

# How They Dyed: A CheMISTRY

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## *Abstract*

In this study, four types of dyes were used to colour eleven types of fibre, and the effectiveness of each dye was examined based on dye uptake and colourfastness. The dyes used were Diamine Fountain Pen Ink (Majestic Purple), ClubHouse Neon Food Colouring (mix of blue, purple, and pink), Rit DyeMore (Royal Purple), and Tulip One-Step Tie Dye (Purple). These are inks, acid dyes, disperse and direct dyes, and reactive dyes, respectively. The fibres chosen for this study were wool, silk, jute, cotton, paper towel, bamboo, nylon, acrylic, polyester, polyurethane, and polyethylene. Eight experiments were performed for each type of dye, to evaluate the impact of temperature and chemical additives on dye uptake. Through this study, our experiments showed that the efficacy of dyeing could be accurately explained by current literature in our research. Our work also demonstrated the importance of chemical structure in dyeing and the potential of using textile colouration as a valuable teaching tool.

As a further demonstration, a multi-material hat was knitted then dyed to demonstrate the differences in chemical structure to create a “secret pattern” reveal.

## *Introduction to the Chemistry*

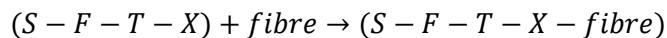
Often, people wear clothes that have been chemically coloured in some way. Whether various types of pigments are used or removed through bleaching, the textile industry – and the adjacent fashion industry – places huge emphasis on picking colours to maximize form utility and consequently, marketability. This is why trends like Pantone’s Colour of the Year exist; why colour theories like the use of opposite colours are helpful; and why people have favourite colours, generally speaking. We carry colours with us everywhere we go. But what are the chemical mechanisms that allow us to do so? We asked ourselves, “**how can we capitalize on our knowledge in chemistry, to ensure the longevity of colours in clothing?**”

There is already a great deal of literature, both in academic and hobbyist communities, regarding the effectiveness of various dyes on various materials used for clothing. Through our research, we found that acid dyes penetrate best into polyamide fibres, reactive dyes are most permanent on cellulosic fibres, and disperse dyes are the only effective post-production colouration method for hydrophobic synthetic fibres.

In order for the eye to perceive colour, a **chromophore** must be present in the molecule. The chromophore is the part of a molecule which causes something to be coloured. Thus, based on the chemical structure of a molecule, a different colour will be perceived. Colour is typically produced

in molecules with a significant number of conjugated pi bonds. Therefore, the addition of pi bonds helps to create colour, and their destruction heralds the removal of colour. In the process of dyeing, a chromophore is in some way attached to the subject that is coloured. This can occur through a number of different mechanisms.

One of the largest classes of dyes is reactive. These are colourants which form covalent bonds with the fibres. They are of the general formula  $S - F - T - X$ , which represents a solubilizing group (S), chromophore group (F), bridging group (T), and reactive group (X). These help to make the dye water-soluble (S), coloured (F), and permanent (X). Being water soluble allows the reactive dye to bond with hydrophilic fibres, such as cotton, wool, and silk. The bridging group binds together the chromophore and reactive groups. When added to the fibre, the addition chemical reaction occurs between the reactive group and the  $-OH$  of cellulosic fibres or  $-NH_2$  of polyamides as follows<sup>1</sup>:



Since there are very few limitations on chromogens which can be converted to reactive dyes, there is an extensive range of shades available for reactive dyes. The specific mechanism which covalent bonds are formed depends on the exact formulation of the product. Since they are water-soluble, they perform best on hydrophilic fibres. In general, they are anionic dyes, and thus prefer to bind to less electronegative fibres, such as wool (as opposed to a more electronegative fibre like cotton). However, the addition of electrolytes (e.g., NaCl) to the dyebath can promote attraction between more electronegative cellulosic fibres and the anionic dyes.

Acid dyes are the most popular choice for polyamide fibres such as wool, silk, and nylon. Generally, these fibres have a vast array of choices for colouration methods; since they are hydrophilic fibres, they can be dyed with many other water-soluble dyes. These include chemical structures such as acid dyes and reactive dyes. However, especially for natural protein fibres, acid dyes are used most often. These are anionic sulfonated chromophores; the structure of a simple acid dye is  $D(-SO_3^-Na^+)_n$ , where D represents a chromophore entity (e.g., azo, anthraquinone, phthalocyanine, etc.), and n is an integer generally ranging from 1 to 3. These fix to the substrate primarily through ionic bonds.

When colouring wool, dyeing is typically carried out at the boil for 1 hour in an acidic dyebath. The uptake of dye has a negative correlation to bath pH (i.e., a more acidic dyebath has greater uptake). Conversely, temperature and uptake have a positive correlation.

One of the primary mechanisms to drive the dyeing process is the Coulombic attraction between anionic sulfonated dyes and protonated amino sites. The wool polyamide contains lysine primary amino groups, histidine secondary/tertiary amino groups, arginine guanidino groups, and  $\alpha$ -terminal amino groups. Overall, there is a molar concentration of about 820  $\mu\text{mol/g}$ ; this is a significant total, which increases the rate of uptake and final saturation value.

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<sup>1</sup>Note that in this equation, “—” represents a single bond, *not* a minus sign.

The outside of the wool fibre is very hydrophobic. Consequently, it is more difficult for reactive dyes to penetrate them deeply; these dyes attempt to form covalent bonds. They are, however, able to react with the proteins in the endocuticle and endocuticular intercellular regions – thus, they demonstrate some modicum of effectiveness.

Some other fibres are entirely hydrophobic (repels water), and therefore require non-water-soluble dyes in order to be effectively coloured. These include polyester, cellulose acetate, nylon, acrylic, and polyolefin (e.g., polyethylene). While nylon is a polyamide – and thus has primary amino end-groups that give them some scintilla of substantivity to water-soluble acid dyes – most of these other fibres are not so fortunate. Consequently, most of the time, these synthetic fibres are dyed using mass-colouration before the solution is spun into filament. However, in the absence of the need for mass-production of a single shade, or if a home-dyeing alternative is desired, the only viable options are disperse dyes.

Disperse dyes are water insoluble dyes which are applied from fine aqueous dispersion, and which have substantivity for hydrophobic fibres. To colour the fabric, they form a solid solution with the fibres; their mode of fixation involves hydrophobic bonds, hydrogen bonds, and van der Waals forces. They have very low molecular weight in order to facilitate dye uptake. Most frequently, they comprise colourants derived from azo, anthraquinone, and diphenylamine materials. They are combined with a dispersing agent in order to increase stability; they reduce the particle size of the disperse dyes and increase their aqueous solubility. While some may have weak solubilising groups, they all have a marked lack of strong solubilising groups (e.g., sulfonic, carboxyl, etc.) and ionic charge. Nonetheless, it is possible that Van der Waals forces and dipole interactions help dye retention post-diffusion. When dyeing with disperse dyes, the process should be carried out at the boil. The ideal dyebath pH varies depending on the specific disperse dye; for example, amino azobenzene dyes see an increase in dye uptake as the pH increases, whereas azo dyes with hydroxyl groups do best in slightly acidic environments, and yet other dyes remain unimpacted by pH levels. The actual transfer mechanism for disperse dyes is not fully understood. Some sources speculate that heat allows the fibres to loosen and allow dyes to enter, and that upon cooling, they re-tighten around the colour. However, this is just conjecture.

