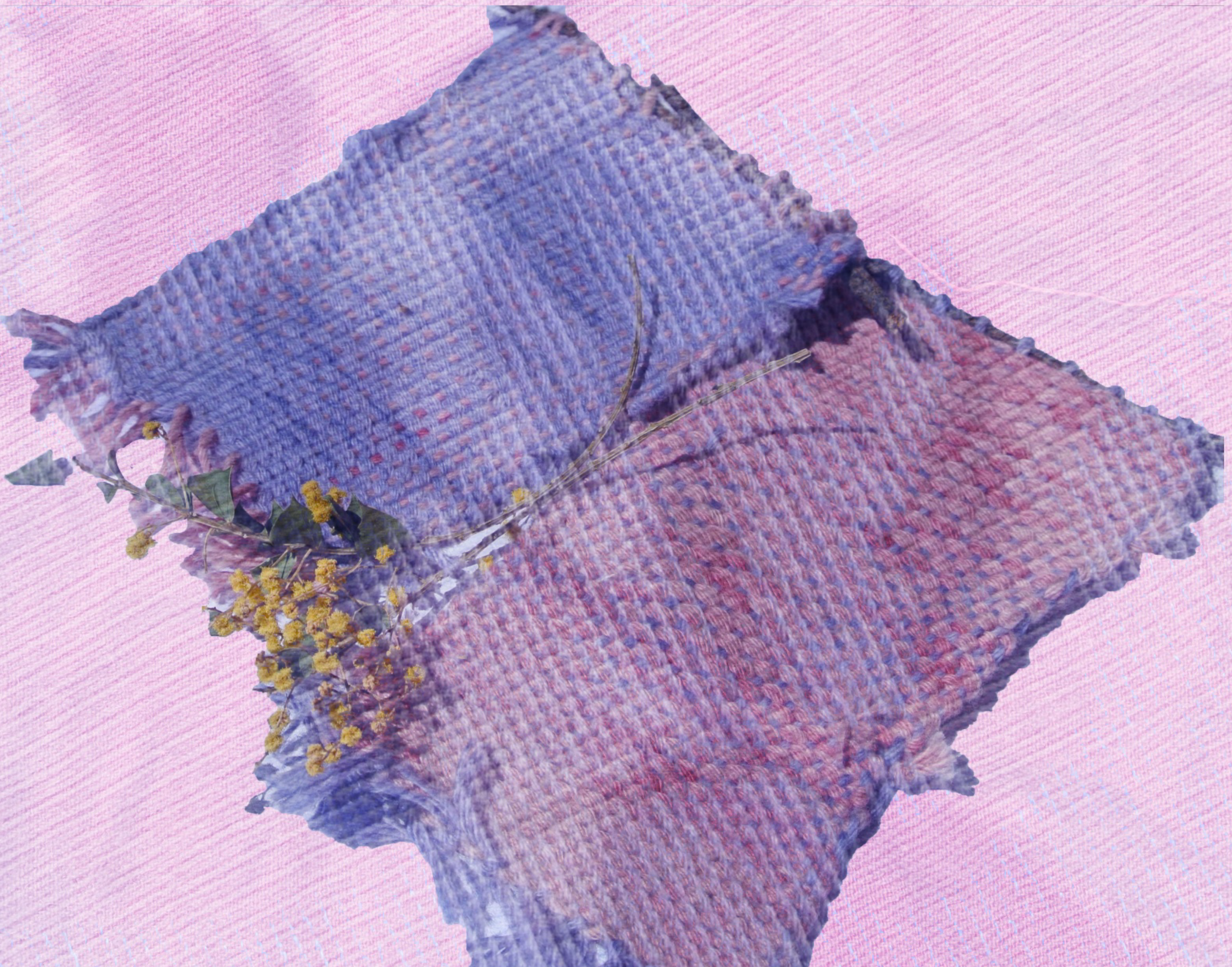
# NATURAL DYEING FOR SMART TEXTILES



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# *Sustainable Natural Dyeing for Developing Cotton-based Smart Textiles*

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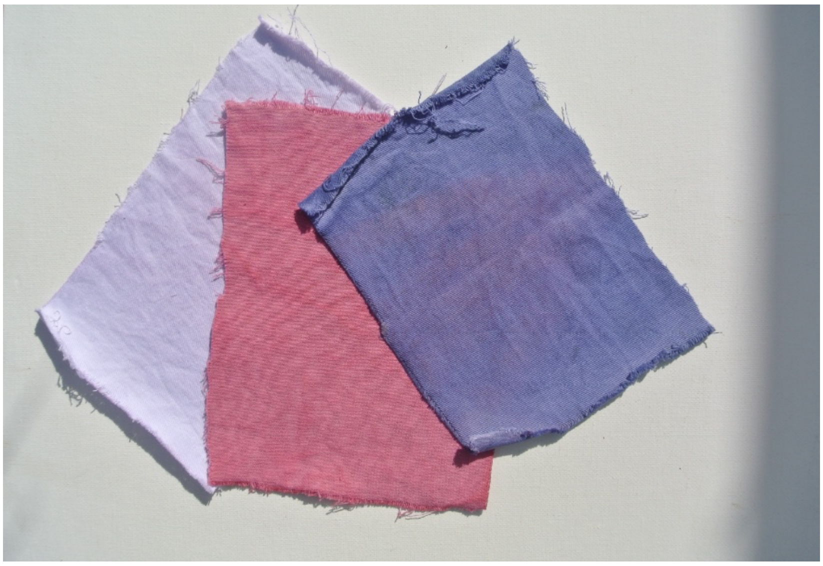

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## Acknowledgement of Country

The author would like to acknowledge the Woi wurrung and Boon wurrung people of the eastern Kulin Nation and thank them for their continuous care and protection of the land, water and sky. They pay their respects to elders and ancestors, past and present. They acknowledge that sovereignty was never ceded. It always was and always will be, Aboriginal land.

