Anthocyanin Dye for Producing Colorimetric Properties in Wool

Research Report

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Abstract

This study investigates the potential of blackberries (*Rubus fruticosus*) as a natural dye source for wool fabric by extracting anthocyanin compounds to examine their colour variation in response to pH. Blackberries were selected due to their abundance in Australia, where they are classified as a Weed of National Significance, presenting an opportunity to repurpose excess organic matter into a sustainable dye source. Wool fabrics were dyed using blackberry extracts under varying pH conditions to observe colour shifts, with a synthetic dye used as a control. Results demonstrated that anthocyanin-based dyes produced a smart textile capable of visible colour change in response to pH variation, though the resulting colour dispersion was less uniform compared to the synthetic dye. This report presents novel findings of developing colorimetric properties in wool fabrics using blackberry-derived anthocyanins, and presents the exploration of the hues achievable using this compound as a dye source.

Contents

1 Introduction

1.1 Background

This project concerns developing natural dyeing processes, a key aspect of creating sustainable fashion. Currently, conventional textile dyeing wastewater is a major global pollutant, often containing synthetic dyes, salts, and hazardous chemicals that degrade water quality and harm aquatic ecosystems (Islam, M., & Mostafa, M. 2019). Synthetic dyes are widely used in textile manufacturing due to their superior colourfastness, wide range of colours, and ease of use. Due to their widespread usage, synthetic dyes have also benefited from economies of scale, making them significantly more cost-effective for large-scale production compared to most natural dye alternatives.

However, wastewater from synthetic dyes contains toxic effluents that cause significant harm to the environment. When discharged into waterways, the high concentration of chemical colourants reduces light penetration, disrupting photosynthesis in aquatic flora and inhibiting the oxygen balance of aquatic ecosystems. This imbalance can weaken biodiversity, reduce the survival of fish populations, and destabilise food chains. Additionally, the presence of heavy metals and salts in dye effluents can contaminate soil and inhibit plant growth. Over time, these substances bioaccumulate in organisms, moving up the food chain and posing risks to both wildlife and humans (Alegbe, E. et al. 2024).

Many synthetic dyes, particularly azo dyes, can also undergo chemical transformations into aromatic amines, some of which are mutagenic or carcinogenic, presenting long-term health hazards to exposed communities and ecosystems. (Lellis, B. et al. 2019). These chemicals can particularly in countries in the global south where much textile manufacturing occurs and lacks sufficient infrastructure to treat the wastewater to be safe for release into the environment.

Alternatively, natural dyes have experienced a resurgence due to their chemical safety, lower environmental impact, and ability to produce unique, patterned shades that appeal to consumers seeking sustainable products. Natural dyes are derived from organic sources such as plant extracts, minerals, or animal sources which makes them biodegradable and renewable. Their production often involves fewer toxic chemicals, reducing the risk of water pollution and chemical runoff into surrounding ecosystems (Candela, R. et al. 2021). Additionally, organic dyes are hypoallergenic, in contrast with synthetic azo dyes that can cause skin irritation and allergic reactions (Chung, K. 2016). This differentiation is particularly significant in textiles that come into contact with skin, such as undergarments and clothing.

1.2 Rationale

The aim of my Woolmark Textile Research is to develop a natural dyeing technique that can exhibit colorimetric change in wool textiles, meaning that the colour of the fabric will change in reaction to the pH level it is exposed to. Throughout this project, I will develop my laboratory research skills, as well as critical thinking and report writing standards. I will aim to create a dye solution using anthocyanins extracted from my chosen natural plant source, the blackberry fruit.

Blackberries were selected as the natural dye source for this study due to their abundance in Australia, where they are classified as a Weed of National Significance. This classification requires landowners to actively control the plant's spread, and its sale or distribution is prohibited. Currently, blackberry management commonly involves the use of herbicides, however, these chemicals cannot be applied to fruiting plants, as it poses risks to wildlife that consume the berries. Developing a dye recipe that utilises blackberry fruit presents an opportunity to repurpose excess organic matter from an invasive species into a sustainable, user-friendly natural dye.

By experimenting with dyeing wool with anthocyanins from blackberries using biodegradable, organic pigments, I aim to contribute to the fashion industry's shift away harmful chemicals, lessen chemical pollution, support cleaner water systems, and reduce the textile industry's overall environmental footprint. I can also demonstrate ability to create smart textiles using natural pigments.

