To What Extent Does the Sucrose Concentration (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 g/mL) of Sucrose-Water Solution Change the Optical Rotation Angle (in Degrees) of the 650 nanometer electromagnetic wave?

3799 words

Contents

1. Introduction

1.1 Background Knowledge

1.1.1. Polarization of Electromagnetic Waves

When defining the concept light (or more scientifically electromagnetic waves), the common definition is “the flow of energy in the form of the electric and magnetic fields that make up electromagnetic waves” (Fritzsche and Phillips, 2024). Electromagnetic waves consist of two vector quantities called electric field and magnetic field perpendicularly oscillating on different axes. These fields can oscillate at different frequencies (which is usually the case). Electric field vector is symbolized by the letter E and the magnetic field vector is symbolized by the letter B. Figure 1 visualizes two vectors that make up the electromagnetic wave. The variation of oscillations of these two vectors are determined by Maxwell’s equations which also explains why these vectors are perpendicular to each other. Maxwell’s equations will not be discussed in this work for the sake of simplicity and coherence.

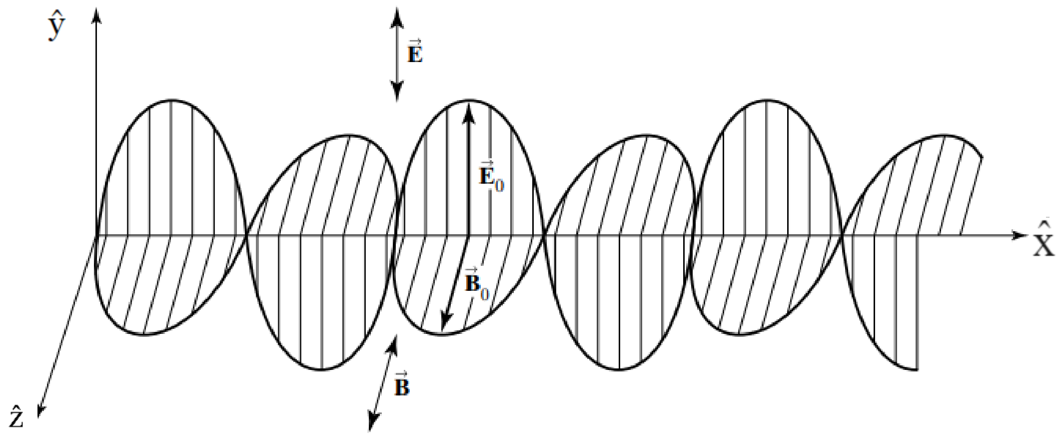


Figure 1: The visualization of an electromagnetic wave (Pedrotti et al., 2007).

The direction of the electromagnetic field is also known as the *polarization* of the electromagnetic wave. There are three types of polarization which are classified according to the resultant vector of the electric and magnetic fields. First case is *linear polarization*. This is a special case where the two vectors are in phase which suggests that they have the same frequency and they reach their maximum and minimum point at the same time. This results in the superposition of these two vectors (the resultant vector) moving in a new direction in the xy-plane. The angle of this plane depends on the amplitudes of electric and magnetic fields.

The second (and the most abundant) case is called *elliptical polarization*. Electromagnetic waves get elliptically polarized when their electric and magnetic fields are not in the same phase. This makes the resultant vector move in an ellipse.

The third case which is a special case of elliptical polarization is the *circular polarization*. In this case, the resultant vector traces out a circle. The figure-2 shows different types of polarizations with electric and magnetic field values given as E_x and E_y.