When sold commercially for home-dyeing use, disperse and acid dyes are often mixed with direct dyes to create “all purpose” solutions. Direct dyes are also known as substantive dyes, since the mechanism by which they function capitalizes on substantivity between dye and cellulose fibre – their mode of fixation is through hydrogen bonding. Consequently, they tend to perform best on fabrics with high cellulose content – and thus, plant materials will take them most effectively. The ideal application environment tends to be at high heat with a basic dyebath. However, since these dyes do not form covalent or ionic bonds with the fabric, they have poor wash-fastness.

While this wealth of information is beneficial to anyone seeking to decide which dye to use, it is also potentially an overwhelming amount of technical specifications that do not necessarily translate well into practical applications. This study seeks to give a visual representation of the implications of this chemistry, and to draw conclusions regarding the effectiveness of household dye products.

# *Experimental Design*

This study was carried out over a series of experiments. 32 dyebaths were prepared, each boasting a different combination of properties. The variables were temperature (hot, cold), dye structure (ink, acid, disperse/direct, reactive), and additives (none, vinegar, salt, detergent). Each dyebath received 11 fabric swatches each, in wool, silk, jute, cotton, paper towel, bamboo, nylon, acrylic, polyester, polyurethane, and polyethylene.

Dye uptake was measured *qualitatively* using visual analysis of the colouration of the fibres. Furthermore, it appears that the dyed samples exhausted minimal amounts of the dyebaths as there was minimal impact on the colour intensity before and after the different experiments.

## *Materials*

### Fibres tested:

- 3-ply (S-plied) wool yarn, 9 wpi, 212 yds/100 g
- 4-ply (S-plied) acrylic yarn, 8 wpi, 188 yds/100 g
- 16-ply (8 by 2 S-cable plied) bamboo yarn, 12 WPI, 241 yds/100 g
- 100% jute burlap, loosely woven, plain weave, 3 warps per cm, 2.5 wefts per cm
- Cotton fabric, balanced plain weave, 12 wefts/warps per cm
- Polyester chiffon, balanced plain weave, 44 wefts/warps per cm
- Polyurethane faux leather, 0.5 mm
- Polyethylene fabric, 70 gsm
- Nylon organza ribbon, balanced plain weave, 36 wefts/warps per cm
- Silk curtain fabric, balanced plain weave, 18 wefts/warps per cm
- 2-ply paper towel, 365 gsm

In preparation for the experiment, fabric yardage (jute, cotton, polyester, polyurethane, polyethylene, nylon, silk, and paper towel) was cut into strips 1" by 6". Yarn lengths (wool, acrylic, bamboo) were cut to 24", then doubled back on themselves, secured at midpoint with an overhead knot, and folded at the knot.

### Dyes tested:

- Majestic Purple Diamine Fountain Pen Ink
- Royal Purple Rit DyeMore (C.I. Disperse Red 17, C.I. Disperse Violet 1, C.I. Disperse Blue 3, C.I. Direct Red 16, C.I. Direct Blue 71, C.I. Direct Black 22)
- Blue, Purple, and Pink ClubHouse Neon Food Colouring (C.I. Food Red 17, C.I. Acid Red 51, C.I. Acid Blue 9)
- Purple Tulip One-Step Tie Dye (C.I. Reactive Blue 4, C.I. Reactive Red 2)

### Additives tested:

- White vinegar, 5% acetic acid concentration (2.5 mL per dyebath)

- Laundry detergent (2.5 mL per dyebath)
- Table salt (2.5 mL per dyebath)

#### **Raw materials used for hand-knitted hat:**

- 3-ply (S-plied) wool yarn, 9 wpi, 212 yds/100 g; and 4-ply (S-plied) acrylic yarn, 9 wpi, 205 yds/100 g
- Golden Yellow, Pink, Violet, Royal Blue, and Teal Wilton Icing Colours (C.I. Food Red 17, C.I. Acid Yellow 23, C.I. Acid Blue 9, C.I. Acid Red 51, C.I. Food Yellow 3, C.I. Acid Blue 74); 3/8 tsp.
- 80 mL water
- White vinegar, 5% acetic acid concentration; 15 mL diluted in 1 L water

## ***Procedure***

### **Immersion-Dyeing Application to Swatches**

In order to mix the dyes with more consistency, a dye stock was prepared in advance of the experiment. 1 mL (20 drops) of Diamine Fountain Pen Ink was diluted into 80 mL water; 10 mL of this solution was added to each dyebath. 80 mL water was added to the Tulip One-Step Tie Dye, and the solution was agitated to dissolve the powder; 10 mL of this solution was added to each dyebath. 3.75 mL Rit DyeMore was added to each dyebath at full concentration. 10 mL of ClubHouse Food Colouring was diluted with 6 mL water; 2 mL of this solution was added to each dyebath.

The dyebaths were prepared inside glass mason jars with capacities of approximately 475 mL. 80 mL water, the relevant dye stock, and additive was added to the jar. (Note that one sample for each dye type and temperature was left without additive.) For dye applications carried out at the boil, this elevated temperature was achieved by placing the dyebath into a pot of boiling water. Once the desired temperature was attained, one swatch of each fibre was added into the dyebath. Dyeing was carried out in full immersion for 20 minutes, after which the fabrics were removed from the dyebath and rinsed in cold water until the water ran clear. The samples were then laid flat to dry.

### **Low-Water Immersion Dyeing Application to Hat**

The hat was presoaked in about 500 mL cold water. 1 L water was brought to a simmer in a large pot, at which point 15 mL white vinegar was added. The hat was then added to the dyebath, and colorant (i.e., diluted food dye) was applied using squirt bottles. After approximately 15 minutes, the fabric was flipped, and the same process was carried out on the reverse side. The water was drained and replaced with clean water; following this, the hat was left to set for 15 minutes. It was rinsed with cold water until the water ran clear, then with warm water and a gentle detergent.

