Supporting Information: Verification of the Beer-Lambert Law Using Tomato Juice and a Halogen Lamp

Hiroki Wadati*

Department of Material Science, Graduate School of Science, University of Hyogo, Ako, Hyogo 678-1297, Japan

E-mail: wadati@sci.u-hyogo.ac.jp

Student Handout

Objective

To measure the absorption spectra of tomato juice dilutions, verify the Beer-Lambert law, and observe its limits at higher concentrations.

Learning Outcomes

- Explain the Beer–Lambert law and its variables.
- Collect transmission spectra and convert them to absorbance.
- Plot absorbance vs. concentration and identify linear and non-linear regions.
- Connect absorption features to the red color of tomatoes.

Materials

- Tomato juice (Amazon Japan, ASIN B00J7C1YPW)
- Tap water
- Measuring spoon (Amazon Japan, B002TYZSYS)
- Polystyrene cuvettes, 1 cm path length (MonotaRO, product no. 03004285)
- Beakers (50-100 mL), pipettes, optical fiber, cuvette holder
- Quartz–tungsten–halogen lamp (Thorlabs QTH10/M, 10 W)
- Compact spectrometer (Thorlabs CCS200/M, 200-1000 nm)
- Safety glasses, lab coat

Procedure

1. Prepare seven dilutions: 0%, 2.5%, 5%, 10%, 25%, 50%, 100%.
2. Mix thoroughly and transfer ∼4.5 mL into a 1 cm cuvette.
3. Record reference spectrum with tap water.
4. Measure transmission spectra (350–800 nm), averaging three scans.
5. Convert to absorbance using

$$A(\lambda) = -\log_{10}\left(\frac{I(\lambda)}{I_0(\lambda)}\right).$$

6. Plot absorbance spectra for all samples.
7. At 500, 600, 700, 800, and 900 nm, plot absorbance vs. concentration.

Safety Notes

- Tomato juice and water are food-grade, posing no chemical hazards.
- Lamp becomes hot; avoid direct contact during/after use.
- Handle cuvettes carefully to avoid breakage.
- Dispose of solutions into the sink with running water.

Pre-Lab Questions

1. Write the Beer–Lambert law and explain each variable.
2. Convert absorbance $A = 1$ to transmission percentage.
3. Why are tomatoes red? (Use absorption and complementary color.)
4. List one reason why Beer's law may fail at high concentration.

Post-Lab Questions

1. Identify the concentration range where your data showed linearity.
2. At which wavelength (500–900 nm) did you obtain the highest absorption?
3. What happens when absorbance exceeds $\sim$1, and why?
4. Propose one improvement to the setup and explain the expected effect.

Instructor Notes

Pilot Implementation

A pilot implementation was conducted with six senior undergraduate research students. Each prepared the dilution series, collected spectra, and analyzed results. All students obtained usable spectra and constructed absorbance–concentration plots, confirming linearity up to absorbance ≈ 1 and observing deviations at higher concentrations. Representative student data and calibration plots are provided in Figures S1–S3. Raw CSV files are deposited on GitHub/Zenodo (DOI supplied in the manuscript).

Assessment Mapping (Table S1)

Table S1: Alignment of Learning Outcomes with Pre- and Post-Lab Questions.

Learning Outcome	Pre-Lab Q	Post-Lab Q / Assessment
Explain Beer–Lambert law	Q1, Q2	Q1, Q3
Interpret absorption spectra/tomato color	Q3	Q2
Collect spectra, convert to absorbance	—	Q2 (figure, explanation)
Discuss error sources, deviations	Q4	Q3, Q4
Relate to textbooks, reflect	—	Q4 (essay/reflection)

Grading Rubric (0–2 per criterion, total 8)

- Spectra quality & labeling
- Linear range identification
- Explanation of deviations
- Quality of written discussion

Pre/Post Quiz Answer Key

Pre-Lab Questions

1. $A = \epsilon c l$, where ϵ is molar absorptivity, c is concentration, l is path length.

2. $A = 1 \Rightarrow T = 10\%$.

3. Tomatoes appear red because lycopene strongly absorbs in the 480–520 nm region (green–blue light), leaving red light transmitted/reflected.

4. Beer's law fails at high concentration due to scattering, turbidity, or inner filter effects.

Post-Lab Questions

1. Linear up to about 25% tomato juice (A $\approx$ 1).

2. Highest absorption typically observed at 500 nm.

3. When absorbance >1, deviations occur due to scattering and detector limitations.

4. Suggested improvements: quartz cuvettes, adjusted integration time, and filtration.

In the following, we present the results obtained by the undergraduate students. The six students were separated into three groups.