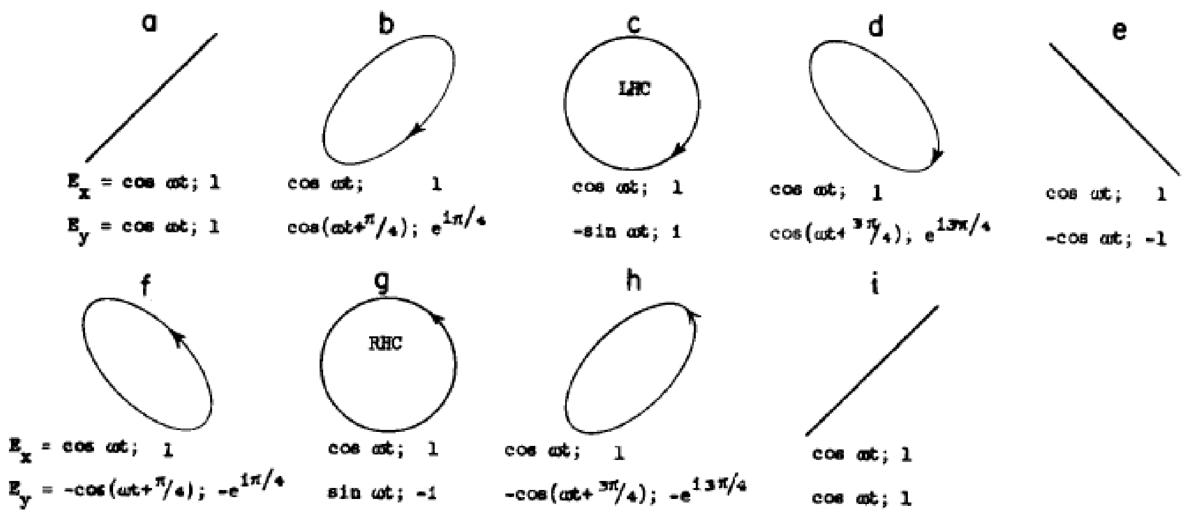


Figure 2: Examples of polarization (Feynman et al., 1963).

Even though an electromagnetic wave should be polarized due to its nature, some (most, actually) beams of electromagnetic radiation are unpolarized. This is due to the fact that innumerable charged particles vibrate and emit electromagnetic radiation in extremely short periods and with different frequencies and polarizations in a body. These electromagnetic waves form a beam with its polarization randomly changing as waves superposition. This phenomenon is called an unpolarized (randomly polarized) electromagnetic wave. Different approaches to polarizations have been discovered in order to observe the polarized properties of the light.

1.1.2. Unpolarized Light and Polarized Light

Unpolarized light consists of electromagnetic waves oscillating in multiple planes perpendicular to the direction of propagation. It is emitted by most natural and artificial sources, such as the sun and traditional light bulbs. In contrast, polarized light has its wave vibrations restricted to a single plane. This is commonly achieved through polarization by transmission, where light passes through a polarizing filter, polarization by reflection, where light reflects off a non-metallic surface at a specific angle (Brewster's angle), or polarization by scattering**,** as seen in atmospheric light scattering.

When unpolarized light passes through a polarizing filter, its intensity is reduced according to Malus' Law, given by:

$$I = I_0 \cos^2 \theta$$

Equation 1: Intensity of polarized light equation where I is the intensity of the transmitted light, I_0 is the initial intensity of the unpolarized light, and θ is the angle between the light's initial polarization direction and the axis of the polarizer (Giancoli, 2014).

This equation highlights how the intensity of polarized light depends on the relative orientation of the polarizer; a key principle used in measuring optical rotation in this experiment.

1.1.3. Chiral Molecules

Chiral molecules have a geometric structure with *nonsuperimposable* mirror image. This usually results from the molecule having an asymmetric center. Enantiomers are pairs of molecules that each of their mirror images are identical to themselves (similar to the hands of humans). Stereoisomers that does not have nonsuperimposable image are called diastereomers.

1.1.4. Optical Activity

Optical activity is the ability of a substance to rotate the polarization of linearly polarized light. This results as two counter-rotating circularly polarized waves move with different velocities through the chiral medium. Different velocities sum up to a plane that is rotating progressively. The change in velocities happens due to the interaction between the electrons in the chiral molecule and light (Graham et al., 2017). The different absorbance rate of the fields in the electromagnetic wave is called *circular dichroism*. The function that gives the circular dichroism of a molecule is given below:

$$\Delta\varepsilon = \varepsilon_L - \varepsilon_R = \frac{A_L - A_R}{[J]l}$$

Equation 2: The function of circular dichroism where J is the molar concentration of the chiral molecule, l is the length that the light travels through, and A is the absorbance rate (Feynman et al., 1963).

The asymmetry of the chiral molecules results in the presence of electric dipole moments within the molecules. The electric field of the electromagnetic wave interacts with the electric dipole moments of the molecules which creates a torque over the chiral molecules. This torque causes the dipole moments to attempt to align with the direction of the external field. However, due to the chiral nature of the molecules and their asymmetric arrangements, the alignment of the dipole moments is not uniform throughout the medium (Atkins et al., 2010). Since the chiral nature of the molecules require asymmetric arrangements, the orthogonal component of the light (the electric wave) experiences a phase shift. This is how polarized light experiences optical activity.

$$\Delta\theta = 2\pi v \Delta t = \frac{2\pi c \Delta t}{\lambda} = (n_R - n_L)\frac{2\pi l}{\lambda}$$

Equation 3: The function of optical rotation ($\Delta\theta$) which gives the amount of rotation in a medium. n_R is the refractive index of the substance whereas n_L is the refractive index of the medium that the light leaves the substance. l is the length that the light travels through the substance and λ is the wavelength of the light (Feynman et al., 1963).