## ***Results + Discussion***

We found that overall, the results were consistent with the literature. Some deviations were recorded; however, it is uncertain whether this was due to experimental flaws. For the colour cards

in this section, the shades were obtained by photographing the samples, then using the eyedropper tool in paint.NET to ascertain the HEX value. This is not a perfectly accurate system, as the lighting environment was not ideal during photography. It is difficult to deduce which point is the “true” colour of the fabric since there are a myriad of shadows and highlights present in a photograph of fabric or yarn. Where possible, colour cards are used to provide clearer demonstrations. In some cases, however, such as with the nylon organza ribbon, sample pictures are also included, since the fabrics are sheer and thus harder to place numerical values on. This will allow the reader to draw their own conclusions regarding the optics of the subjects in question.

Nonetheless, the following are some general observations.

### **Impact of Vinegar on Hue**

Due to resource constraints, we were unable to accurately measure either the pH of the dyebaths or the hue of the resultant samples. However, in general, there seems to be a correlation between acidity and uptake of red colour. This is similar to pH indicators such as red cabbage (which turns pink in acidic solution, and blue in alkaline solution), indigo (which turns yellow in acidic solution and blue in alkaline solution), and litmus paper (which turns red in acidic solution, and blue in alkaline solution). It should be noted that not all substances follow this same trend of acids creating warm tones and bases creating cool tones (e.g., hydrangeas grow blue in acidic soil, and pink in alkaline soil; phenolphthalein turns pink as pH increases; etc.).

To measure this quantitatively, the HSV (hue, saturation, value) values of the aforementioned HEX values were taken. Following this, the hue values were recorded.

|                 | COLD              |           | HOT     |           |     |
|-----------------|-------------------|-----------|---------|-----------|-----|
|                 | Vinegar           | Detergent | Vinegar | Detergent |     |
| ACID            | Polyacrylonitrile | 14        | 26      | 344       | 29  |
|                 | Bamboo            | 352       | 7       | 348       | 20  |
|                 | Cotton            | 358       | 5       | 355       | 15  |
|                 | Jute              | 8         | 26      | 7         | 27  |
|                 | Nylon             | 344       | 17      | 351       | 352 |
|                 | Paper Towel       | 348       | 355     | 350       | 26  |
|                 | Silk              | 344       | 12      | 296       | 3   |
|                 | Wool              | 4         | 18      | 358       | 357 |
| DISPERSE/DIRECT | Polyacrylonitrile | 16        | 19      | 287       | 276 |
|                 | Bamboo            | 333       | 325     | 289       | 298 |
|                 | Cotton            | 326       | 328     | 289       | 285 |
|                 | Jute              | 1         | 0       | 317       | 323 |
|                 | Nylon             | 345       | 322     | 282       | 288 |
|                 | Paper             | 330       | 306     | 265       | 257 |
|                 | Polyester         | 15        | 13      | 330       | 325 |
|                 | Polyurethane      | 9         | 8       | 325       | 298 |
|                 | Silk              | 356       | 352     | 320       | 312 |
|                 | Wool              | 11        | 352     | 307       | 293 |

Since colour hue is a cyclic scale which uses angular measurements, these values must be adjusted before comparison. The hue circle ranges from 0-360, and the red primary is defined as 0; hence, values must be compared based on their proximity to either 0 or 360. Therefore, if  $h_r < 180$ , then  $h_r = h_a$ , but if  $h_r > 180$ , then  $360 - h_r = h_a$  (where  $h_r$  represents the recorded hue, and  $h_a$  represents the adjusted hue). This measures the difference between the hue of the sample, and the hue of true primary red. The following is the table of adjusted values:

|                 |                   | COLD    |           | HOT     |           |
|-----------------|-------------------|---------|-----------|---------|-----------|
|                 |                   | Vinegar | Detergent | Vinegar | Detergent |
| ACID            | Polyacrylonitrile | 14      | 26        | 16      | 29        |
|                 | Bamboo            | 8       | 7         | 12      | 20        |
|                 | Cotton            | 2       | 5         | 5       | 15        |
|                 | Jute              | 8       | 26        | 7       | 27        |
|                 | Nylon             | 16      | 17        | 9       | 8         |
|                 | Paper             | 12      | 5         | 10      | 26        |
|                 | Silk              | 16      | 12        | 64      | 3         |
|                 | Wool              | 4       | 18        | 2       | 3         |
| DISPERSE/DIRECT | Polyacrylonitrile | 16      | 19        | 73      | 84        |
|                 | Bamboo            | 27      | 35        | 71      | 62        |
|                 | Cotton            | 34      | 32        | 71      | 75        |
|                 | Jute              | 1       | 0         | 43      | 37        |
|                 | Nylon             | 15      | 38        | 78      | 72        |
|                 | Paper             | 30      | 54        | 95      | 103       |
|                 | Polyester         | 15      | 13        | 30      | 35        |
|                 | Polyurethane      | 9       | 8         | 35      | 62        |
|                 | Silk              | 4       | 8         | 40      | 48        |
|                 | Wool              | 11      | 8         | 53      | 67        |

In cases where  $|h_{av} - h_{ad}| \leq 2$  (where  $h_{av}$  represents adjusted hue in vinegar, and  $h_{ad}$  represents adjusted hue in detergent), a retest was performed, using photos of the two samples in questions next to each other, *captured in the same photograph*. The following are annotated examples of such a retest:



Left: direct comparison of nylon organza ribbons dyed with acid dyes at room temperature; the dyebaths had vinegar and detergent added to them, respectively (left to right)

*Right: direct comparison of nylon organza ribbons dyed with acid dyes at the boil; the dyebaths had detergent and vinegar added to them, respectively (left to right)*

This improves the consistency of lighting conditions and allows for more direct comparison of values. Adjusting these values in the same manner as before yields the following table.

|      | COLD              |           | HOT     |           |     |
|------|-------------------|-----------|---------|-----------|-----|
|      | Vinegar           | Detergent | Vinegar | Detergent |     |
| ACID | Polyacrylonitrile | 14        | 26      | 16        | 29  |
|      | Bamboo            | 33        | 63      | 22        | 33  |
|      | Cotton            | 2         | 5       | 5         | 15  |
|      | Jute              | 8         | 26      | 7         | 27  |
|      | Nylon             | 27        | 9       | 6         | 19  |
|      | Paper             | 12        | 5       | 10        | 26  |
|      | Silk              | 16        | 12      | 64        | 3   |
|      | Wool              | 4         | 18      | 10        | 18  |
|      | Polyacrylonitrile | 16        | 19      | 73        | 84  |
|      | Bamboo            | 27        | 35      | 71        | 62  |
|      | Cotton            | 103       | 92      | 71        | 75  |
|      | Jute              | 7         | 60      | 43        | 37  |
|      | Nylon             | 15        | 38      | 78        | 72  |
|      | Paper             | 30        | 54      | 95        | 103 |
|      | Polyester         | 19        | 22      | 30        | 35  |
|      | Polyurethane      | 51        | 120     | 35        | 62  |
|      | Silk              | 4         | 8       | 40        | 48  |
|      | Wool              | 11        | 8       | 53        | 67  |

The lower hue value represents one that is closer to primary red. In 75% of cases, the samples dyed in vinegar had lower hue values than their detergent-dyed counterparts. Furthermore, if all the hue values are summed, the vinegar-dyed samples have a total hue value 307 less than the detergent-dyed ones. It is thus clear that the vinegar-dyed samples have a greater tendency towards red uptake.