Student Quiz Results

The pre- and post-lab quiz scores from the three groups are summarized in Table S2. After the experiment, the students' understanding was clearly enhanced.

Table S2: Pre- and Post-Lab Quiz Scores for Six Undergraduate Students (10 points total).

Group	Pre-Lab Score	Post-Lab Score
1	4	6
2	5	7
3	3	8

Student Experimental Results

Due to the 1.5-hour time limit of the class, the three groups were required to make the plot shown in Fig. 3(b). Figures S1-S3 show their results. While the results were overall reasonable, issues were noted, including the omission of the vertical axis and difficulties in preparing sufficiently dilute solutions.

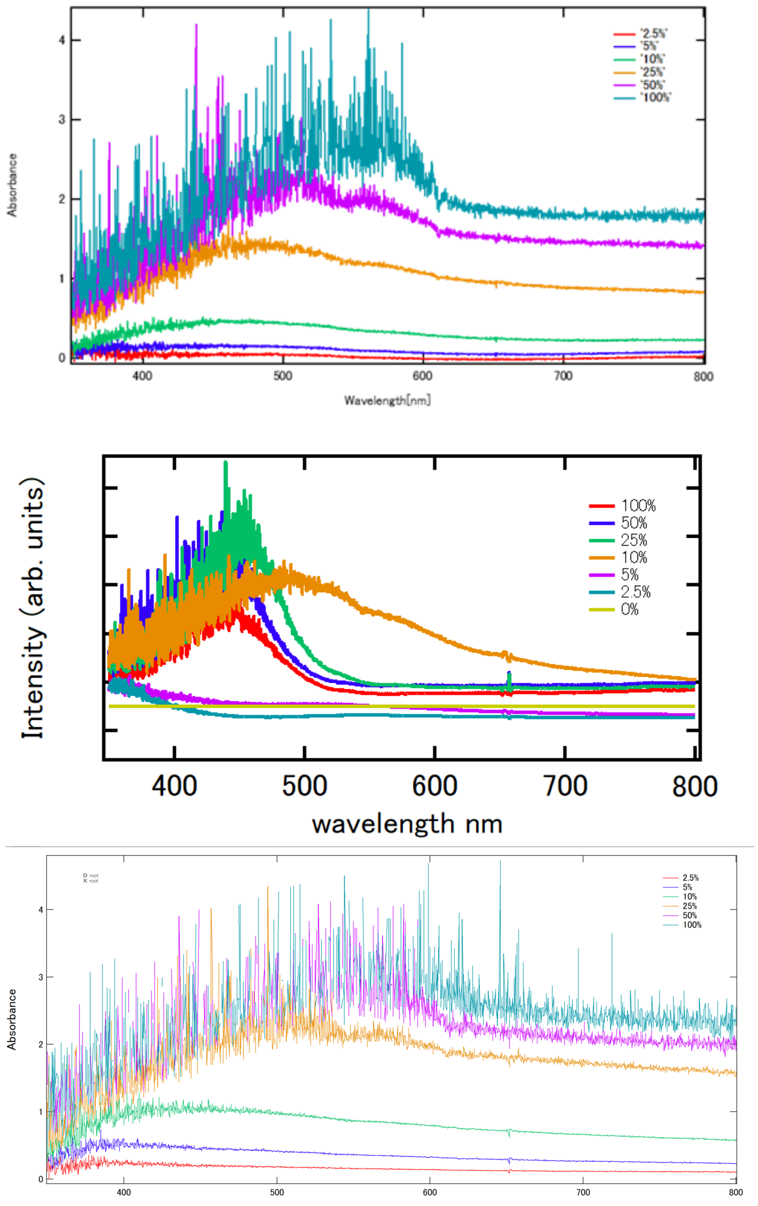

Figure S1: Absorbance spectra of tomato juice dilutions, plotted as a function of wavelength.

Student feedback

- I felt uncertain about whether the values were being measured correctly while experimenting. This time, I set the integration time to 2 ms, which was much shorter than expected. As a result, the measured intensity at 50% and 100% concentrations became too small, and the errors were particularly significant in the high-concentration region. Furthermore, these errors and fluctuations could not be corrected within the scope of this experiment."

- As for my impressions, I thought it was nice to be able to study spectroscopy using familiar materials. However, handling the analysis software was difficult, and my impression was that the analysis might be challenging for undergraduate students."

- In this experiment, I set the integration time to 0.5 ms (because something like an error was displayed). As a result, more noise appeared on the shorter-wavelength side, and I think the linearity in the absorbance–concentration graph was also disrupted."