1.1.5. Polarimeters

Polarimeters are instruments which measures the optical rotation of any compound. They use two polarizers: one before the light enters solution and one after the light leaves the solution. One of these polarizers are rotated in order to find the optimal angle which gives the maximum intensity of light, referring to Equation 1, which gives the final polarization of the light. Then, the angles of the polarizers are subtracted in order to find the total optical rotation of the light. Polarimeters are used in industries such as sugar plants where the chemical produced has chiral properties. The diagram of a polarimeter is given in the next page for further visualisation.

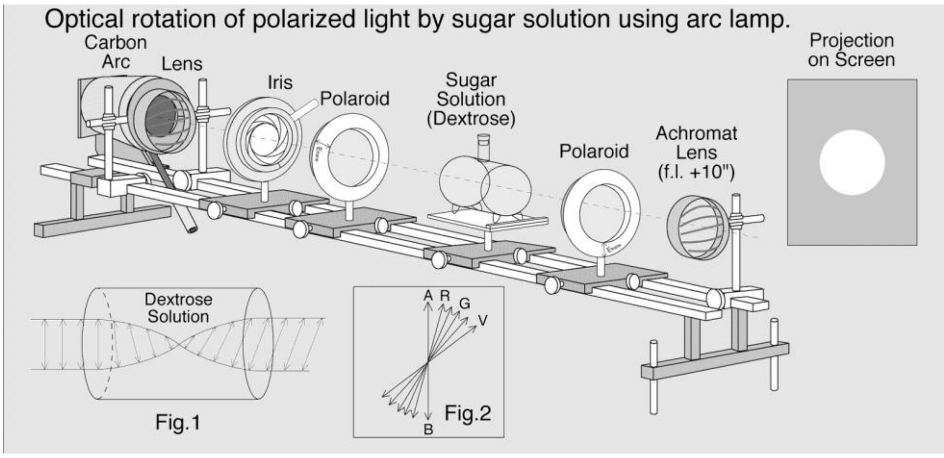


Figure 3: A polarimeter diagram.[1]

From Equation 3, it can be interpretted that the optical rotation angle should be proportional to the refractive index of the medium it is travelling. In the context of this investigation, it can be discussed that the refractive index of water-sucrose solution is proportional to the sucrose concentration (Khodakarami and Jafari, 2017). According to this, it can be hypothesized that optical rotation angle is proportional to the concentration of the water-sucrose solution, measured through the application of polarimeter instrument, which brings us to the research question of this investigation.

2. Research Question

To what extent does the sucrose concentration (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 g/mL) of sucrose-water solution change the optical rotation angle (in degrees) of the 650 nanometer electromagnetic wave?

Independent Variable: Gram/mililitre concentration of sucrose-water solution.

[1] Physics Lecture Demonstrations, University of Berkeley. *Optical Rotation of Polarized Light by Sugar Solution, Using Arc Lamp.* Berkeley Physics Demonstrations, https://berkeleyphysicsdemos.net/node/613. Accessed 02/01/2025.

Dependent Variable: Angle of the final polarizer (in degrees) when the maximum illuminance is observed (with a photometer) for the 650nm electromagnetic wave.

Controlled Variables: (The table continues on the next page)

Controlled Variable	How is it controlled?	How can the variable affect the result of the experiment if not controlled?
Wavelength of the electromagnetic wave (650nm)	Using the same laser light source with 650nm specified on its manual. Additionally, measured with wavemeter before each measurement.	Wavelength is directly proportional with optical rotation angle.
Initial polarization angle (90°)	Keeping the initial polarizer stationary at 90° and controling before each measurement.	This experiment assumes the light comes with a constant polarization angle, otherwise, there would be a systematic error.
Temperature of the water (≈20°C)	Controlling the temperature of the laboratory and the solution to make sure it is around 20°C	Temperature changes can alter the specific rotation angle of the solution.
Ambient lighting	Working in minimal ambient light with curtains closed in order to avoid the change of sunlight entering in. Controlling with photometer to make sure the illuminance is somewhat the same.	External light can interfere wit the polarized light beam causing false readings.