It should be noted that it is possible that this trend is related to the overall uptake of colour; in the following two examples, the samples dyed with vinegar are both more red and more saturated in general. This is not necessarily the case; more experimentation must be done to ascertain causation.



Nylon organza ribbon dyed in hot acid dyebath with vinegar (left) and detergent (right)



Acrylic yarn dyed in a hot disperse/direct dyebath with vinegar (left) and detergent (right)

### Acid Dye Hue

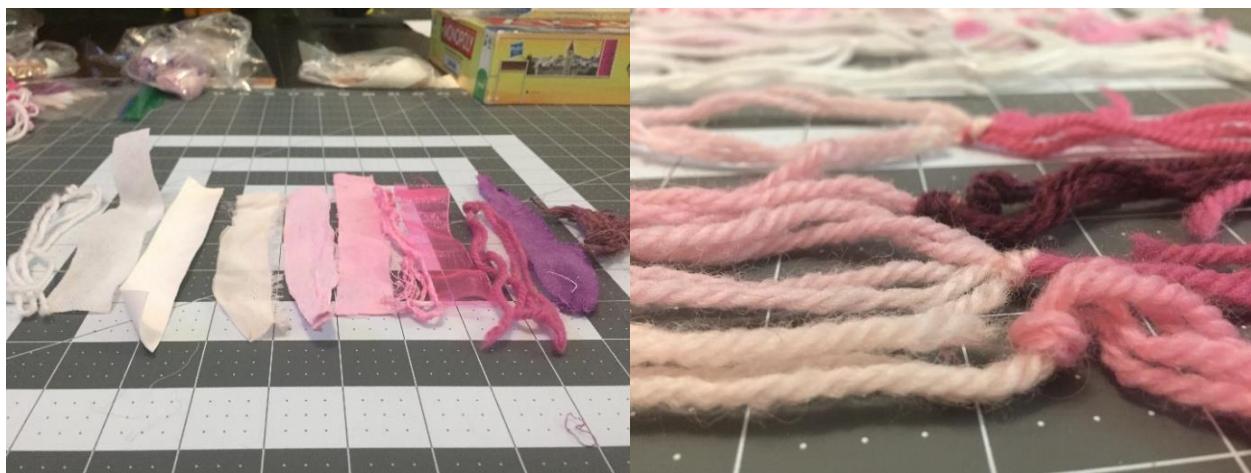
Similarly, for acid dyes, the uptake of the red colourant was far faster than blue. When wiping down the finished product, the decomposition of the blue dye was evident. This phenomenon tends to be especially problematic in purple dyes, which happens to be the colour we used in this experiment.



Left: Violet Wilton Icing Colour - which is composed of Red 3 (Erythrosine;  $C_{20}H_{6}I_4Na_2O_5$ ) and Blue 1 (Brilliant Blue FCF;  $C_{37}H_{34}N_2Na_2O_9S_3$ ) - broken on a tissue after wiping down a surface

*Right: jars with remnants of dyebaths after the swatches were dyed; the left is a purple hue similar to the original colour of the dyebath, and the right is a blue hue with a significant decrease in red from the original dyebath*

We observed that despite using a purple dye solution, most of the fabrics dyed pink. There were a few exceptions to this observation, such as the silk swatches dyed at high heat with salt and vinegar, as well as the wool swatch dyed in hot solution with vinegar. We hypothesize that the elevated temperature and acidity allowed faster dye uptake, which consequently allowed the blue dye to have time to strike.



*Left: samples dyed in hot acid dye with salt added; from left to right, acrylic, polyethylene, polyurethane, polyester, paper towel, cotton, bamboo, nylon, wool, silk, jute*

*Right: wool samples dyed in acid dye, in cold medium on the left and hot medium on the right; from foreground to background, with the addition of detergent, with the addition of salt, with the addition of vinegar, with no additives*

|                   |           |                |                     |
|-------------------|-----------|----------------|---------------------|
| cold acid vinegar | cold acid | cold acid salt | cold acid detergent |
| hot acid vinegar  | hot acid  | hot acid salt  | hot acid detergent  |

*Silk colour card for acid dyes; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*



*Wool colour card for acid dyes; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

The data for the hue value of the acid-dyed samples were collected into the following table. For the sample colour swatch, saturation and value are held constant at 100, in order to provide better grounds for comparison. The table header shows the colour of the dyebath (HEX: 211F2A), again adjusted to saturation and value of 100 (i.e., HSV: 250, 100, 100).

|         |                   | COLD   |        | HOT    |        |
|---------|-------------------|--------|--------|--------|--------|
|         |                   | Number | Colour | Number | Colour |
| NONE    | Polyacrylonitrile | 18     |        | 32     |        |
|         | Bamboo            | 355    |        | 5      |        |
|         | Cotton            | 354    |        | 356    |        |
|         | Jute              | 11     |        | 16     |        |
|         | Nylon             | 348    |        | 352    |        |
|         | Paper             | 344    |        | 357    |        |
|         | Polyester         | 27     |        | 24     |        |
|         | Polyethylene      | 27     |        | 32     |        |
|         | Polyurethane      | 26     |        | 348    |        |
|         | Silk              | 349    |        | 339    |        |
| VINEGAR | Wool              | 11     |        | 352    |        |
|         | Polyacrylonitrile | 15     |        | 344    |        |
|         | Bamboo            | 353    |        | 349    |        |
|         | Cotton            | 358    |        | 356    |        |
|         | Jute              | 8      |        | 7      |        |
|         | Nylon             | 344    |        | 345    |        |