Arising from the background and rationale for this research, the following research question will be used to guide my practice.

How can the development of bio-based fabric dyeing techniques contribute to creating smart materials and solving systemic sustainability issues in fashion, such as circularity and waste reduction?

1.3 Literature Review

The use of natural dyes has re-emerged in recent years as a sustainable alternative to synthetic colouring agents, largely due to increasing awareness of the environmental impacts of textile dye wastewater. Synthetic dyes, which dominate the global textile industry, are often derived from petrochemical sources and contribute to significant chemical pollution through non-biodegradable effluents, heavy metals, and toxic by-products (Yusuf et al., 2017). In contrast, natural dyes derived from plant-based sources such as berries, roots, and leaves are biodegradable and pose minimal ecological harm (Yadav, S. et al. 2023).

Among natural dye compounds, anthocyanins are of particular interest due to their vivid pigmentation and natural pH sensitivity. Anthocyanins are water-soluble flavonoid compounds responsible for the red, purple, and blue hues found in many fruits, including blackberries, blueberries, and grapes. Their molecular structure (Figure 1) allows them to exhibit reversible colour changes depending on the pH of their surrounding environment, appearing red in acidic solutions and shifting to blue or green in alkaline conditions (Giusti & Wrolstad, 2001). This pH-responsive property gives anthocyanins potential for smart textile applications, where colour change can be used as a visual indicator of chemical or environmental changes (Yusoff et al., 2021).

Previous studies have demonstrated that protein-based fibres, such as wool and silk, exhibit a higher affinity for natural dyes than cellulose-based fibres due to their amino acid composition. (Samanta & Agarwal, 2009). Under mildly acidic conditions, the amino groups in wool form ionic bonds with the negatively charged anthocyanin molecules, allowing successful dye uptake without the need for a mordant. However, colour fastness remains a major limitation, as anthocyanins are highly sensitive to light, heat, and oxidation (Enaru, B. et al. 2021).

Recent research has also examined the extraction efficiency of anthocyanins from various plant materials using solvents such as methanol, ethanol, and water. While organic solvents tend to yield higher pigment concentrations, water is favoured in sustainable dyeing research for its lower toxicity and environmental compatibility (Castañeda-Ovando et al., 2009). Studies within the Heliyon chemistry collection have demonstrated that aqueous extraction can achieve excellent pigment yield for textile applications while maintaining safer laboratory practices.

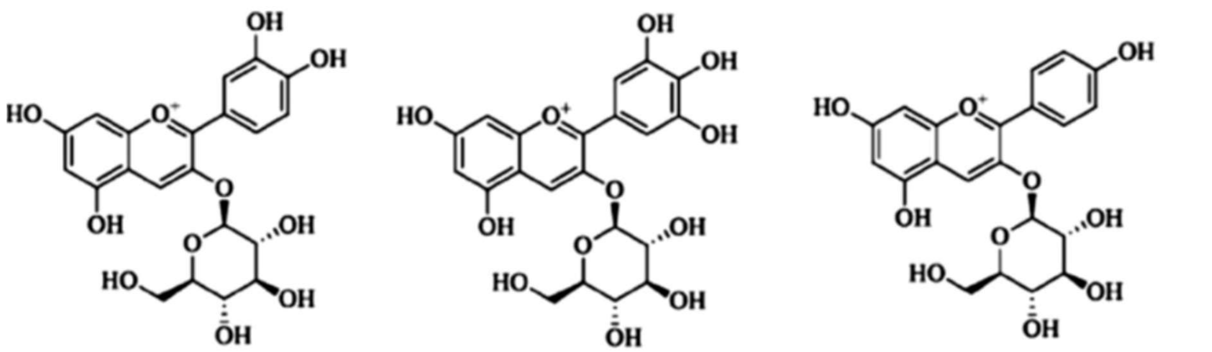
Overall, the literature suggests that while anthocyanin-based dyes offer significant environmental benefits over synthetic dyes, challenges remain in achieving colour stability, consistency, and scalability. This study builds on these findings by examining the colourimetric behaviour of blackberry-derived anthocyanins on wool across varying pH levels, aiming to assess their potential for sustainable smart textile development.

1.4 Identifying Gaps in Existing Research

The colour spectrum achievable from blackberry-derived anthocyanins is under-researched, with limited study dedicated specifically to this topic. While several studies have examined the dyeing potential of other anthocyanin-rich organic materials such as butterfly pea flower, blueberries, and purple carrot, the full extent of colour variation achievable from blackberries has not yet been comprehensively investigated.