Size (path length 10.0cm and diameter 3.0cm) of the tube	Using the same tube each measurement.	Length of the tube (path length) is directly proportional to the optical rotation angle
Location of the polarizers, light source, and photometer	Stabilizing the light source and polarizers by locking them in the slider. Photometer is taped to the slider.	The total path length that light travels through the air should be the same in order to avoid the fluctuations caused by the optical activity in the air.
Humidity	Doing the measurements at the same time interval and ensuring there is no major change in humidity with subjective sensory evaluation.	High humidity can affect the concentration of the solution. Also, it may affect the optical rotation as the light moves through the air.
Homogenity (amount of stirring)	Using visual senses to ensure every solution is fully solved	Different homogenity levels prevent achieving the desired concentration values.
Purity of Sucrose	Using the same batch of sucrose.	Impurities in sucrose may alter the specific rotation angle of the solution.
Type of Solvent (Distilled water)	Using distilled water from the same source in each measurement.	Different water sources may contain varying levels of ions, ultimately affecting the specific rotation angle.

Table 1: Controlled variables with justification and explanation of methodology.

3. Experiment Design

3.1. Materials

1. Cylinder tube (10 centimeter long with each ends cut open)
2. Table sugar (Sucrose, 200 grams)
3. Distilled water (500 cm^3)
4. Laser light source (650 nanometers wavelength)
5. Vernier LabQuest 2
6. Photometer
7. Stretch film
8. Graduated cylinder (100 mL ±0.5)
9. Protractor (±0.5°)
10. Polarimeter with built-in polarizing filters and ruler with uncertainty of ±0.25 cm.
11. Erlenmayer flask
12. Beakers (200 cm^3)
13. Digital scale (±0.001 grams)
14. Weighing boat
15. Plastic scoop

3.2. Experiment

In the experiment, laser light emitted from the polarimeter's source first gets polarized by the polarizing filter. After that, the light will enter the cylinder tube containing the sugar solution. As the light leaves the solution, there will be another polarizing filter which will measure the direction of polarization in terms of degrees. Therefore, the amount of optical rotation caused by the solution could be measured with a photometer which is mounted behind the second polarizer.

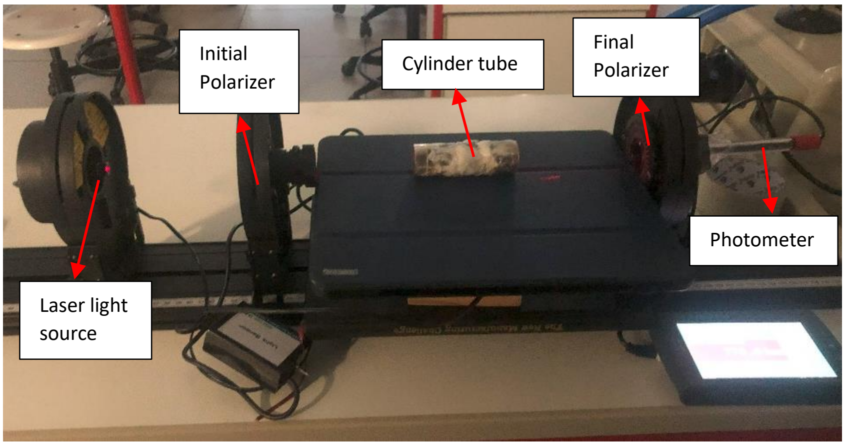


Figure 4: The experimental setup.

3.3. Procedure

Preparation of the Solution

1. The sucrose is moved from the tube to the weighing boat on the digital scale with the help of a plastic scoop. The required mass of sucrose for each trial is weighed.
2. 200 mL of distilled water is measured in graduated cylinder and transported to an erlenmayer flask.
3. The weighed sucrose is poured to the erlenmayer flask and thouroughly mixed for 2 minutes until it is fully dissolved. Afterwards, it should be made sure that there is no sucrose particles visible to eye in the solution.
4. Each solution is poured to clean beakers with a tag indicating their concentration on them.

Preparation of the polarimeter and the environment

5. The following components are mounted on the rail of the polarimeter in respective order: Laser light source, initial polarizer, housing of the cylinder tube, final polarizer, the LabQuest 2 photometer.
6. Each component is located so that they are adjacent, as close as possible, to each other in order to reduce any errors caused by the ambient light. Also, all components should be parallel in order to avoid refraction.
7. Initial polarizer is rotated in order to meet the angle of 0° to the vertical (initial polarizer will stay parallel to the vertical throughout the experiment).

Preparing the Cylinder Tube

8. One end of the cylinder tube is sealed securely with a single layer of strech film. There should be no creases which could possibly cause refraction of the laser light.
9. One of the water-sucrose solution is poured to the tube until the tip of the tube. When sealing the other end, there should be no air left in the tube.
10. The other end of the tube is sealed securely with a single layer of strech film. There should be no creases which could possibly cause refraction of the laser light.
11. The tube is then placed securely to the housing, parallel to the path of the laser beam in order to avoid refraction.

Test Measurement

12. The cylinder tube is first filled with distilled water.
13. The laser light source is turned on.
14. Tube is then placed to its housing.