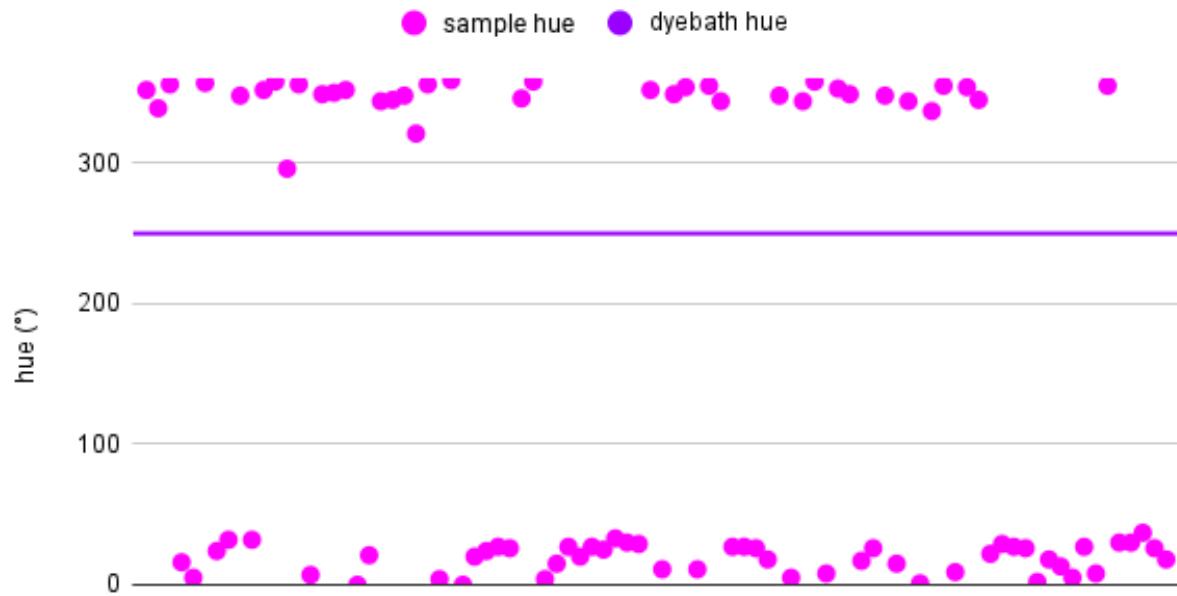
|           |                   |     |     |  |
|-----------|-------------------|-----|-----|--|
|           | Paper             | 349 | 350 |  |
|           | Polyester         | 17  | 352 |  |
|           | Polyethylene      | 26  | 0   |  |
|           | Polyurethane      | 348 | 21  |  |
|           | Silk              | 344 | 296 |  |
|           | Wool              | 5   | 358 |  |
| SALT      | Polyacrylonitrile | 26  | 26  |  |
|           | Bamboo            | 354 | 359 |  |
|           | Cotton            | 355 | 356 |  |
|           | Jute              | 9   | 4   |  |
|           | Nylon             | 2   | 346 |  |
|           | Paper             | 345 | 0   |  |
|           | Polyester         | 22  | 20  |  |
|           | Polyethylene      | 29  | 24  |  |
|           | Polyurethane      | 27  | 27  |  |
|           | Silk              | 337 | 321 |  |
| DETERGENT | Polyacrylonitrile | 26  | 29  |  |
|           | Bamboo            | 8   | 20  |  |
|           | Cotton            | 5   | 15  |  |
|           | Jute              | 27  | 27  |  |
|           | Nylon             | 18  | 352 |  |
|           | Paper             | 355 | 27  |  |
|           | Polyester         | 30  | 25  |  |
|           | Polyethylene      | 30  | 33  |  |
|           | Polyurethane      | 37  | 30  |  |
|           | Silk              | 13  | 4   |  |
|           | Wool              | 18  | 358 |  |

Some allowance should be given for these values, considering the initial colour of the fabrics (which skews yellow/orange), the lighting conditions (which has a warm tint), and the use of a photo of the dye stock *after* dyeing to determine the HSV of the initial dye solution (all photos of the dye solution at saturation were too dark for the technology to properly interpret). These factors all combine to cause increased deviation between dyed fabric hue and initial dyebath hue.

Nonetheless, there is a clear and significant difference between the dyed fabric hue and initial dyebath hue. The closest match – the silk dyed in a hot acid bath with vinegar added – has a hue of 296, which is still 46 off from the dye stock (250). The migration between these values goes ~12.78% around the hue circle.

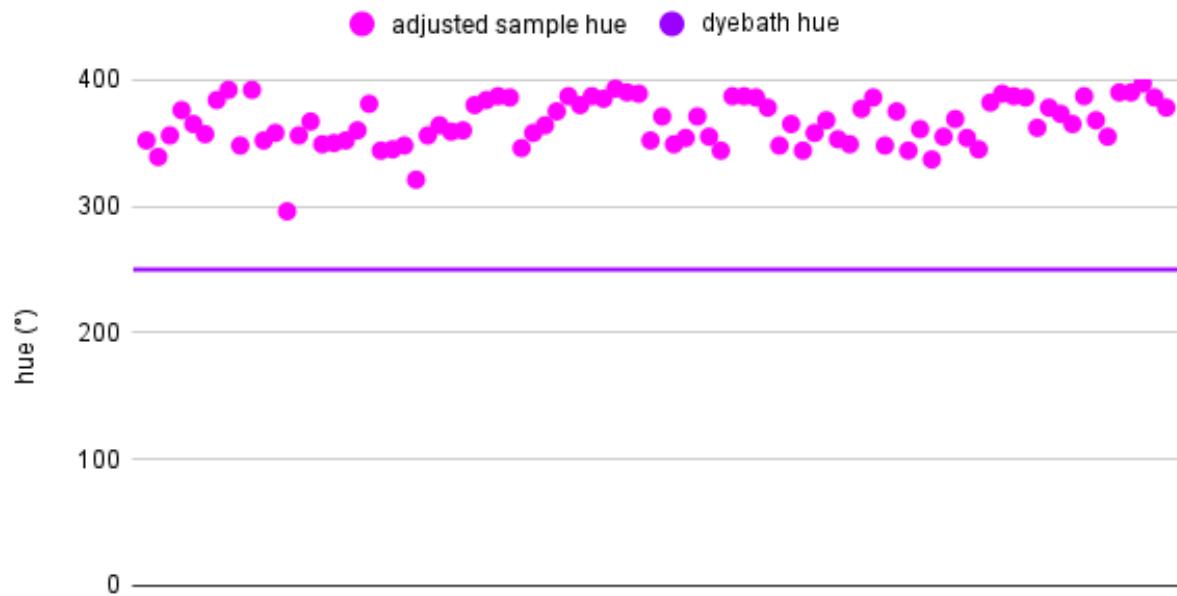
Graphing the hue of the fabric against the dye stock, the following is obtained:

## Sample Hue and Dyebath Hue



For clarity, this graph can be adjusted by adding 360 to the hues of the values under 180, since hue is an angular measurement.