## Abstract

With the increasing demand for sustainability in fashion, natural materials play an important role in providing both high-functioning and environmentally friendly textiles. This study addresses the ongoing need for more sustainable colouration techniques by using natural anthocyanin dyes. Cotton fabrics were dyed with anthocyanin extracts derived from Butterfly Pea flower, Hibiscus Sabdariffa L. and Red cabbage. The cotton samples were successfully dyed, and the resulting textiles were subjected to varying pH conditions to test their reactive functionality. Colourimetric analysis confirmed that the dyed fabrics exhibited high colour uptake and significant measurable colour changes across the pH range, successfully validating their sensing capabilities. The development of a woven prototype showcased the practical, real-life application with both aesthetic and functional properties. The findings demonstrate that anthocyanin dyes provide multifunctional solutions for creating sustainable, cotton-based smart textiles, such as wearable body sensors for health monitoring. Note, pre-mordanting of cotton was not conducted in this study. It is recommended that further research is conducted with a focus on the feasibility and viability of integrating such pH-sensitive dyes into textiles on a much larger scale.

## 1. Introduction

Natural dyes have played an integral role in the fashion and textile industry for centuries, with particular significance seen in traditional textile practices. Nowadays, synthetic dyes are the most utilised textile colourant and have a relatively low cost with efficient outputs. However, their heavy use has raised toxin exposure risks and contributed to environmental harm through chemical waste and water pollution. Understanding natural colourants is essential for developing sustainable dyeing techniques within the textile industry. By identifying the characteristics and properties of natural dyes, there is an opportunity to explore environmentally responsible solutions that can be effectively implemented in fashion and textile production. Smart textiles offer new possibilities for how textiles can function and interact with their external environment. Through continuous innovation, they are poised to revolutionise the fashion industry by introducing new capabilities and applications that go beyond traditional uses.

Many different types of plants and vegetables produce red, purple, blue, and black colours. These colours are formed from a water-soluble pigment called anthocyanins, which are part of the plant chemicals called Flavonoids.  Pelargonidin, cyanidin, peonidin, delphinidin, petunidin and malvidin are the most common anthocyanins in the plant kingdom (Vidana Gamage et al, 2021). Many studies have found that anthocyanins also have health benefits due to their antioxidant properties. Interestingly, it has been found that anthocyanin compounds contain a smart component where they can change colour in response to different pH levels. This change is dependent on the type of anthocyanin present, with each producing a different colour palette. Anthocyanins are known to be unstable and extremely sensitive to external factors such as temperature and light, and according to Castañeda-Ovando (2009), their extensive use in textiles has been limited because of their instability and low extraction percentages.

One example of a plant containing anthocyanins is the Butterfly Pea Flower or *Clitoria ternatea.* It is a Southeast Asian (although commonly found in Australia and other tropical areas) blue flower that produces a natural blue-purple dye colour. The Butterfly Pea Flower has delphinidin as the main chemical compound and is classified as a polyacrylate anthocyanin (Handayani et al, 2024). The chemical structure of Butterfly Pea Flower can be found in **Figure 1.** Though blue is a common colour found in nature, the blue from Butterfly Pea flower is rare among Flavonoids and produces a colour changing palette ranging from pink/purple to green/yellow as pH increases. Another flower containing anthocyanins and able to demonstrate colour changing properties is the Hibiscus Sabdariffa L. Hibiscus consists of a cyanidin compound (see **Figure 2**) and exhibits a much simpler structure than that of Butterfly Pea flower. This specific Hibiscus produces a pink/red dye colour with colour change ranging from pink to brown when subject to different pH conditions. Both these flowers produce naturally attractive colours while also having the ability to change colour, showcasing both aesthetic and functional properties.  Although not used in the final outcome in this report, extraction and dyeing of anthocyanins from Red cabbage (Brassica oleracea var. capitata f. rubra) was also tested.

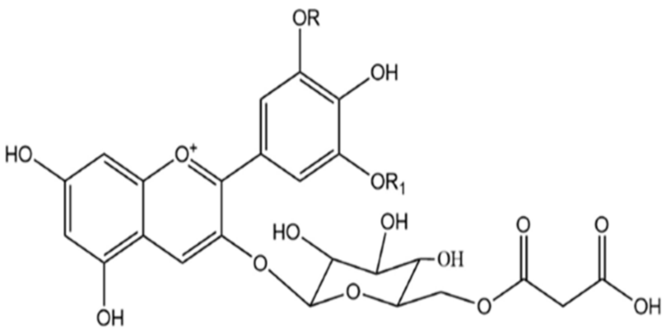


**Figure 1**. Butterfly Pea Flower structure as DelpHinidin 3-malonyl glucoside. From Jeyaraj et al, 2020.


**Figure 2.** Hibiscus Sabdariffa L. structure as Cyanidin-3-glucoside. From Vankar and Shukla, 2010.

The extraction of anthocyanins from these plant materials primarily involves methods that optimise the concentration of the dye. Distilled water is the primary solvent used for anthocyanin extraction due to its cost-effectiveness and non-toxic nature. However, the choice of solvent can significantly impact the concentration yield, and effective extraction methods should maximise anthocyanin recovery and minimise impurities in the final extract (Jin Kang et al, 2013). Methanol and ethanol are other solvents frequently used when extracting anthocyanins, and previous research found that methanol extraction was 20% more effective than ethanol and 73% more effective than water when used for anthocyanin recovery from grape pomace (Metivier et al, 1980). Other conditions to optimise the extraction of anthocyanins from the source include temperature and time. In this study, Ultrasound Assisted Extraction (UAE) was performed due to previous evidence supporting it increases dye extraction yields due to its ability to maintain a consistent temperature.