15. The final polarizer is rotated and the angle where the highest amount of light brightness observed is controlled.
16. If the angle of the final polarizer is 0° to the vertical, parallel to the initial polarizer, there is no problem with the calibration of the polarimeter system.

Measurement

17. The cylinder tube is filled with the first solution and placed to the housing.
18. The laser light source is turned on.
19. Polarizing Filter 2 is rotated slowly while the photometer readings are observed. The angle from the vertical at which maximum light transmission occurs is identified and recorded as the final polarization angle.
20. The solution is carefully removed, and the tube is rinsed thoroughly with distilled water before introducing the next solution.
21. Steps 17-20 are repeated for each sucrose concentration – 8 trials for each concentration level in order to increase reliability of the measurements – while ensuring identical experimental conditions are maintained.

3.4. Rationale for the Methodology

The use of a laser light allows for a monochromatic light source which is required to observe and measure the optical activity of sucrose solutions without interference from multiple wavelengths. Additionally, the first polarizing filter allows light with a specific polarization to interact with the optically active sucrose solutions and the photometer in order to measure the total optical activity accurately. Confounding factors were minimized by changing the concentration of the sucrose while maintaining controlled variables - such as the locations of the polarimeters, ambient lighting, and the path length of laser light through the solution -

potential. This allowed the change in the optical rotation angle could be solely attributed to the change in sucrose concentration. Furthermore, taking multiple trials for each concentration improves the reliability of the data by reducing the impact of random errors. The use of LabQuest 2 and a photometer allowed for precise and repeatable measurements of light brightness while ensuring accurate determination of the polarization angle.

This methodology follows the fundamental principles of scientific rigor by carefully controlling variables, minimizing human related and methodological errors, and employing standard practices for optical rotation experiments. The experimental design is directly focused on the research question which makes it a suitable and justified approach for this investigation.

3.5. Environmental and Ethical Considerations

In this experiment, the chemicals used - water and sucrose - are considered to be environmentally safe. However, even though sucrose is biodegradable, deposition of large amounts of sucrose to the environment can disrupt microbial activity. In order to mitigate this, propal distposition should be conducted by diluting the solution and pouring them into designated laboratory wase systems.

The usage of energy intensive laboratory equipments like laser light and photometer causes concerns on energy waste. These equipments should be used efficiently while avoiding redundant usage and waste of energy. Additionally, for sealing the cylinder tubes, recyclable or biodegradable stretch film options should be preferred for reducing plastic pollution.

Furthermore, this experiment does not pose major safety hazards. However, the laser light could possibly cause vision loss in case of direct exposure. To avoid this, safety glasses could be used. It is also important to consider careful handling of glassware and electronic equipments to avoid potential breakages and electric shocks.

Lastly, this investigation does not involve any sort of personal data, public interaction, or harm to organisms which make it ethically sound. However, it is important to report measurements as they are with no manipulation or selective reporting of datas.

4. Measurement and Results

4.1. Reference Values

In this experiment, the relationship between the concentration of sucrose solutions and their optical rotation was examined using the known specific rotation value of sucrose, which is $+66.5°g^{-1}mL^{-1}$ at a wavelength of 589 nm (which is relatively close to the wavelength of the light used in the experiment which is 650 nm) and a temperature of 20°C. The optical rotation for sucrose solutions was calculated as a function of concentration assuming a linear relationship. Using the equation:

$$Optical\ Rotation = Specific\ Rotation \times Concentration$$

the optical rotation for sucrose solutions at concentrations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 g/mL was calculated. The results are given in the next page:

Concentration Level (g/mL)	Optical Rotation for 1 dm long track (degrees)
0.1	6.65°
0.2	13.30°
0.3	19.95°
0.4	26.60°
0.5	33.25°
0.6	39.90°
0.7	46.55°

Table 3: Theoretical reference values for the optical rotation.

In the following chapter, the experimental data will be analyzed and compared with these reference values.

4.2. Raw and Processed Data

Uncertainty propagation for the concentration

It is already known that the formula of the concentration is:

$$C = \frac{m_{sucrose}}{V_{solution}}$$

Where C is the concentration of the solution, $m_{sucrose}$ is the mass of the sucrose within the solution, and $V_{solution}$ is the total volume of the solution. According to this, it can be deduced that the uncertainty of the concentration could be calculated by the following formula:

$$\Delta C = \left(\frac{\Delta m}{m} + \frac{\Delta V}{V}\right) C$$

Here is a sample calculation for the 0.1 g/mL concentration level:

$$\left(\frac{0.5}{200\ mL}+\frac{0.001}{20\ g}\right)\times 0.1 = 0.000255 \approx 0.0003 g/mL$$

Where ΔC is the uncertainty of the concentration, Δm is the uncertainty of the mass, and ΔV is the uncertainty of the volume.