## Adjusted Sample Hue and Dyebath Hue



### Dyebath Temperature

Disperse dyes struck best at high heat; there is an incredibly noticeable difference in dye uptake when applied cold vs. hot. In the case of polyurethane, the uptake is barely present at cold temperatures. Even if it does dye at cold temperatures, such as in the case of wool, the saturation is far greater at high temperatures.

|                       |               |                    |                         |
|-----------------------|---------------|--------------------|-------------------------|
| cold disperse vinegar | cold disperse | cold disperse salt | cold disperse detergent |
| hot disperse vinegar  | hot disperse  | hot disperse salt  | hot disperse detergent  |

Polyurethane colour cards for disperse/direct dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot

|                       |               |                    |                         |
|-----------------------|---------------|--------------------|-------------------------|
| cold disperse vinegar | cold disperse | cold disperse salt | cold disperse detergent |
| hot disperse vinegar  | hot disperse  | hot disperse salt  | hot disperse detergent  |

Wool colour cards for disperse/direct dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot

The same is true of most dyebaths. In most cases, heat speeds up chemical reactions, since it adds energy to the system. Furthermore, heat tends to increase solubility. As a result, dye uptake occurs much faster in hot environments.

In general, the synthetic fibres struggled to accept any dye. Nonetheless, hot dyebaths of disperse dyes had promising results, and it stands to reason that increasing the time in immersion would yield favourable results. The hot acid dyebath with the addition of vinegar was able to take some dye; however, it does appear to be particularly washfast, and the texture of the fibre is markedly crunchier. Consequently, this is still not a viable option for practical textile dyeing.

|                       |               |                    |                         |
|-----------------------|---------------|--------------------|-------------------------|
| cold reactive vinegar | cold reactive | cold reactive salt | cold reactive detergent |
| hot reactive vinegar  | hot reactive  | hot reactive salt  | hot reactive detergent  |

*Acrylic colour cards for reactive dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

|                  |          |               |                    |
|------------------|----------|---------------|--------------------|
| cold ink vinegar | cold ink | cold ink salt | cold ink detergent |
| hot ink vinegar  | hot ink  | hot ink salt  | hot ink detergent  |

*Acrylic colour cards for ink; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

|                       |               |                    |                         |
|-----------------------|---------------|--------------------|-------------------------|
| cold disperse vinegar | cold disperse | cold disperse salt | cold disperse detergent |
| hot disperse vinegar  | hot disperse  | hot disperse salt  | hot disperse detergent  |

*Acrylic colour cards for disperse/direct dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

|                   |           |                |                     |
|-------------------|-----------|----------------|---------------------|
| cold acid vinegar | cold acid | cold acid salt | cold acid detergent |
| hot acid vinegar  | hot acid  | hot acid salt  | hot acid detergent  |

*Acrylic colour cards for acid dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

While in most cases, heat and saturation were positively correlated, there are some cases where the opposite was true. This includes the application of acid dyes to cellulosic fibres. It is likely that this is the case since heat promotes the breakdown of weak bonds, whereas it aids setting in cases where there is high substantivity between dye and fibre.

|                   |           |                |                     |
|-------------------|-----------|----------------|---------------------|
| cold acid vinegar | cold acid | cold acid salt | cold acid detergent |
| hot acid vinegar  | hot acid  | hot acid salt  | hot acid detergent  |

*Cotton colour cards for acid dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

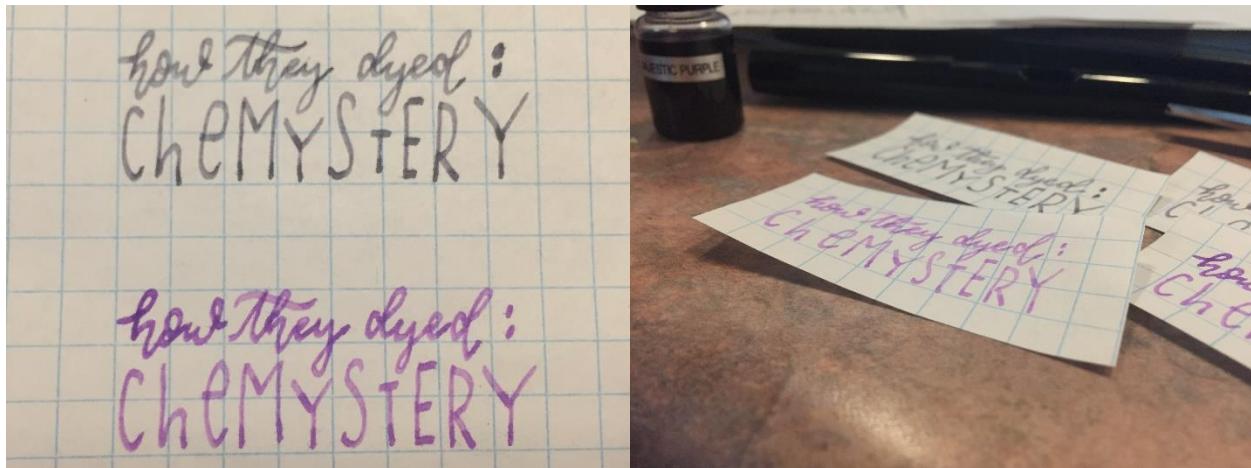
|                   |           |                |                     |
|-------------------|-----------|----------------|---------------------|
| cold acid vinegar | cold acid | cold acid salt | cold acid detergent |
| hot acid vinegar  | hot acid  | hot acid salt  | hot acid detergent  |

*Polyurethane colour cards for acid dye; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot*

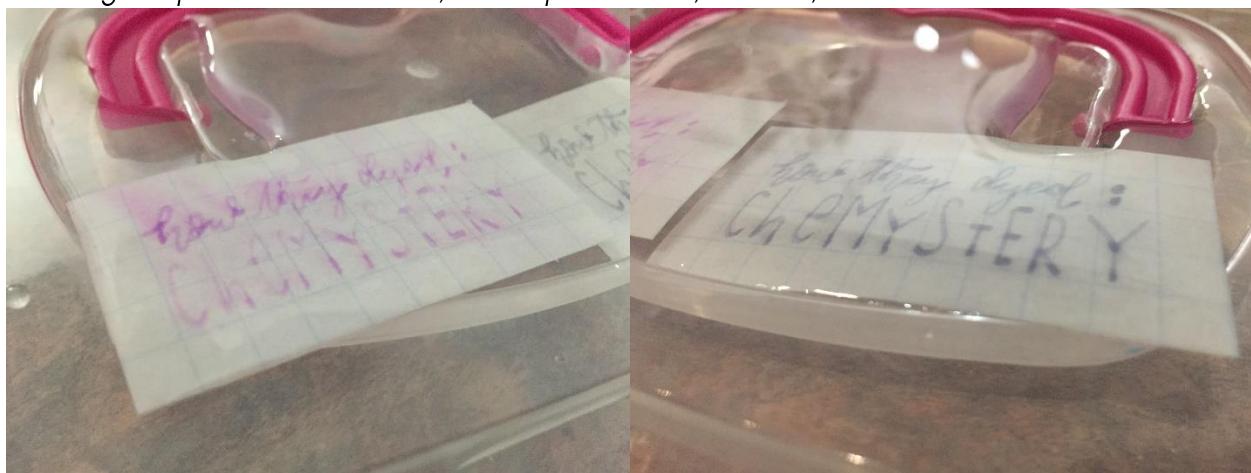
### Ink Uptake

In most cases, the ink was unable to bond to the fabric samples. We were unable to ascertain the chemical composition of the Diamine Fountain Pen Ink, so the reasoning behind this is dubious. However, given that the product was not formulated for textile colouration purposes, it is likely that there is an absence of binding agents, and that the chemical structure is not optimized for permanent application.