## 2. Aim and objectives

To help promote a circular economy for Australian cotton, this report proposes to use natural dyeing as a sustainable colouration alternative to developing smart textiles with chemical sensing capacity triggered by the pH colour-changing mechanism. The core objective is to investigate these mechanisms on cotton fabrics and their dyeability, which will be beneficial towards the functional textile industry. The sensing capacity of the samples will be tested and fine-tuned for further application. The colour-changing performance will be assessed and analysed using chemicals with different pH levels, i.e. lemon and vinegar. Various experiments have studied the diverse types of anthocyanins and their unique colour changes; however, few have explored this colour-changing mechanism on cotton textiles with both smart and aesthetic effects.

## 3. Materials and Methods

### 3.1 Plant material

Butterfly Pea flower and Hibiscus Sabdariffa L. were obtained as dried flowers and sourced from a local store in Melbourne, Australia. Fresh Red Cabbage was sourced from a local supermarket in Melbourne, Australia. Note: No purification methods were conducted on the plant materials, and pesticides may/may not have been present before extraction of the anthocyanins.

### 3.2 Chemicals

pH tested chemicals were: Acetic Acid ($CH_3COOH$), Hydrochloric Acid (HCl), Acidic buffers (pH 3-5), Alkaline buffers (pH 7-9), Chlorine bleach (pH 11.8), Industrial detergent (pH 8), home laundry detergent (pH 9), Vinegar (pH 2.6) and White Wine Vinegar (pH 3.05).
Distilled water (DW).

### 3.3 Apparatus

1. Ultrasound Assisted Extraction (GT Sonic, VGT-17300QTD): For anthocyanin extraction from Butterfly Pea flower, Hibiscus Sabdariffa L. and Red cabbage.
2. ColorFlex EZ Spectrophotometer: For analysing the colour metrics of dyed cotton samples.
3. Mortar and pestle: For grinding the dried Butterfly Pea flower and Hibiscus Sabdariffa L. and the fresh red cabbage.
4. 600ml Glass beakers: Immersing the grounded Butterfly Pea flower, Hibiscus Sabdariffa L. and the Red cabbage in M:L of distilled water.
5. IEC Hotplate: Heating the dye extract to dye the cotton fabrics.
6. Stainless steel beakers: Used for immersing the cotton fabrics into the dye extract.

### 3.4 Anthocyanin extraction

A comprehensive study by Ekici et al (2013) determined that anthocyanins degraded more rapidly at higher temperatures, which is attributed to differences in the anthocyanin compounds present. Considering this, all extraction processes followed a temperature fluctuating between 40°C and 50°C. After conducting an initial trial on Butterfly Pea flower, it was decided that no additional solvents needed to be used for extraction due to safety measures and the high concentration yield already produced without a solvent.

The first anthocyanin extraction was carried out using the dried Butterfly Pea flowers, which were first ground in the mortar and pestle. 17.3g of dried grounded Butterfly Pea flowers were mixed with approximately 173ml of distilled water (material to liquid ratio was 1g:10ml) and the UAE was set to 40°C for 45 minutes with occasional stirring. According to Zou et al (2011), Ultrasound extraction allows for greater penetration of solvent (water) into the tissue (flowers) via acoustic vibrations, optimising the dye yield. Hence, the UAE was used as the main extraction method for all further experiments.

This similar process was followed for the Red Cabbage anthocyanin extraction. 52g of fresh Red Cabbage was ground, however, a wetter solution appeared, and the M:L ratio was adjusted to 1g:5ml to account for the extra moisture present. 52g of ground red cabbage was combined with 260ml of distilled water. This solution was then added to the UAE and left at 40°C for 45 minutes with occasional stirring.

For the last trial, 10g of crushed dried Hibiscus Sabdariffa L. was combined with 200ml of distilled water in a glass beaker (material to liquid ratio 1g:10ml). This mixture was then added to the UAE and left at 40°C for 45 minutes with occasional stirring. Once extractions were complete, the extracted liquid was filtered through a fabric cloth using a glass filter and beaker, and the excess pulp was disposed of. The pure concentrated anthocyanin liquid extractions were collected for dyeing and further testing.

**Figure 3**. Crushed Butterfly Pea flowers.

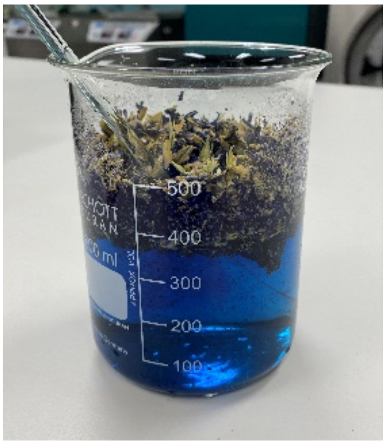


**Figure 4**. Butterfly Pea flowers dissolving in distilled water.

**Figure 5.** Butterfly Pea flowers under UAE extraction.


**Figure 6.** Liquid extract from Butterfly Pea flowers.

### 3.5 Fabric dyeing

Twill cotton fabric (approx. 20cm x 20cm with varying weights) was used as the base sample fabric across the three experiments. The cotton fabric was dyed using the anthocyanin extracts obtained from the Butterfly Pea flower, Hibiscus Sabdariffa L. and Red cabbage. They were soaked in distilled water for approximately 15 minutes prior to the dye bath. Due to time restraints and the strong dye yield already obtained, no mordants were used on the cotton fabric before dyeing. Ono Hangai et al (2024) further explained that the optimal dyeing conditions for cotton fabrics using Butterfly Pea flower extract were a temperature of 50°C and a time of 60 minutes and advised that temperatures over 70°C would destabilise the anthocyanin molecule's ability to fasten to the fibres. Therefore, in this experiment, dye bath temperatures stayed lower than 70°C for no longer than 60 minutes.