This represents a significant area of interest, as anthocyanins from different botanical sources exhibit distinct colour spectrums depending on their molecular structure and environmental conditions. Generally, anthocyanins display purple hues under acidic conditions, transition to blue near neutral pH, and shift toward green or yellow tones under alkaline environments. Understanding the specific colorimetric properties of blackberry anthocyanins could contribute valuable insight into their potential applications in natural dyeing and smart textile development.

Furthermore, exploring blackberry-derived anthocyanins presents an opportunity to repurpose an invasive species. In Australia, the wild blackberry plant (Rubus fruticosus complex) is classified as a noxious weed, known for its rapid spread and ecological disruption. Developing methods to utilise this abundant resource for sustainable dye production could transform an environmental challenge into a productive material opportunity, contributing to concepts of circular design by providing an accessible use of waste material from weed-clearing.



Cyanidin 3-O-glucoside | Delphinidin 3-O-glucoside | Pelargonidin-3-O-glycosides

Fig. 1. Chemical structure of the 3 anthocyanins in blackberries.

2 Methodology

This research is a qualitative study supported by laboratory experimentation, investigating the extraction of anthocyanins from blackberries and their application as a natural dye on wool fabric. The outcomes are analysed through both visual observation and colour spectrophotometer readings to determine whether the extracted anthocyanins produce measurable colour variations across different pH levels.

2.1 Research Design

Originally, two different methods of anthocyanin extraction were proposed, using water and methanol as solvents. This decision was guided by findings in the literature review, which identified both solvents as effective in extracting anthocyanins from organic compounds. However, following initial experimentation with water as the sole solvent, the focus was redirected exclusively toward the water-based extraction method. Methanol, being a corrosive and hazardous chemical, required the use of a laboratory fume hood, adherence to strict chemical safety protocols, and constant supervision, which were factors that proved logistically challenging due to timetable conflicts between the student researcher and the supervisor. The results obtained from the water-based dye were sufficient to observe and measure the colourimetric properties on wool fabric, and therefore water was chosen as the sole solvent for the remaining experimentation.

For the extraction of anthocyanins from blackberries using a water solvent, the mixture of blackberries and water was placed in an ultrasonic cleaning machine. This process emits high-frequency ultrasonic waves through the solution, which help to break down the cellular structure of the fruit and release the anthocyanin compounds more effectively (Sharma, P. 2025). While optional, ultrasonic extraction improves potency of the dye by increasing pigment release from the organic matter.

The decision to include a synthetic dye as a comparative study was made in consultation with the supervising professor. Using a synthetic dye in a shade similar to the anticipated blackberry-derived dye allowed for a direct comparison of dye uptake, retention, and colour dispersion on wool fabric. This comparison aimed to highlight the contrasting performance characteristics of natural and synthetic dyes, thereby illustrating both the challenges and advantages of using natural dye alternatives in textile applications.

2.2 Ethics and Risk

The risks associated with this project affect myself, other lab users, and individuals who share the lab space, including my supervisor, Ayomi. Working with chemicals requires careful attention to physical safety to minimise the risk of harm to myself and others in the laboratory.

Sodium sulphate (10%) is a moderately hazardous chemical capable of causing skin and eye irritation upon contact. In its liquid form in this study, it does not pose risk by inhalation. Care was taken through the use of PPE and ventilation to prevent risk by ingestion or skin contact.

Formic acid, used in preparing the synthetic dye solution, is corrosive and toxic, posing risks of skin burns, eye damage, and respiratory irritation. The concentration used in this study was 10%, and although considered a weak acid by chemical definition, it is capable of causing severe burns to skin and eyes. To minimise hazards, all work was conducted in a ventilated laboratory space with PPE (gloves, goggles, and lab coat). The use of formic acid was limited to only the essential quantities needed in order to reduce exposure risks to both the researcher and others in the shared lab space.

Additionally, I will be using a hot plate to heat the dye solution to approximately 70 °C. The hot plate presents a risk of burns to both myself and others in the lab, as the heating surface is exposed and remains hot during and after use. Attached is a complete risk assessment sheet that evaluates the chemical and physical risks associated with this project.