Some cursory research reveals that Diamine Fountain Pen Ink is dye-based and water-soluble. This typically means that the ink is not waterproof, since the ink is water-soluble but does not bond to the cellulosic fibres of the paper (the "normal" application of pen ink). A separate category, "bulletproof" ink, is used to denote dye-based inks with greater colourfastness owing to reactive dye components – however, Diamine's Majestic Purple is decidedly not "bulletproof". This is proved through an informal soak test of Diamine Majestic Purple Fountain Pen Ink and (months old) Black Tulip One-Step Tie Dye, both of which were applied through a fountain pen to graphing paper:



Lettering samples before soak test, from top to bottom, reactive, ink



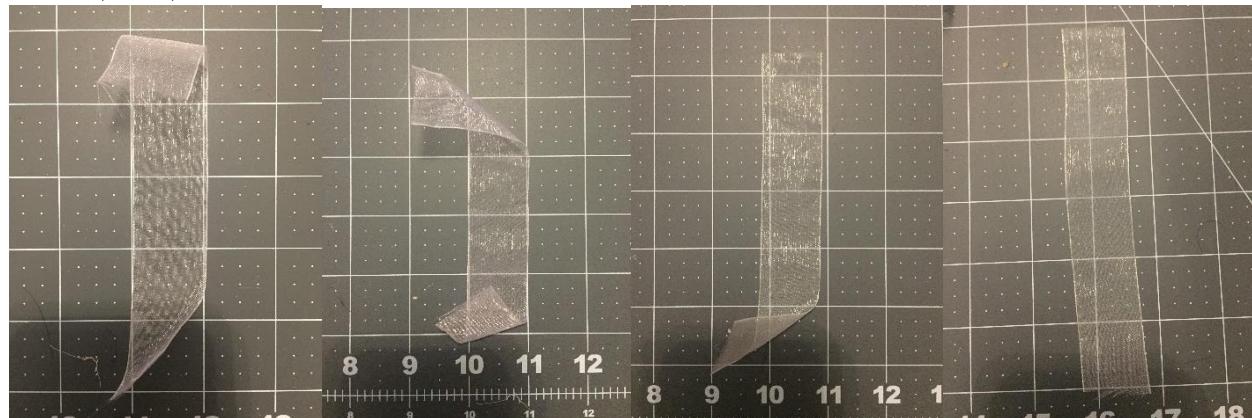
Lettering samples after soaking for 5 minutes (left: ink; right: reactive)

It is immediately clear that the fountain pen ink does not display wet-fast properties. While the reactive dye faded, it still retained sharp character. However, the fountain pen ink immediately displays feathering and extreme fading. This shows clearly that this ink does not contain a reactive group suitable for cellulose. Given the intended use of fountain pen ink – i.e., paper – it is unlikely that the manufacturers specialized the product for covalent bonding with protein fibres. Consequently, it is a viable conclusion that the ink contains no reactive groups with substantivity for fibres.

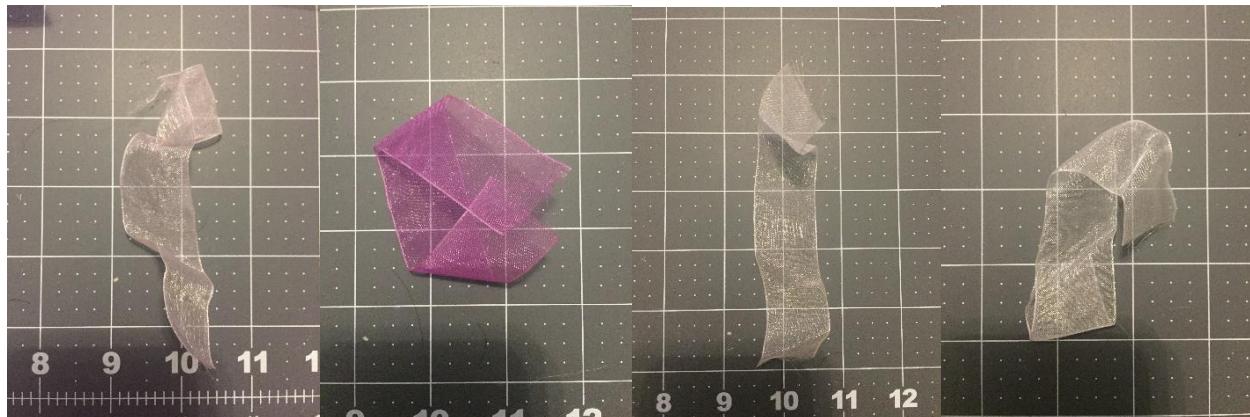
This can be demonstrated through the dyed nylon samples. In general, nylon took the dyes extremely well, but in the case of ink, it was only able to take any colour in the hot dyebath with vinegar.

|                  |          |               |                    |
|------------------|----------|---------------|--------------------|
| cold ink vinegar | cold ink | cold ink salt | cold ink detergent |
| hot ink vinegar  | hot ink  | hot ink salt  | hot ink detergent  |

Nylon colour cards for ink; additives from left to right, vinegar, none, salt, detergent; from top to bottom, cold, hot