For dyeing cotton with Butterfly Pea flower extract, the material to liquor ratio was 1g: 20ml. Cotton fabric weighing 8.65g was added to a dye bath containing 200ml of extract (173ml was rounded to 200ml) at 60°C and placed on the hotplate for approximately 60 minutes. Dyeing with Hibiscus extract was carried out in the same conditions but using a material liquid ratio of 10g cotton to 200ml of extract. The Red Cabbage dye bath contained 178ml of Red Cabbage extract and cotton fabric weighing 8.90g (material to liquid ratio 1g:20ml) and was placed on the hotplate for 30 minutes at 50°C. The dyed cotton samples were rinsed with cold water and left to dry at room temperature before pH tests were undertaken. The Red Cabbage sample was not rinsed with water due to poor colour fastening and obvious pale colour, resulting in an inability to conduct further experiments if it were washed.

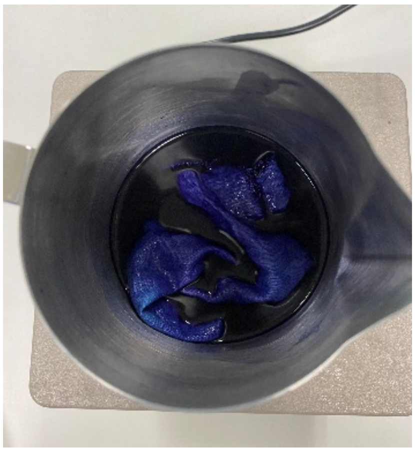

**Figure 7.** Dye bath of Butterfly Pea flower extract.

**Figure 8.** Dye bath of Hibiscus extract.

**Figure 9.** Dye bath of Red Cabbage extract.

### 3.6 Yarn dyeing

An additional experiment was conducted to investigate anthocyanin dye on cotton yarn instead of fabric, with the intent to weave with the dyed yarn for developing a smart textile prototype. 100% 8ply cotton yarn was used for this experiment, and the chosen anthocyanin extracts were Butterfly Pea flower and Hibiscus Sabdariffa L., as they had proven to yield the highest colour strength with the potential to deliver the most noticeable colour-change. Colourfastness of the yarns will largely depend on the method used for yarn dyeing.

A new batch of liquid extracts from Butterfly Pea flower and Hibiscus was developed. For extraction of both plants, M:L ratio was 12.5g of dried flower to 250ml of distilled water. They were then left in the UAE at 40°C for 45 minutes with occasional stirring. For dyeing, the yarn was pre-soaked overnight in distilled water to remove impurities. 25g of yarn was weighed (wet weight) in two separate batches and wound into a hank for dyeing (see **figure 11**). The yarns were then put into a dye bath containing 250ml of Butterfly Pea flower and Hibiscus extracts and placed on the hotplate for approximately 60 minutes at 60°C.

**Figure 10.** Butterfly Pea flower and Hibiscus under UAE extraction.

**Figure 11**. Cotton yarn in a hank pre-dyeing.

**Figure 12.** Hibiscus dyed cotton yarn**.**

**Figure 13.** Butterfly Pea flower dyed cotton yarn.

**Figure 14.** Butterfly pea flower and Hibiscus dyed yarns once dried.

## 4. Results and findings

### 4.1 pH test results of anthocyanin liquid extracts

The first round of experiments tested the change in colour of anthocyanin liquid extracted from the Butterfly Pea flower, Hibiscus Sabdariffa L. and Red cabbage when subjected to chemicals with different pH levels. Butterfly Pea flower extract (**figure 15**) shows a change in colour from purple to green as pH increases. Pink and purple indicate pH values 1&3, blue colours signal neutral pH (5&9), while greens depict alkaline (pH 9&11). **Figure 16** illustrates the colours that Red Cabbage gives depending on the pH value added. Like Butterfly Pea flower, the base colour for Red Cabbage is purple; however, as pH increases from acidic to alkaline, colour-change is evident, where red/pink indicates acid mediums (pH values 1&3), purple and blue is neutral (pH values 5&9) and green/dark green suggests alkaline mediums (pH values 9&11). Hibiscus extract demonstrated little colour-change as the pH value increased, with visible colour change only noticeable at pH 9 (see **figure 17)**.