2.3 Blackberry Anthocyanin Dye Recipe

Materials

Unscoured Wool Fabric

250g Fresh Blackberry Fruit

250ml Water

Buffer Solutions (Ascending Order by pH)

White Vinegar (pH 2.59)

White Wine Vinegar (pH 3.0)

Lab Detergent (pH 8)

Washing Detergent (pH 9)

Chlorine Cleaner (pH 11.8)

Equipment

Hot Plate

Ultrasonic Cleaner

Drying Rack

Pipette

Using the following formula for the dye solution

1g of blackberry fruit: 2.5ml water

Method

1. Crush 134g of blackberries in mortar and pestle until the fruit becomes a pulp.
2. Using the 1 : 2.5 ratio, combine the blackberry pulp with 228ml of distilled water in a glass beaker.
3. Place the dye mixture in an ultrasonic cleaner to extract the anthocyanins at 30 degrees Celcius for 45 minutes.
4. Remove beaker of dye from the ultrasonic cleaner and pour the mixture through a mesh cloth to separate the pulp from the liquid.
5. Transfer the strained dye solution to a hot plate and heat until 70 degrees Celcius.
6. Scour the wool by washing thoroughly with a mild detergent and rinse with water.
7. Submerge a 10cm square of wool fabric into the dye solution for 45 minutes, stirring occasionally to ensure even dye absorption.

8. Remove the fabric from the dye solution and wash with water., then leave to dry on a drying rack.
9. After drying, cut 5x squares of 2cm from the dyed wool cloth.
10. Prepare vials of buffer solutions with varying pH levels.
11. Using a pipette, saturate each piece of cloth with a corresponding buffer solution and leave the fabric to dry.
12. Observe the colour shifts in the treated fabric, scanning under the CIELAB colour spectrometer to obtain the L, a and b values for analysis.

Note: Photos of experimental setup and processes are attached in Appendix.

2.4 Synthetic Telen Red Dye Recipe

Materials

200ml Water

5ml Sodium Sulphate (10%)

1ml Formic Acid (10%)

5ml Dye Solution (1% Telen Red A-2R)

Methodology

1. Cut a 10cm square of wool fabric and scour by washing thoroughly with a mild detergent and water.
2. Combine water, formic acid, sodium sulphate, and dye solution in a beaker.
3. Introduce the wool fabric into the dye bath and heat on hot plate to boil.
4. Boil the fabrics in the dye bath for 30 minutes, stirring occasionally.
5. Observe the dye bath, as the pigment will be absorbed into the fabric and the solution will lose colour.
6. Rinse the fabrics with water and dry in the oven at 60 degrees Celcius.
7. Take CIELAB colour spectrometer readings in 4 different areas of the fabric switch, noting the L, a, and b values.

Note: Photos of experimental setup and processes are attached in Appendix.

3 Results and Discussion

3.1 Presentation of Data

Sample pH	Reading No.	L*	a*	b*	CIELAB Colour using https://www.nixsensor.com/free-color-converter/		
					L*	a*	b*
pH 2.6 (Sample no 1)	1	42.97	15.31	2.04	42.86	15.17	2.17
	2	42.42	15.3	2.01			
	3	42.39	15.33	2.01			
	4	43.27	14.96	2.36			
	5	43.27	14.94	2.45			
pH 3.05 (Sample no 2)	1	38.83	15.89	2.08	38.44	15.91	2.09
	2	38.67	16.22	2.13			
	3	38.22	15.62	2.13			
	4	38.63	15.69	1.92			
	5	37.84	16.14	2.18			
pH 8 (Sample no 3)	1	37.84	4.91	-0.48	38.41	4.19	-1.93
	2	37.91	4.08	-1.98			
	3	38.03	4.08	-2.11			
	4	38.5	3.96	-2.21			
	5	39.78	3.94	-2.86			
pH 9 (Sample no 4)	1	37.45	7.48	3.96	37.41	7.47	3.97
	2	37.5	7.48	3.96			
	3	37.33	7.46	3.92			
	4	37.57	7.49	3.97			
	5	37.2	7.44	4.05			
pH 11.82 (Sample no 5)	1	38.89	3.01	12.45	38.47	3.11	12.46
	2	38.88	3.04	12.27			
	3	38.59	3.05	12.4			
	4	38.56	3.08	12.46			
	5	37.45	3.36	12.74			

Fig. 2. CIELAB reading colour values and colour swatch of 5 samples.