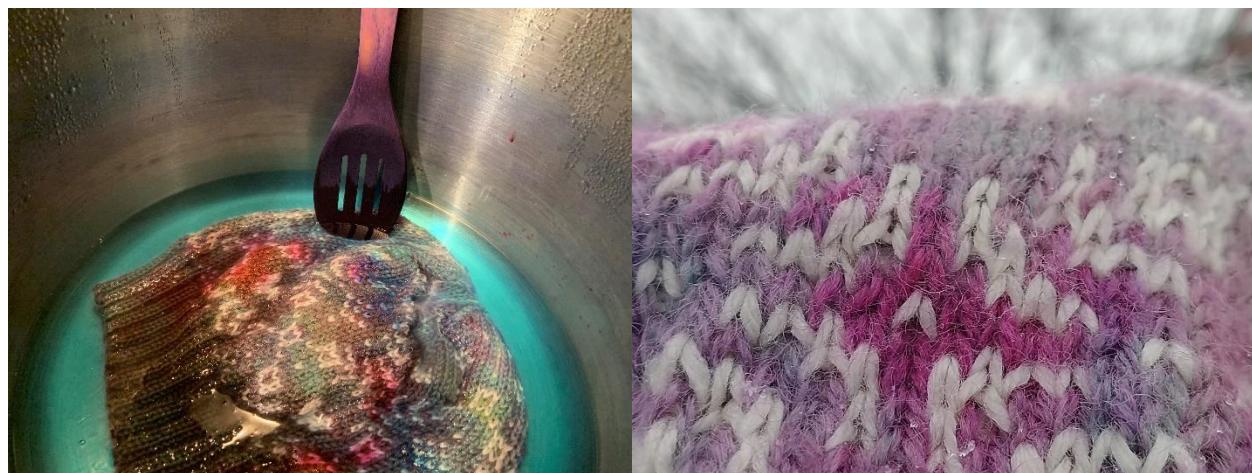
From left to right: nylon organza ribbon dyed in a cold ink bath with no additives, with vinegar, with salt, and with detergent



From left to right: nylon organza ribbon dyed in a hot ink bath with no additives, with vinegar, with salt, and with detergent

### Hat Dyeing

With the hat, we found that the wool took the dye well, and the acrylic did not take the dye at all. This supports our research showing that hydrophobic fibres (such as acrylic) are incapable of absorbing acid dyes.



Left: hat in the process of low-water immersion dyeing

Right: tight shot of hat after dyeing and washing

## Conclusions

Based on our thorough study and series of experiments, it is evident that there is no “ideal” solution to which dyes are most effective. Depending on one’s goals, different dyes might prove to be more effective. Acid dyes, while brilliant in applications, are difficult to set if using blue shades. For more colourfast results, heat would be greatly beneficial; however, if wash fastness is not required, it may be best to use low heat in some cases. Out of all the different dyes, Rit DyeMore performed the best. Although acid dyes used were still effective, the ones we used here were meant for food; and while reactive dyes are also effective, the ones we used here are marketed towards kids’ crafts, resulting in the lack of durability. Certainly, fountain pen inks which are marketed for use on

absorbent paper (such as onion paper) showed the worst performance, and would only be recommended for experimental endeavours seeking to satisfy intellectual curiosity, or in cases of upcycling.

With regards to additive impact, the pH of the dyebath had a clear impact on uptake. It was found that a lower pH led to greater red uptake as well as greater overall dye uptake due to a lowered activation energy for bonding. Likewise, *ceteris paribus*, the addition of heat to the system contributed to a greater amount of dye uptake. In order for dye uptake to be effective at all, however, it was necessary that the dye be able to bond to the substrate; thus, hydrophobic colourants and hydrophobic textiles had to be combined, as did hydrophilic colourants and hydrophilic textiles. It was found, in the case of ink, that in the absence of covalent, ionic, hydrogen, or hydrophobic bonding, washfastness cannot be achieved.

In the future, more experiments should be performed with different colours and brands of dyes, as well as in various increments of dye and additive concentrations and temperature. Furthermore, instruments (e.g., spectrophotometer, pH meter, thermometer, dropper, etc.) should be obtained to more accurately quantify different properties such as temperature, weight, colour and pH.

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## References

- Abrahart, E.N., et al. (March 5, 2019.) Dye. *Encyclopedia Britannica*.  
<https://www.britannica.com/technology/dye>.
- Allie. (November 23, 2021.) Re: Rit DyeMore Composition [Email].
- Ashenhurst, J. (January 25, 2020). *Conjugation and Color (+ How Bleach Works)*. Master Organic Chemistry.  
[https://www.masterorganicchemistry.com/2016/09/08/conjugation\\_and\\_color/](https://www.masterorganicchemistry.com/2016/09/08/conjugation_and_color/)

- Damant, A.P. (2011). Food colourants. In M. Clark (Ed.), *Handbook of textile and industrial dyeing* (pp. 252–305). Woodhead Publishing Limited.
- Fiber Reactive Dye Chemistry*. (N.d.) Dharma Trading Company. [https://www.dharmatrading.com/techniques/batik/fiber-reactive-dye-chemistry.html?lnav=techniques\\_batik.html](https://www.dharmatrading.com/techniques/batik/fiber-reactive-dye-chemistry.html?lnav=techniques_batik.html)
- Forte, P. (2011). Dyeing of environmentally friendly pretreated cotton fabric. *Textile Dyeing*. <https://doi.org/10.5772/21723>
- Hunter, C.A., & Sanders, J.K.M. (1990). *The Nature of π-π Interactions*. *Journal of the American Chemical Society*, 112(14), 5525–5534. <https://doi:10.1021/ja00170a016>
- Jose-Yacaman, M. (October 2006). Chemical Composition of a Fountain Pen Ink. *Journal of Chemical Education*. 83(10), 1476–1478. <https://doi.org/10.1021/ed083p1476>
- Koh, J. (2011). Dyeing of cellulosic fibres. In M. Clark (Ed.), *Handbook of textile and industrial dyeing* (pp. 129–146). Woodhead Publishing Limited.
- Lewis, D.M. (2011). The coloration of wool. In M. Clark (Ed.), *Handbook of textile and industrial dyeing* (pp. 3–39). Woodhead Publishing Limited.
- Neon Food Colouring. (N.d.) ClubHouse. <https://www.clubhouse.ca/en-ca/products/baking/food-colours/neon-4-vials-food-colour-preparation>
- Rit DyeMore; MSDS No. 01272 [Online]; Nakoma Products, LLC.: Bridgeview, IL, July 12, 2018.
- Roy-Choudhury, A.K. (2011). Dyeing of synthetic fibres. In M. Clark (Ed.), *Handbook of textile and industrial dyeing* (pp. 40–128). Woodhead Publishing Limited.
- Sadeghi-Kiakhani, M., & Safapour, S. (2015). Salt-free reactive dyeing of the cotton fabric modified with chitosan-poly(propylene imine) dendrimer hybrid. *Fibers and Polymers*, 16(5), 1075–1081. <https://doi.org/10.1007/s12221-015-1075-9>
- The Editors of Encyclopaedia Britannica. (2011, December 6). *chromophore*. *Encyclopedia Britannica*. <https://www.britannica.com/science/chromophore>
- Tulip One-Step Tie Dye Kit; MSDS No. 01281 [Online]; Duncan Enterprises: Fresno, CA, December 18, 2018.
- Wilton. (2014.) *Icing Colours: ingredients*. Woodridge, IL.
- Yarnspirations. (2021.) *Patons Canadiana: ball band*. Listowel, ON, Canada.
- Yarnspirations. (2021.) *Patons Classic Wool Worsted: ball band*. Listowel, ON, Canada.