**Figure 15**. Butterfly pea flower extract colour changes after varying pH values were added.

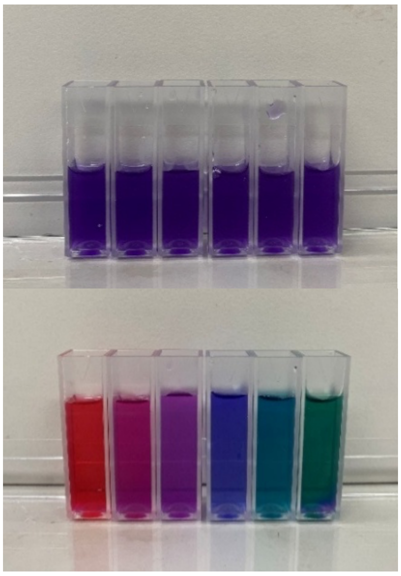

**Figure 16.** Red Cabbage extract colour changes before and after pH values added.

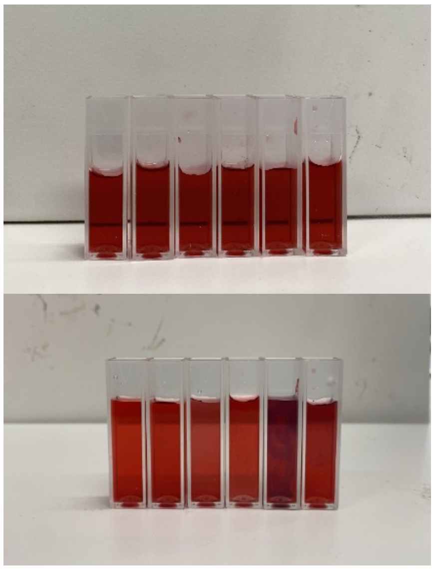

**Figure 17.** Hibiscus extract colour changes before and after pH values added.

### 4.2 pH test results of anthocyanin on dyed cotton fabric

These experiments evaluated the colour-change capabilities of anthocyanins when applied to cotton fabrics by testing samples exposed to varying pH levels (pH 1 to 11). All three experiments used chemicals which can be found in the home environment. Dyed cotton with the Butterfly Pea flower extract was the first sample tested for colour-change capacity. Six small (approx. 1cmX1cm) strips of the dyed fabric were cut up and placed into containers. From initial inspection with the naked eye, it's visible in **Figure 18** that the purple/blue colour of the controlled variable changed as pH rose from acetic to alkaline. The presence of the delphinidin anthocyanin in Butterfly Pea flower is what contributes to this unique colour change. When the pH value of 1 (Acetic Acid) was applied to the dyed sample, a fast change from blue/purple to orange/red occurred, with fast absorption rate. Neutral pH value 8 presented a deep blue colour, while the most alkaline pH value of 11 (Chlorine bleach) changed the control to green.

A bright and noticeable colour change was observed for Red Cabbage dyed cotton (**figure 19**), with colours changing from pink at acidic solutions (pH 1 & 3.95) to green and blue at Alkaline solutions (pH 8-11). The colour change from different pH values of Hibiscus (**figure 20**) was far more evident on cotton fabric than as a liquid extract. Visible changes could be seen as the pH values increased, with the original pink colour changing from pink to purple (at pH 8) and then to green/brown at alkaline values (pH 9 &11).

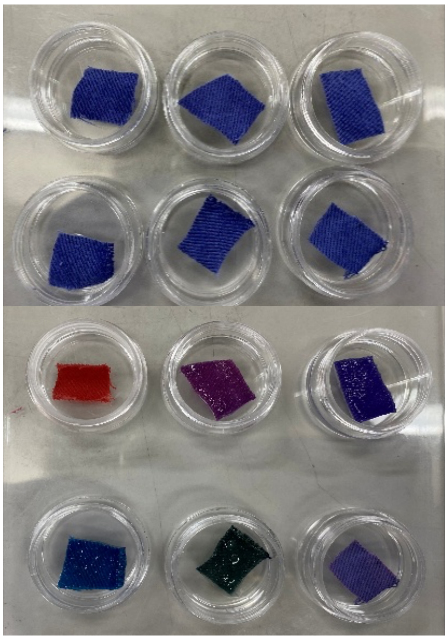

**Figure 18**. Colour-change capacity of Butterfly Pea flower dye from varying pH values on cotton fabric.


**Figure 19.** Colour-change capacity of Red Cabbage dye from varying pH values on cotton fabric.

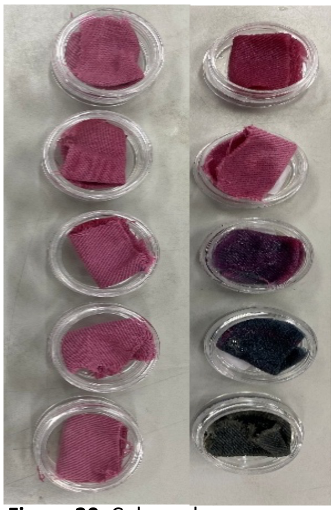

**Figure 20**. Colour-change capacity of Hibiscus dye from varying pH values on cotton fabric.

### 4.3 Colourmertic data

A Colorflex EZ Spectrophotometer was used to obtain precise colour identification measurements using CIELAB values (L*, a*, b*, C*) of the dyed samples before pH was added (**Table 1**) and after different pH levels were added (**Tables 2,3 & 4**). The colour difference value ($\Delta E$) of the pH tested fabric samples was calculated using the formula below, and individual results are presented in **Appendix 1**.

$$\Delta \boldsymbol{E} = \sqrt{(\boldsymbol{L} *_1 - \boldsymbol{L} *_2)^2 + (\boldsymbol{a} *_1 - \boldsymbol{a} *_2)^2 + (\boldsymbol{b} *_1 - \boldsymbol{b} *_2)^2}$$

This data can be interpreted as L* referring to lightness, a* the amount of red-green present and b* indicates the yellow-blue spectrum. As seen in **Table 1**, Red cabbage had the highest L* value, Hibiscus has the highest a* reading and Butterfly Pea flower has the greatest b* value. These measurements help to validate the visual appearance of the dyed samples obtained, as seen in **Figure 21.**

**Table 1:** Colourmetric readings of dyed cotton with averaged values and digital colour match.

| Extract type | Reading No | L* | a* | b* | CIELAB Colour ( average reading value) using https://www.nixsensor.com/free-color-converter/ | | |
|---|---|---|---|---|---|---|---|
| | | | | | L* | a* | b* |
| Hibiscus | 1 | 54.2 | 29.44 | -3.1 | 53.77 | 29.46 | -3.04 |
| | 2 | 53.38 | 29.63 | -2.94 | | | |
| | 3 | 53.84 | 29.28 | -2.95 | | | |
| | 4 | 53.82 | 29.58 | -3.19 | | | |
| | 5 | 53.6 | 29.37 | -3.02 | | | |
| Butterfly pea flower | 1 | 42.93 | 0.75 | -21.38 | 44.46 | 0.82 | -22.77 |
| | 2 | 44.93 | 0.79 | -22.95 | | | |
| | 3 | 45.69 | 1.04 | -23.97 | | | |
| | 4 | 45.11 | 1.11 | -23.51 | | | |
| | 5 | 43.64 | 0.4 | -22.05 | | | |
| Red cabbage | 1 | 81.7 | 5.32 | -16.21 | 80.93 | 5.42 | -16.24 |
| | 2 | 81.42 | 5.22 | -15.97 | | | |
| | 3 | 81.5 | 5.44 | -16.21 | | | |
| | 4 | 80.87 | 5.47 | -16.22 | | | |
| | 5 | 79.16 | 5.66 | -16.57 | | | |