		Angle of the Final Polarizer When Maximum Level of Illuminance is Observed (°Degrees ±0.5)							
Concentration (g/mL)	*Uncertainty of the Concentration (g/mL)*	*Trial 1*	*Trial 2*	*Trial 2*	*Trial 2*	*Trial 2*	*Trial 6*	*Trial 7*	*Trial 8*
0.1000	*±0.0003*	*6.0*	*7.0*	6.0	8.0	7.0	7.0	7.0	6.0
0.2000	*±0.0005*	13.0	12.0	14.0	13.0	13.0	15.0	13.0	14.0
0.3000	*±0.0008*	20.0	19.0	21.0	20.0	20.0	21.0	20.0	19.0
0.400	*±0.001*	26.0	27.0	28.0	27.0	27.0	26.0	28.0	27.0
0.500	*±0.001*	34.0	33.0	32.0	33.0	34.0	33.0	32.0	33.0
0.600	*±0.002*	41.0	39.0	40.0	40.0	40.0	39.0	41.0	40.0
0.700	*±0.002*	47.0	46.0	48.0	47.0	47.0	46.0	48.0	47.0

Table 4: Raw data table of the measurements of the final polarization angles and the illumination observed.

The calculation below shows a mean optical rotation angles for 0.1 g/mL concentration level as a sample calculation:

$$Mean\ value\ for\ 0.1\frac{g}{mL} solution = \frac{6+7+6+8+7+7+7+6}{8} = 6.75°$$

The uncertainty of the mean optical rotation angle is:

$$Uncertainty = \frac{maximum\ angle - minimum\ angle}{2}$$

The sample calculation of the uncertainty of the optical rotation angle for the 0.1 g/mL concentration level is given below:

$$Uncertainty = \frac{8.0 - 6.0}{2} = 1\ g/mL$$

The uncertainty of the concentrations of the solutions are the same as the ones of the raw data table.

The standard deviation for each concentration level is calculated in order to find the divergence in each concentration level. The standard deviation is calculated with the equation below:

$$\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{N}}$$

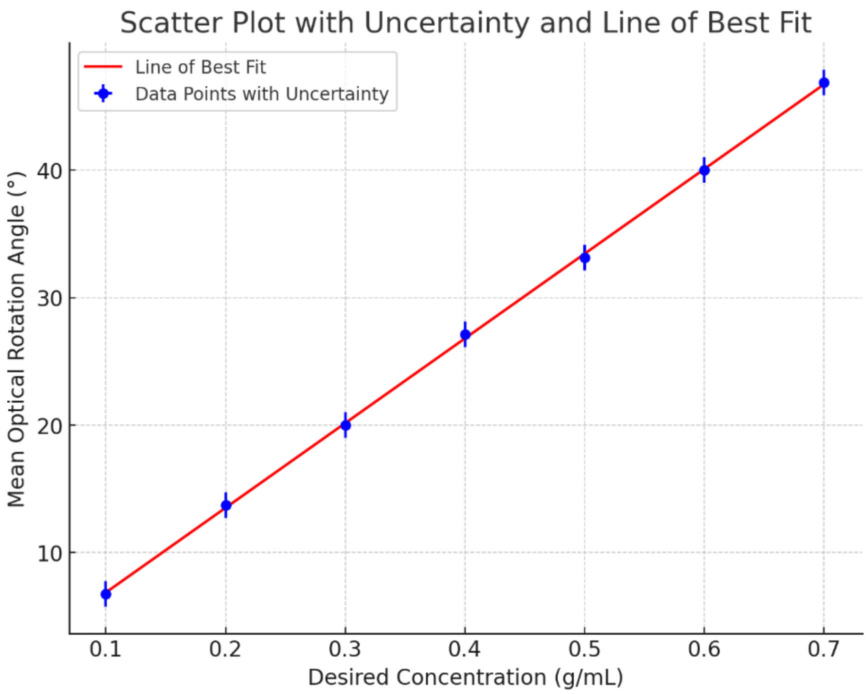
Where x_i is the individual trial and $\bar{x}$ is the average optical rotation angle for each concentration level, and *N* is the number of trials in each concentration level.

