Beer's Law: Dyeing Silk

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1 Introduction

1.1 Purpose

Observe how the adhesion of an acid dye, Fast Green FCF, changes due to changes in the protonation state of the fabric, silk (Fig. 1). Determine the unknown concentration of a solution from its absorbance based on a dilution series collected using Vernier SpectroVis Plus ultraviolet-visible spectrometer.

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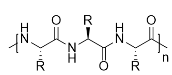

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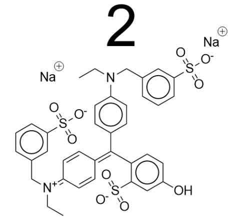

Figure 1: A representation of the chemical structure of (1) amino acid chains in silk and (2) Fast Green FCF

1.2 References

McQuarrie, D. A.; Simon, J. D. *Physical Chemistry: A Molecular Approach*; University Science Books: Sausalito, CA, 1997.

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Fast Green FCF Certified, DcGf-17 (CAS: 2353-45-9). 15500, lot 250211-67 Electron Microscopy Sciences: Hatfield, PA, Sept 4, 2025.`https://www.emsdiasum.com/docs/technical/msds/15500.pdf`

Citric acid, anhydrous ACS (CAS: 77-92-9). 0529. VWR International LLC: Radnor, PA, Sept 4, 2025. `https://www.avantorsciences.com/us/en/product/7422557/citric-acid-anhydrous-acs`

Vernier Software & Technology. (2023). Vernier Spectral Analysis (Version 4.12) Beaverton, OR: Vernier Software & Technology. Retrieved September 4, 2025. Available from `https://www.vernier.com/product/spectral-analysis`

1.3 Safety Information

Citric Acid
Causes serious eye irritation.
• Flush eyes with water immediately after exposure • Keep in sealed container in well ventilated area • Wear protective eye goggles
Fast Green FCF
Toxic if swallowed. Causes skin and eye irritation.
• Wash thoroughly after handling. • Keep container tightly sealed. • Wear gloves and protective goggles

2 Methods

2.1 Dye Solution

10 mL of 1.00×10^{-4} M stock solution of dye was diluted with 90 mL of deionized (DI) water to a final concentration of 1.00×10^{-5} M in a 250 mL beaker. Soln. was heated to a temperature between 80°C and 90°C.

2.2 Citric Acid Bath

2.2 g of citric acid was dissolved in 500 mL of room temperature DI water in a 1000 mL beaker.

2.3 Dyeing Silk

A 100% silk handkerchief made in China was weighed, for a mass of 2.8997 g, and evenly divided into 8 sections, each with a mass of 0.36246 g.

The first section was saturated with DI water before being added to the dye bath. The other seven sections were saturated with citric acid solution before being added to the dye bath. The sections were dyed one at a time. They were gently stirred in the dye bath for 60 seconds before being rinsed with tap water and set aside to dry (Fig. 2).

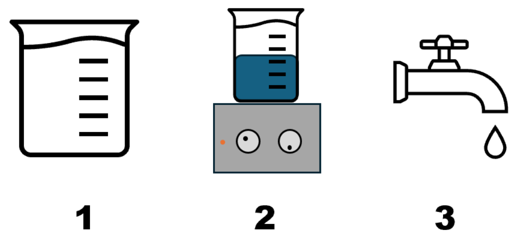

Figure 2: Cartoon of stages of silk dyeing: (1) citric acid bath, (2) heated dye bath, and (3) rinse with tap water.

2.4 Dilution Series

A dilution series was prepared by diluting a stock solution with a concentration of 5.00×10^{-6} M with DI water (Table 1). Ultraviolet-visible spectroscopy (UV-vis) data was collected by a Vernier SpectroVisPlus spectrometer using plastic cuvette with a path length of 10 mm. Spectra were collected over a range of 400 nm to 700 nm and the max absorbance was recorded.

Table 1: Dilution series of dye solution used for Beer's Law plot displaying the ratio of stock solution to DI water used to produce desired concentrations.

Conc. (M)	**Vol. Stock (mL)**	**Vol. DI Water (mL)**
5.00×10^{-6}	3	0
4.00×10^{-6}	2.4	0.6
3.00×10^{-6}	1.8	1.2
2.00×10^{-6}	1.2	1.8
1.00×10^{-6}	0.6	2.4

3 Results/Data

3.1 Use of the Citric Acid Bath

The addition of the citric acid bath improved the adhesion of the dye. The amine groups in the silk were protonated, which allowed for ion-ion interactions between the silk and the dye. The washfastness of the dyed fabric increased from losing all color to losing very little color when rinsed (Fig. 3). Without the acid bath, the dye was unable to bind to the silk, therefore the citric acid bath was necessary.

3.2 Exhaustion of the Dye Bath

Over time, as more pieces of silk were dyed, the dye bath faded from a deep blue-green to a pale sky blue. The color of the fabric dyed in the bath also shifted accordingly (Fig. 3).

Figure 3: Gradient of final color of silk sections. Section 1 was dyed without a citric acid bath and did not retained color after being rinsed. By section 7, the dye bath was exhausted and the color lightened.