**Figure 21.** Close up photo of cotton fabric dyed with Hibiscus, Butterfly Pea flower and Red Cabbage.

**Table 2:** Colorimetric readings for Red Cabbage when suggested to varying pH levels, with averaged values and digital colour match.

| Sample pH | Reading No | L* | a* | b* | CIELAB Colour ( average reading value) using https://www.nixsensor.com/free-color-converter/ | | |
|---|---|---|---|---|---|---|---|
| | | | | | L* | a* | b* |
| pH 2.6 (pink) | 1 | 85.45 | 5.53 | -15.35 | 85.33 | 5.49 | -14.80 |
| | 2 | 85.63 | 5.32 | -15.21 | | | |
| | 3 | 86.24 | 5.61 | -14.61 | | | |
| | 4 | 85.91 | 5.61 | -14.47 | | | |
| | 5 | 85.33 | 5.4 | -14.35 | | | |
| pH 3.05 (Peach) | 1 | 82.49 | 6.28 | -4.86 | 82.72 | 6.12 | -4.92 |
| | 2 | 82.59 | 6.13 | -4.99 | | | |
| | 3 | 82.64 | 6.28 | -4.92 | | | |
| | 4 | 82.69 | 5.97 | -4.86 | | | |
| | 5 | 83.2 | 5.95 | -4.96 | | | |
| pH 8 (blue) | 1 | 81.12 | -3.35 | -7.59 | 81.43 | -3.10 | -7.49 |
| | 2 | 80.8 | -3.67 | -7.19 | | | |
| | 3 | 82.32 | -2.82 | -8.04 | | | |
| | 4 | 81.49 | -2.92 | -7.42 | | | |
| | 5 | 81.49 | -2.92 | -7.42 | | | |
| | 6 | 81.36 | -2.92 | -7.27 | | | |
| pH 9 (grey) | 1 | 87.31 | 2.29 | -4.85 | 87.04 | 2.35 | -4.85 |
| | 2 | 87.26 | 2.28 | -4.81 | | | |
| | 3 | 86.9 | 2.31 | -4.61 | | | |
| | 4 | 86.85 | 2.43 | -4.99 | | | |
| | 5 | 86.88 | 2.42 | -5 | | | |
| pH 11.82 (off whit) | 1 | 89.18 | 3.13 | -7.24 | 89.08 | 2.71 | -6.94 |
| | 2 | 89.06 | 2.62 | -6.61 | | | |
| | 3 | 89.05 | 2.64 | -6.67 | | | |
| | 4 | 89.06 | 2.58 | -7.09 | | | |
| | 5 | 89.04 | 2.58 | -7.09 | | | |

**Table 3:** Colorimetric readings for Hibiscus when suggested to varying pH levels, with averaged values and digital colour match.

| Sample pH | Reading No | L* | a* | b* | CIELAB Colour ( average reading value) using https://www.nixsensor.com/free-color-converter/ | | |
|---|---|---|---|---|---|---|---|
| | | | | | L* | a* | b* |
| pH 2.6 (pink) | 1 | 61.92 | 21.03 | -3.9 | 62.05 | 20.84 | -3.94 |
| | 2 | 61.71 | 21.27 | -3.93 | | | |
| | 3 | 61.26 | 21.48 | -3.92 | | | |
| | 4 | 62.61 | 20.14 | -3.92 | | | |
| | 5 | 62.77 | 20.26 | -4.01 | | | |
| pH 3.05 (dark pink) | 1 | 54.78 | 28.02 | -3.35 | 54.66 | 27.47 | -3.45 |
| | 2 | 54.69 | 28.19 | -3.36 | | | |
| | 3 | 54.66 | 28.31 | -3.36 | | | |
| | 4 | 53.6 | 28.08 | -3.34 | | | |
| | 5 | 55.57 | 24.77 | -3.84 | | | |
| pH 8 (purple) | 1 | 62.44 | 12.97 | -7.22 | 62.63 | 12.83 | -7.23 |
| | 2 | 62.83 | 12.54 | -7.3 | | | |
| | 3 | 62.63 | 12.91 | -7.23 | | | |
| | 4 | 62.68 | 12.88 | -7.21 | | | |
| | 5 | 62.57 | 12.98 | -7.18 | | | |
| | | | | | | | |
| pH 9 (brown) | 1 | 59.01 | 6.58 | 7.41 | 59.51 | 6.93 | 7.76 |
| | 2 | 59.42 | 6.62 | 7.57 | | | |
| | 3 | 59.32 | 6.57 | 7.79 | | | |
| | 4 | 60.56 | 7.4 | 7.83 | | | |
| | 5 | 59.22 | 7.49 | 8.21 | | | |
| pH 11.82 (off whit) | 1 | 70.89 | 6.13 | 7.44 | 71.58 | 5.97 | 6.85 |
| | 2 | 71.16 | 6.09 | 7.4 | | | |
| | 3 | 70.79 | 6.14 | 7.39 | | | |
| | 4 | 70.82 | 6.04 | 7.31 | | | |
| | 5 | 74.25 | 5.43 | 4.72 | | | |