The sample calculation of the uncertainty for the concentration was given above. Even though it is low enough to be negliged, it is calculated for each concentration level and given in the table on the next page:

Desired Concentration (g/mL)	Absolute Uncertainty of the Concentration	Percentage Uncertainty of the Concentration	Mean Angle of the Change of Polarization (Optical Rotation) of Laser Light (°Degrees)	Absolute Uncertainty of the Optical Rotation Angle	Percentage Uncertainty of the Optical Rotation Angle	Standard Deviation of the Optical Rotation Angle
0.1	±0.0003	0.255%	6.75	±1	14.81%	0.661
0.2	±0.0005	0.253%	13.75	±1	7.27%	0.866
0.3	±0.0008	0.252%	20.00	±1	5.00%	0.707
0.4	±0.001	0.251%	27.13	±1	3.69%	0.620
0.5	±0.001	0.251%	33.13	±1	3.02%	0.780
0.6	±0.002	0.251%	40.00	±1	2.50%	0.707
0.7	±0.002	0.251%	46.88	±1	2.13%	0.647

Table 4: Processed data table for the sucrose concentration, corresponding optical rotation angle and their uncertainties and the standard deviation.

4.3. Data Analysis



Graph 1: Graph of the resulting data of the experiment.

The data analysis reveals a very strong positive linear relationship between the sucrose concentration and the observed angles of the final polarizer across multiple trials. When considering the entire dataset with all trials and concentration levels included, the Pearson correlation coefficient is an important indicator of linear relation and founded with the following formula:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2(y_i - \bar{y})^2}}$$

Substituting the values:

$$r \approx 0.999$$

The high correlation coefficient suggests that ther is a strong positive relationship between the optical rotation angle and the concentration of the sucrose solution. Therefore, as the concentration of the solution increases, the observed angle of the final polarizer also increases, which is likely the result of the optical properties of the chiral molecule sucrose. Standard deviations for each concentration level were below 1, suggesting a minimal variation between trials which indicates that the experimental setup is reliable, and the trend is robust across multiple measurements. In order to further assess this relationship, the equation of the line of best fit will be calculated.

In order to find the slope of the line of best fit, least squares method will be applied which is given below:

$$m = \frac{\sum(x_i - \bar{x})\,(y_i - \bar{y})}{\sum(x_i - \bar{x})^2}$$

Where x_i represents sucrose concentration of the specific sample, $\bar{x}$ represents the average concentration of all samples, y_i represents the optical rotation measured for each sample, and $\bar{y}$ represents the average optical activity of all sucrose molecules. According to this, it is found that the slope of the line of best fit is $67.2°$ mL g^{-1}. Next, the y-intercept of the graph (b) will be calculated:

$$b = \bar{y} - m\bar{x}$$

According to this, it is found that:

$$b = 0.01°$$

Next, uncertainty values for both slope and y-intercept will be calculated. To calculate the uncertainty in the slope, the standard error of the slope was determined using the following formula:

$$Uncertainty\ in\ Slope = \sqrt{\frac{\sum(y_i - mx_i - b)^2}{(n-2)\sum(x_i - \bar{x})^2}}$$

The new introduced symbol, *n*, represents the number of trials done. According to this, it is found that:

$$\Delta m = 2.0°\mathrm{mL\ g^{-1}}$$

The uncertainty of the y-intercept (b) is found with the given formula:

$$\Delta b = \Delta m \sqrt{\frac{\sum x_i^2}{n}}$$

Substituting the values:

$$\Delta b = 0.5°$$

Therefore, the formula of the line of best fit is given below:

$$\theta = (67 \pm 2)x + (0.0 \pm 0.5)$$

This equation indicates that for each unit increase in concentration (g/mL), the optical rotation angle increases by 67 degrees, on average. The relatively low uncertainty of the slope, ±2, suggests that the measured data points are closely aligned with the trend, highlighting the precision and reliability of the experimental results. The strong linearity of the data further supports the conclusion that the optical rotation angle is directly proportional to the concentration of the solution and that the experimental setup successfully captures this relationship with minimal random error. The calculated slope and its associated uncertainty provide a solid basis for understanding the quantitative relationship between concentration and optical rotation angle in this context.

Furthermore, the fact that the y-intercept is rounded to 0.0 suggests that there were effectively no major systematic errors which have influenced the measurements of the experiment.

5. Conclusion

The The aim of this investigation was to answer the research question: *To What Extent Does the Concentration (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 g/mL) of Sucrose-Water Solution Change the Final Polarization Angle (in Degrees) of the 650 nm Light?* The results of the experiment indicates that the concentration of sucrose is directly proportional to the optical rotation angle of the solution. The data supported by graphical trends and statistical measures such as Pearson's correlation coefficient and the uncertainty of the slope suggests a linear relationship consistent with the theoretical predictions based on Biot's law and the initial hypothesis. It is also important to point out that the slope of the graph, 67.2 is significantly close to the specific rotation of sucrose (for 589 nanometer of wavelength) which is +66.5° around room temperature. This value represents the optical rotation angle per gram per milliliter of solution when measured in a 1 dm long path. This furthermore shows that the experiment is consistent with the state-of-the-art physics and literature data (Elwakeel et al. 2019).