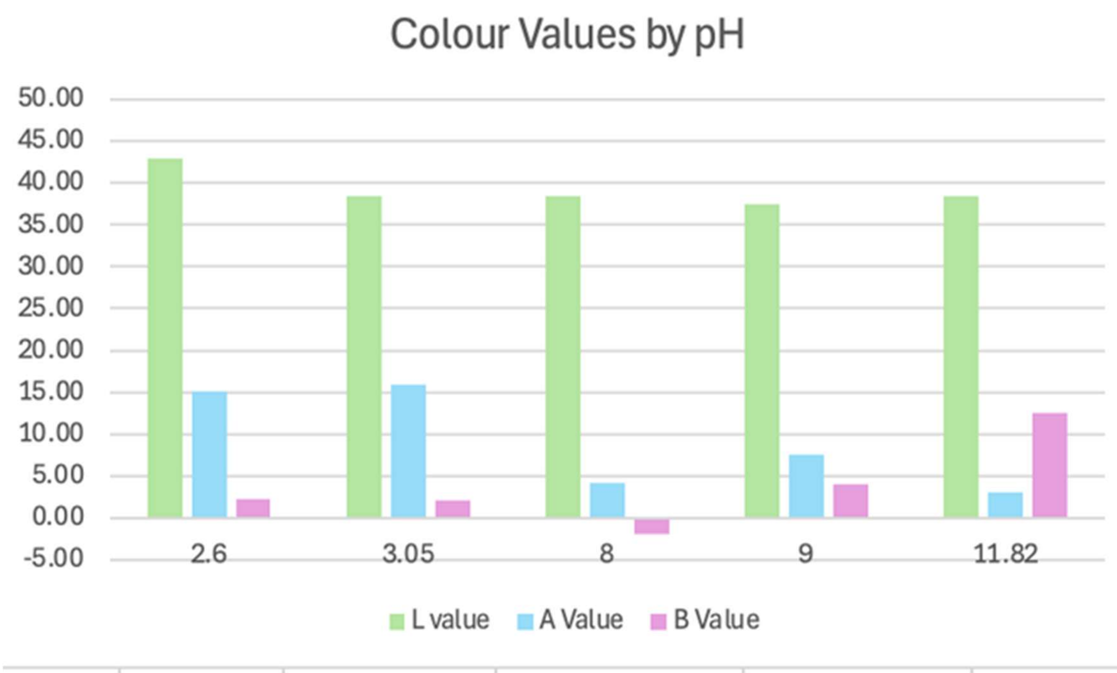


Fig. 3. Graph depicting L, a and b values of 5 samples.

3.2 Discussion

Each treated fabric sample was saturated with a corresponding buffer solution and left to dry to develop the colour shift. The samples were then analysed in the colour spectrometer in four different positions, and then the average value was taken to develop the final colour reading. Four multiple readings were taken to ensure an accurate and even representation of the entire fabric sample.

The CIELAB values in Figure 2 indicate a clear and measurable change in the colour of the dyed wool fabrics across varying pH levels. The average results, presented in the table below in ascending order of pH, display the characteristic colorimetric transition of anthocyanins when exposed to different buffer solutions. As the pH increases, a distinct shift in hue, lightness, and chroma is observed.

Specifically, blackberry-derived anthocyanins exhibit a deep reddish-purple tone under acidic conditions (pH 2–4), corresponding to the presence of the flavylium cation form. Around neutral pH (6–7), the samples shift towards a bluish-violet appearance, reflecting the formation of the quinoidal base. At alkaline pH levels (8–10), the fabrics transition to greenish or yellowish hues, a result of the structural transformation into chalcone and related derivatives (Wang, H. 2016). These colour patterns align with other colour spectrums of other oragnic sources of anthocyanins (refer to Appendix Figure 9).

Referring to Figure 3 above, the L value represents lightness, ranging from 0 (pure black) to 100 (pure white). The lightness of the samples remain fairly consistent throughout the pH spectrum. The *a* value represents the red–green spectrum, where negative values indicate green and positive values indicate red. Across the pH scale in the readings of this wool fabric, a decrease in the a value denotes a shift from red at more acidic conditions toward green at higher pH levels. Furthermore, the b value, which represents the blue–yellow spectrum (with negative values corresponding to blue and positive values to yellow), shows that the anthocyanin compound shifts toward greenish-yellow hues under alkaline conditions, consistent with expected colour changes in response to pH.