**Table 4:** Colorimetric readings for Red Cabbage when suggested to varying pH levels, with averaged values and digital colour match.

| Sample pH | Reading No | L* | a* | b* | CIELAB Colour ( average reading value) using https://www.nixsensor.com/free-color-converter/ | | |
|---|---|---|---|---|---|---|---|
| | | | | | L* | a* | b* |
| pH 2.6 (pink) | 1 | 51.84 | 2.32 | -20.4 | 52.73 | 2.59 | -20.14 |
| | 2 | 51.82 | 2.31 | -20.41 | | | |
| | 3 | 55.14 | 3.36 | -19.95 | | | |
| | 4 | 52.13 | 2.51 | -19.99 | | | |
| | 5 | 52.1 | 2.46 | -19.95 | | | |
| pH 3.05 (Purple) | 1 | 55.14 | 3.2 | -19.81 | 54.53 | 3.22 | -20.02 |
| | 2 | 55.14 | 3.15 | -19.85 | | | |
| | 3 | 54.02 | 3.07 | -20.47 | | | |
| | 4 | 53.99 | 3.04 | -20.5 | | | |
| | 5 | 54.36 | 3.64 | -19.45 | | | |
| pH 8 (blue) | 1 | 53.73 | -9.14 | -17.33 | 53.50 | -9.23 | -17.01 |
| | 2 | 53.51 | -9.22 | -16.98 | | | |
| | 3 | 53.49 | -9.2 | -16.96 | | | |
| | 4 | 53.47 | -9.24 | -16.92 | | | |
| | 5 | 53.31 | -9.36 | -16.85 | | | |
| | 6 | | | | | | |
| pH 9 (grey) | 1 | 32.93 | -6.34 | -11.84 | 35.45 | -7.10 | -11.23 |
| | 2 | 32.85 | -6.29 | -11.92 | | | |
| | 3 | 37.15 | -7.64 | -10.79 | | | |
| | 4 | 37.14 | -7.57 | -10.83 | | | |
| | 5 | 37.17 | -7.67 | -10.77 | | | |
| pH 11.82 (Green) | 1 | 37.4 | -5.03 | -1.67 | 37.42 | -5.03 | -1.74 |
| | 2 | 37.41 | -4.95 | -1.76 | | | |
| | 3 | 37.46 | -5.04 | -1.79 | | | |
| | 4 | 37.42 | -5.07 | -1.69 | | | |
| | 5 | 37.4 | -5.04 | -1.78 | | | |

## 5. Discussion

***Effect of pH on anthocyanin colour of liquid extracts***

Anthocyanin liquid extract from Butterfly Pea flower and Hibiscus proved to be more deeply concentrated in colour than the Red Cabbage extraction. However, the colour-change strength of Red cabbage and Butterfly Pea flower extracts were visibly higher than that of Hibiscus as pH increased. This may be attributable to the use of dried flowers rather than fresh plant material, which alters the concentration ratios for the extraction process. Additionally, Hibiscus contains the same type of anthocyanin (Cyanidin) as Red cabbage; however, it exhibits a distinctly different colour, appearing pink rather than purple. This is due to the structural differences giving rise to unique colour variations per plant. Research suggests that Red cabbage is extremely sensitive to pH colour-change due to the existence of acyl groups, which prevent the red flavylium colour from breaking down into a colourless carbinol base, allowing the formation of blue quinoidal bases (McDougall et al, 2017).

***Effect of pH on anthocyanin colour on fabric***

The dyeing process applied to the cotton fabrics yielded notably different outcomes in each of the three tests conducted (**see figure 21**). Dyeing with Butterfly Pea flower extract displayed a deep blue-purple colour, indicating the cotton fabric has high dye uptake to this specific anthocyanin. Similarly, the Hibiscus extract generated a dark hot pink colour. These strong colour strengths may be caused by the higher concentration achieved through the extraction process. Considering no pre-mordanting was undertaken, dye-ready cotton is an optimal choice to use for anthocyanin dyeing when mordanting is not available. Conversely, dye results from the Red cabbage produced a very light/pale colour with low dyeability. This is an unexpected result considering that the conditions were the same across all tests. The most probable explanation is the presence of extra moisture from the fresh cabbage during the extraction method. As data from Haque et al (2022) demonstrates, using low M:L ratios mean anthocyanin particles are not distributed enough, causing low dye-uptake and uneven dyeing. It is recommended to use dried plant material when extracting anthocyanins so that the concentration of anthocyanin is higher compared to water, and extraction is optimised. Similar results can be noticed for the dyed yarns; however, generally lighter colours appeared on the yarns compared to the woven fabrics (refer to **figure 14**).

***Colourimetric data analysis***

It can be understood from the data in **Table 1** that cotton dyed with Red Cabbage produced the lightest colour (L*=80.93), Hibiscus was the most red/green (a*=29.46) and Butterfly Pea flower contained the most yellow/blue (b*= -22.77). Data results presented in **Tables 2, 3 & 4** show the Colourimetric data collected from the dyed fabrics after their exposure to different pH levels. This data helped to verify the changes in colour and confirmed that the pH environment significantly impacts the visual appearance of the dyed samples.

The colour difference values ($\Delta E$) for all three tests also supports this. It was revealed that there are significant colour differences across all samples, which generally increase as pH increases. The biggest colour differences were seen at pH 11.82 for Hibiscus ($\Delta E = 31.1$), pH 9 ($\Delta E = 13.28$) for Red cabbage and pH 11.82 ($\Delta E = 22.94$) for Butterfly Pea flower.