The standard deviation values for every trial are lower than 1, this suggests that there is less fluctuations caused by random errors. The minor variations for the optical rotations might be caused by the methodological errors such as the refraction of laser beam caused by the strech film and random errors such as the misalignment of polarizers for each trial. Furthermore, even though the percentage uncertainty for the optical rotation angle measurements were relatively low, a more precise protractor can be used to further increase the precision of the readings. The use of automated polarimeters and more advanced optical alignment tools could increase the reliability of future investigations as well.

To sum up, the results of this investigation suggests that the optical rotation angle increases proportionally with sucrose concentration which supports the theoretical knowledge on the optical activity. This experiment aligns with the literature and further creates a baseline for further exploration of the effects of light interactions with optically active substances.

6. Evaluation

6.1. Strengths

The main strength of this investigation is the fact that the experimental set up is simple and easy to prepare which reduced the possibility for systematic errors and allowed for higher replicability. The experiment does not require highly specialized, expensive equipment or a complicated mechanism. The laser source and polarizing films were the part of the polarimeter so they were mounted with parallel alignment on the rail. The photometer was securely taped to the rail and the cylinder tube was mounted on a horizontal groove. This simplicity avoids possible errors caused by complex setup and makes the experiment more accessible and applicable for any sort of laboratory conditions and equipments. Moreover, the low likelihood of systematic errors further increases the reliability of the results. The experiment minimizes potential sources of bias when the experiment is conducted with properly calibrated equipment and under controlled environmental conditions.

Furthermore, the solution used in the experiment, sucrose-water solution, is a simple solution which shows low chemical reactivity and accessible. This makes the experiment even more accessible and the simplicity of the solution preparation process reduces possible errors in the concentration levels.

This investigation demonstrates the direct relationship between sucrose concentration and optical rotation which aligns with the Biot's Law. The findings support the literature knowledge which suggests that optical rotation increases proportionally with concentration. The relatively low y-intercept ($0.0° \pm 0.5°$) indicates minimal external influences on the results and therefore low random errors. The low standard deviation in all concentration levels suggests that random errors were minimal which further shows the reliability of the data. Conducting high number of trials further allowed minimizing the effect of random errors in the experiment.

6.2. Weaknesses and Limitations

The experiment was conducted using a 650-nanometer wavelength, which limited the availability of relevant literature. The most relevant investigations in terms of the wavelength were done with light with 589 nanometers. Although the difference is relatively low, it still restricts calculating standard error in order to assess the presence of systematic errors. However, it is important to note that the findings of this investigation were close to the literature results for 589-nanometers, indicating that there were no major systematic errors.

Even though standard error could not be assessed because of the lack of literature, there are some possible sources of systematic error. One significant systematic error was the use of a stretch film as a light-permitting layer. The inevitable refraction of the laser light caused light scattering, diverting it from the second polar filter and the photometer, leading to inaccurate intensity readings. A possible solution to this issue would be replacing the stretch film with a thin glass layer, which would allow light to pass through without significant refraction or distortion while keeping the tube impermeable.

Another possible source of systematic error was the alignment of the photometer. Due to refraction of light inside the solution, the laser beam got scattered and did not directly hit the photometer. As the polarizing filter was rotated, the photometer sometimes detected an incorrect maximum brightness based on refraction patterns rather than the actual polarization angle. A precise alignment mechanism or a collecting lens could be used to concentrate all laser beams to a single point which would allow for accurate measurements while avoiding destructive interference.

The standard deviation for each concentration level were under 1 which suggests a relatively low number of random errors. This shows that there were no major random errors and the measurements were precise, however, the minor random errors should be assessed and discussed in order to fully evaluate the weaknesses of this investigation. One major issue was low reaction time when rotating the second polarizing filter while observing photometer readings. This led to difficulties in precisely identifying the angle at which the highest brightness was observed, introducing inconsistencies in angle measurements. A solution to this issue would be using a precise digital system to automatically locate and record the polarization angle where the minimum brightness occurs to reduce variability caused by human error and further improving measurement accuracy.

6.3. Further Research

While the investigation succeeded in answering the research question, it also raised additional questions. For example, would the observed relationship hold true across different isomers of sucrose such as trehaluose and turanose or even other sugar molecules such as glucose, lactose and maltose. These extensions could serve as a foundation for future research. Additionally, the relation between the temperature of the solution and the optical rotation angle could be investigated for further explore the phenomena of optical activity.

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