These findings confirm the sensitivity of anthocyanin dyes to pH variation and align with previously reported colour responses in biochromic textiles. The distinct L, a, and b value changes in the CIELAB system quantitatively support these visual transitions, highlighting the potential of blackberry anthocyanin-dyed wool as a multichromic, pH-responsive material for smart textile applications.

3.3 Implications and Applications

The results of this research demonstrate the potential application of anthocyanins as a natural textile dye. The water used in the dyeing process is free from synthetic and toxic effluents, fully biodegradable, and safe for immediate release into the environment, highlighting the environmental advantage over conventional synthetic dyes. By eliminating chemical effluent in the wastewater, this study aligns with a key principle of the circular economy: achieving zero waste. The remaining blackberry residue, consisting of seeds and pulp, can be easily composted, returning nutrients to the soil.

The dyed wool fabric exhibited good saturation and retained a colour true to the source anthocyanin, with fairly even absorption as reflected in the four spectrophotometer readings of the untreated fabric. In contrast, the synthetic dye achieved superior dye uptake and more uniform colour dispersion, as demonstrated by comparative readings, reflected in the similar values of the readings (Appendix Figure 10).

Despite the promising outcomes achieved in this experiment, the long-term usability of anthocyanin dyes is constrained by several factors. The colour stability of the anthocyanins is highly sensitive to changes in temperature, pH, and washing conditions, making natural dyes less durable than synthetic alternatives for standard wearable textiles. Nonetheless, the colorimetric properties of anthocyanins offer opportunities beyond conventional clothing, particularly in medical, chemical, and environmental applications. For example, pH-responsive textiles can serve as visual indicators in protective clothing, detecting the presence of corrosive chemicals and providing an immediate, visible warning in laboratory or industrial settings.

Scaling this technology for commercial viability presents additional challenges. Achieving consistent quality, colour fastness, and production efficiency requires technological innovation, while improvements in global standards for textile workers and manufacturing safety require broader systemic solutions. The adoption of natural dyes in localised communities can reduce dangerous chemical exposure and environmental pollution, but tangible impact across the fashion industry requires holistic policy measures and international co-operation.

4 Conclusion

4.1 Summary of Findings

This study has demonstrated clear potential in incorporating natural dye compounds into creating wearable and functional smart wool textiles. The CIELAB values show clear shift in hue consistent with anthocyanins derived from other organic compounds such as fruits and plants, and the resulting wool fabric was able to display colour changing effects upon contact with pH buffer solutions across the acidic, neutral, and alkaline conditions.

However, to answer the research question 'How can the development of bio-based fabric dyeing techniques contribute to creating smart materials and solving systemic sustainability issues in fashion, such as circularity and waste reduction?', requires understanding that the systems that perpetuate these issues are complex and steadfast. Although this study was successful in exploring colorimetric properties of blackberry anthocyanins, there are currently no technological frameworks to support the large-scale replacement of synthetic dyeing with natural alternatives.

Natural dyeing represents only one dimension of broader industry change. Although it offers potential to reduce chemical pollution and support circularity, a multifaceted approach encompassing consumer perception, product durability, and market desirability, is essential to achieving long-term systems transformation in fashion sustainability.

4.2 Future Research Directions

Building upon this research, further experimentation could include wash testing for both the naturally dyed and synthetically dyed wool fabrics to assess durability and colour retention over time. Recording and analysing the colour shift after multiple wash cycles would provide quantitative data on colourfastness. Although it is widely established that natural dyes generally exhibit lower durability, a comparative analysis would help to measure and visualise the extent of difference between natural and synthetic dye performance.

Another valuable area for further investigation would be to examine real-world case studies of textile manufacturers transitioning away from harmful synthetic dyes. Documenting the resulting improvements in worker health, environmental quality, and local ecosystems could provide evidence of the broader social and ecological benefits of sustainable dyeing practices. Such findings could inform predictive models of community impact, demonstrating how developing products using organic compounds can generate positive outcomes for vulnerable populations in manufacturing regions.

A third potential direction would involve consumer perception and market research. Marketing campaigns could be designed to highlight the shifting hues of natural dyes as unique, artisanal, and environmentally conscious, reframing colour inconsistency as an indicator of craftsmanship rather than a flaw. Measuring consumer willingness to pay for naturally dyed products after engaging with such campaigns could offer insights into market viability and demand. For natural dyeing methods to replace even a portion of synthetic dye production, there must first be economic incentive and demonstrated consumer interest. Establishing market demand would encourage companies to invest in and adopt these environmentally responsible alternatives at a larger scale.