It was also observed that colour strength and hues were different on the dyed fabric samples compared to the liquid extracts. Differences are specifically evident with dyed Red cabbage, which showed a noticeably lighter colour gradient as pH increases, as opposed to the liquid extract. In contrast, Hibiscus liquid extract displayed little colour-change as pH value increased, but on cotton fabrics, the difference is significant, both visually and confirmed from ($\Delta E$) values. These findings highlight the sensitivity of anthocyanin dyed cotton fabrics to pH changes and promote their use as textile pH indicators.

Additionally, it was found that after several days the fabric dyed with the Red cabbage visibly had the greatest loss of colour, while the other two samples remained relatively stable. **Figure 23** exhibits the rapid colour deterioration of Red cabbage dye and highlights the impact UV has on pH-sensitive dyes. Due to the sensitivity and instability of anthocyanins, the lightfastness of Red cabbage on cotton fabric will be an ongoing challenge for industry adoption. Cristea and Vilarem (2005) stated that the lightfastness of naturally dyed textiles is related to the chemical structure and physical characteristics of the fibre itself. Therefore, the properties of cotton could have also influenced this fading. Other explanations may be due to low dye concentration and no pre-mordanting. Appropriate storage conditions and limited UV exposure are recommended to ensure pigment stability and limit degradation. It is important to note that because mordanting was not tested in this study, statements on the impact mordanting has upon dyeability of anthocyanins are limited. Additional analysis is needed to fully understand thin impact mordanting has on colour strength, fastness, and overall dyeing behaviour of anthocyanins in textile applications.

**Figure 23.** Results from Red Cabbage after 2-3 days with varying pH levels.

## 5.1 Application prototype

An opportunity to develop a prototype showcasing the unique ability of natural dyes to be used as textile pH sensors has been presented. The cotton yarns dyed with Butterfly Pea flower and Hibiscus extract were hand-woven together using a picture frame loom. Two separate weaves were made with opposite wefts and warp (e.g. pink over purple and purple over pink, pink referring to Hibiscus and Purple to Butterfly Pea flower). A live demonstration was conducted to illustrate this colour change capacity in real time. Participants were encouraged to use different pH chemicals to show an interesting display of colours on the weave, which has both aesthetic and smart properties.

The prototype aimed to explore the real-life application of colour-changing textiles and the smart mechanism present in anthocyanins. It is speculated that this prototype can be used as a wearable body sensor patch for monitoring health conditions like sweat pH level or infections, with the potential to indicate the health or illness of the wearer. Other biochemical processes affecting pH, such as acid rain or minerals in rainwater, could be monitored using a similar textile-based prototype. The outcome seeks to visualise and promote conversations around the integration of science and design for developing sustainable technologies.

**Figure 23.** Woven prototype using dyed Butterfly Pea flower and Hibiscus yarn.

**Figure 24.** Example of the various colour changes from Butterfly Pea flower and Hibiscus dyed yarn.

## 6. Conclusions and Recommendations

Finally, this research investigated the development of sustainable dyeing methods and their potential to contribute positively to the textile industry. Experiments explored UAE extraction and dyeing of anthocyanins from Butterfly Pea flower, Hibiscus Sabdariffa L. and Red cabbage, and tested the effect different pH levels had on colour-changing capacity. Colourimetric data validated significant colour differences in response to varying pH levels. Results showed that natural anthocyanin dyes can be successfully applied to cotton fabrics with good dyeability and share promising insight into the development of smart textiles. Additionally, a prototype was developed to showcase practical outcomes of the research, with potential application in the health, sport or other functional textile industries. Limitations of the data include access to non-toxic mordanting and safe solvent extraction practices, which could have improved this study. Key recommendations involve further analysis of the impact of mordanting, using dried plant material to improve dye concentration and techniques to increase lightfastness for scalability.

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# 8. Appendices

**Appendix 1:** Colour difference ($\Delta E$) results using averaged CIELAB values for each pH sample and dye type

**Hibiscus**

| Term | Reference value | Sample value (ph 2.6) | Sample value (ph 3.05) | Sample value (ph 8) | Sample value (ph 9) | Sample value (ph 11.82) |
|---|---|---|---|---|---|---|
| L* | **53.768** | 62.054 | 54.66 | 62.63 | 59.506 | 71.582 |
| a* | **29.46** | 20.836 | 27.474 | 12.825 | 6.932 | 5.966 |
| b* | **-3.04** | -3.936 | -3.45 | -7.228 | 7.762 | 6.852 |
| ΔE | | **11.99** | **2.22** | **19.31** | **25.63** | **31.1** |

**Red cabbage**

| Term | Reference value | Sample value (ph 2.6) | Sample value (ph 3.05) | Sample value (ph 8) | Sample value (ph 9) | Sample value (ph 11.82) |
|---|---|---|---|---|---|---|
| L* | **80.93** | 85.33 | 82.722 | 81.43 | 87.04 | 89.078 |
| a* | **5.422** | 5.494 | 6.122 | -3.1 | 2.346 | 2.71 |
| b* | **-16.236** | -14.798 | -4.918 | -7.48 | -4.852 | -6.94 |
| ΔE | | **4.63** | **11.48** | **12.23** | **13.28** | **12.66** |

**Butterfly Pea**

| Term | Reference value | Sample value (ph 2.6) | Sample value (ph 3.05) | Sample value (ph 8) | Sample value (ph 9) | Sample value (ph 11.82) |
|---|---|---|---|---|---|---|
| L* | **44.46** | 52.7325 | 54.53 | 53.502 | 35.448 | 37.418 |
| a* | **0.818** | 2.592 | 3.22 | -9.232 | -7.102 | -5.026 |
| b* | **-22.772** | -20.14 | -20.016 | -17.008 | -11.23 | -1.738 |
| ΔE | | **8.86** | **10.71** | **14.7** | **16.65** | **22.94** |