The temperature of the bath had a significant effect on the adhesion of the dye. The first two section of silk were dyed at the lower end of the temperature range, around $80°C$ and resulted in a lighter color than sections 3 and 4 despite the concentration of the dye bath being lower.

The wavelength of max absorbance λ_{max} can be predicted using the particle in a box method. When the equations

$$\Delta E = \frac{h^2 n^2}{8 m_e a^2} \tag{1}$$

and

$$\lambda = \frac{hc}{\Delta E} \tag{2}$$

are combined to form

$$\lambda = \frac{8 m_e a^2 c}{h n^2} \tag{3}$$

then the wavelength of max absorbance can be solved for using the length of a box formed from the 6 membered conjugate chain. If each bond is considered to be 1.4 Å, then the total length of the box is $6 \cdot 1.4$ Å= 8.4 Å= $8.4 \cdot 10^{-10}$m. This value, along with the mass of an electron m_e, $1.9 \cdot 10^{-31}$ kg, the speed of light c, $2.88 \cdot 10^{8}$ m/s, Planck's constant h, $6.626 \cdot 10^{-34}$ J·s and $n = 2$ were added to the equation and produced the result.

$$\lambda_{max} = 582nm \tag{4}$$

The true λ_{max} was lower and closer to 400 nm.

An sample with unknown concentration was given as the last concentration that successfully dies the silk an acceptable, non-pastel shade of green. The concentration of this unknown was calculated to be 1.50×10^{-5} M using Beer's Law. (Table 2 and Fig. 4).

Table 2: Absorbance of dilution series and unknown.

Conc. (M)	Abs.
5.00×10^{-6}	0.561
4.00×10^{-6}	0.534
3.00×10^{-6}	0.474
2.00×10^{-6}	0.374
1.00×10^{-6}	0.292
1.50×10^{-5}	1.28

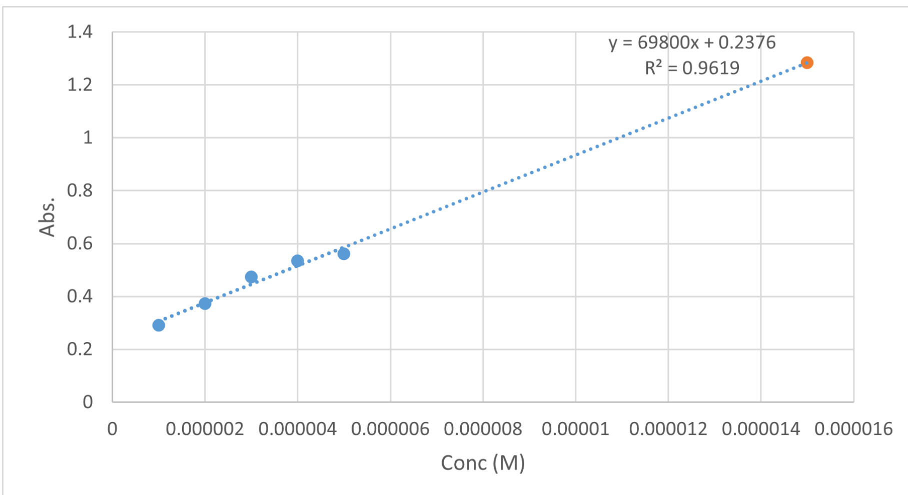

Figure 4: Beer's Law plot of concentration vs absorbance. A linear fit of known concentrations (blue) resulted in the equation Abs. $= 69800(\text{Conc.}) + 0.2376$. This equation was used to determine the concentration of an unknown (orange). The R^2 value, of 0.9619, is close to 1 which indicates a good fit.

The amount of dye needed to replenish the bath can be calculated from the difference in concentration, with the assumption that the volume of solution removed from the dye bath during dyeing is negligible, using the equation:

$$m = MW(VC_2 - VC_1) \tag{5}$$

Where m is the mass of dye added, MW is the molecular weight of the dye, V is the volume of the solution, C_1 is the initial concentration, and C_2 is the desired concentration. This equation can be used to replenish the dye bath after it has been depleted. However, the calculated concentration of the unknown (1.50×10^{-5} M) was above the starting concentration of the dye bath (1.00×10^{-5} M), so this is nonapplicable.

4 Conclusion

To dye silk with an acid dye such as Fast Green FCF, an acid bath is required. The acid bath protonates the silk allowing for strong ion-ion intermolecular interactions that preserve the wash-fastness of the fabric. Without the acid bath, the ion-dipole interactions are not strong enough to prevent the color from rinsing out. Evidently, the tag of the handkerchiefs are not make of silk, as the acid bath had no effect on its lack of color retention.

Five sections of silk were dyed to a reasonable color before the dye bath was depleted. We were unable to determine the depth of shade for Fast Green FCF and silk.

The dye bath can be replenished if the concentration of the bath after dyeing a set number of pieces is known. Unfortunately we were unable to obtain this information as the concentration after dying all 8 sections of silk was too low to by detected by the UV-Vis spectrometer.