4.3 References

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4.4 Appendices

Fig. 1. Crushed Blackberry Pulp

Fig. 2. Unfiltered Blackberry Pulp

Fig. 3. Ultrasonic Machine Extraction

Fig. 4. Strained Blackberry Dye

Figure 5. Anthocyanin Dye with buffer solutions added.

Fig 6. Dyed Wool Fabric

Fig 7. Wool fabrics with buffer solutions added.

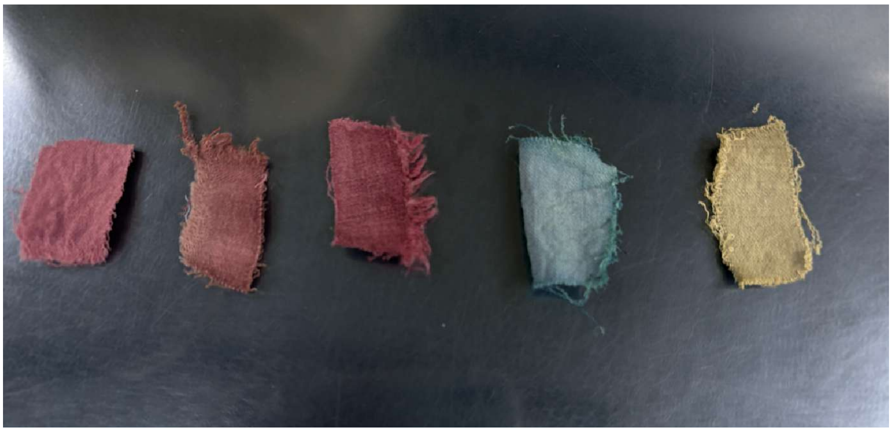

Fig. 8. Dried wool fabrics with buffer solutions. (Ascending order by pH)

Source of anthocyanins	pH ~2	pH ~3	pH ~4	pH ~5	pH ~6	pH ~7	pH ~8	pH ~9	pH ~10	pH ~11	pH ~12	Reference
Rose (*Rosa rugosa*)												Kang et al. (2020)
Iranian borage (*Echium amoenum*)												Mohammadalinejhad et al. (2020)
Jambolan (*Syzygium cumini*)												Merz et al. (2020)
Purple sweet potato (*Ipomoea batatas*)												Chen et al. (2020)
Manchurian cherry (*Prunus maackii*)												Sun et al. (2020)
Red cabbage (*Brassica oleracea* var. capitata f. rubra)												Liu et al. (2021)
Saffron petal (*Crocus sativus*)												Alizadeh-Sani et al. (2021)
Barberry (*Berberis vulgaris*)												Sani et al. (2021)
Mulberry (*Morus nigra*)												Yang et al. (2021)
Roselle (*Hibiscus sabdariffa* L.)												Liu et al. (2021)
Centaurea arvensis												Forghani et al. (2022)

Fig 9. Colour spectrum of other common organic anthocyanin sources.

	A	B	C	D	E	F	G	H	I
1	Wavelengt	400	410	420	430	440	450	460	470
2	original-2	8.02	8.96	9.73	10.11	10.2	10.16	10.13	10.1
3	original-3	8.31	8.94	9.63	10.15	10.18	10.16	10.17	10.06
4	original-4	8.17	9.02	9.83	9.94	10.24	10.18	10.12	10.07
5	original-5	8.74	9.98	10.84	10.99	11.19	11.22	11.21	11.16
6	original-6	8.84	9.69	10.67	11.24	11.16	11.13	11.13	11.15
7	original-8	9.72	10.95	12.19	12.86	13.11	13.15	13.22	13.33
8	synthetic-1	8.89	8.18	6.85	5.19	4.04	2.97	2.28	1.82
9	synthetic-2	8.77	8.13	7.06	5.26	4.06	3	2.24	1.8
10	synthetic-3	10.15	9.38	8.11	6.35	4.91	3.72	2.83	2.24
11	synthetic-4	10.08	9.44	8.19	6.23	4.89	3.66	2.83	2.25
12	synthetic-5	9.99	9.51	8.26	6.2	4.9	3.66	2.8	2.21
13	synthetic-6	8.75	8.5	7.02	5.29	4.13	3.06	2.33	1.83
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Fig. 10. CIELAB values of untreated anthocyanin dyed wool fabric vs synthetic dyed wool fabric.