (2025). Potential of new plant sources as raw materials for obtaining natural pigments/dyes. *Agronomy*, 15(2), 405. <https://doi.org/10.3390/agronomy15020405>
- Muruganandham, M., Tamilselvi, Y., Sivasubramanian, K., Velmurugan, P., Oleyan Al-Otibi, F., & Sivakumar, S. (2025). Sustainable dyeing of cotton, silk and leather using natural dye from Bixa orellanaseeds: extraction, optimization and assessment of antibacterial activity. *Frontiers in Chemistry*, 13, 1474160. <https://doi.org/10.3389/fchem.2025.1474160>
- Nour, V., Panaite, T. D., Ropota, M., Turcu, R., Trandafir, I., & Corbu, A. R. (2018). Nutritional and bioactive compounds in dried tomato processing waste. *CyTA – Journal of Food*, 16(1), 222–229. <https://doi.org/10.1080/19476337.2017.1383514>
- Odrizola-Serrano, I., Soliva-Fortuny, R., & Martín-Belloso, O. (2008). Effect of minimal processing on bioactive compounds and color attributes of fresh-cut tomatoes. *LWT – Food Science and Technology*, 41(2), 217–226. <https://doi.org/10.1016/j.lwt.2007.03.002>
- Pérez-Alonso, J., Torres, L., & García, M. (2025). Lycopene and other bioactive compounds' extraction from tomato processing industry waste: A comparison of ultrasonication versus a conventional stirring method. *Horticulturae*, 11(1), 71. <https://doi.org/10.3390/horticulturae11010071>
- Sharma, V., & Ali, S. W. (2023). Functionalization of cellulosic and polyester textiles using reduced Schiff base (RSB) of eco-friendly vanillin. *Cellulose*, 30(5), 3317-3338. <https://doi.org/10.1007/s10570-023-05085-z>

Silva, Y. P. A., Borba, B. C., Pereira, V. A., Reis, M. G., Caliar, M., Brooks, M. S. L., & Ferreira, T. A. P. C. (2018). Characterization of tomato processing by-product for use as a potential functional food ingredient: Nutritional composition, antioxidant activity and bioactive compounds. *International Journal of Food Sciences and Nutrition*, 70(2), 1–11. <https://doi.org/10.1080/09637486.2018.1489530>

Singh, A., Patel, V., & Rao, R. (2024). Bioactive compounds from fruit and vegetable waste: Extraction and possible utilization. *Foods*, 13(5), 775. <https://doi.org/10.3390/foods13050775>

Singleton, V. L., Orthofer, R. M., & Lamuela-Raventós, R. M. (1999). Analysis of total phenols and other oxidation substrates and antioxidants by means of Folin–Ciocalteu reagent. *Methods in Enzymology*, 299, 152–178. [https://doi.org/10.1016/S0076-6879\(99\)99017-1](https://doi.org/10.1016/S0076-6879(99)99017-1)

Socaci, S. A., Fărcaș, A. C., Vodnar, D. C., & Tofană, M. (2017). Food wastes as valuable sources of bioactive molecules. In N. Shiomi (Ed.), *Superfood and functional food: The development of superfoods and their roles as medicine* (pp. 75–93). InTech. <https://doi.org/10.5772/66115>

Socaci, S. A., Socaciu, C., Mureșan, C., Fărcaș, A. C., Tofană, M., Vicaș, S., & Pinte, A. (2014). Chemometric discrimination of different tomato cultivars based on their volatile fingerprint in relation to lycopene and total phenolics content. *Phytochemical Analysis*, 25(2), 161–169. <https://doi.org/10.1002/pca.2483>

Song, B., Liu, K., Gao, Y., Zhao, L., Fang, H., Li, Y., ... & Xu, Y. (2017). Lycopene and risk of cardiovascular diseases: A meta-analysis of observational studies. *Molecular Nutrition & Food Research*, 61(9), 1601009. <https://doi.org/10.1002/mnfr.201601009>

Szabo, K., Cătoi, A. F., & Vodnar, D. C. (2018). Bioactive compounds extracted from tomato processing by-products as a source of valuable nutrients. *Plant Foods for Human Nutrition*, 73(4), 268–277. <https://doi.org/10.1007/s11130-018-0691-0>

Uddin, M. S., Hossain, M. K., & Ahmed, S. (2023). Optimisation of a green dyeing process using *Corchorus olitorius* dye extract. *Cleaner Materials*, 8, 100253. <https://doi.org/10.1016/j.clema.2023.100253>

Zahid, M., Ahmad, S., & Hassan, T. (2024). *Rhus coriaria* L. in tradition and innovation: Natural dyeing and functional applications on textiles. *Dyes and Pigments*, 222, 111045. <https://doi.org/10.1016/j.dyepig.2024.111045>

Zhou, L., Wang, Y., & Li, H. (2025). Sustainable leather alternatives: High-performance and dyeable bio-based materials from fungal chitin and tannic acid. *Carbohydrate Polymers*, 327, 1210269. <https://doi.org/10.1016/j.carbpol.2024.1210269>