A mobile application that uses fiber optics to test the polarimetry of various substances

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ABSTRACT

In this work, a 633 nm laser is used. The light beam passes through a fixed linear polarizer before hitting a rectangular container where the solution is located. Different solutions were used, including distilled water, standard sugar, refined sugar and brown sugar. The beam finally travels to a polarizer that can rotate on its own axis and then reaches an optical fiber connector where the signal is processed. The rotating polarizer has a gear configuration and a stepper motor controlled by an ESP32 microprocessor and an external power source, allowing precise control of the polarizer's rotation by the microprocessor. The resulting signal is captured in optical fiber by means of a photodiode and sent to the microprocessor where it is processed and then sent to a mobile device, where it is stored and processed for better understanding.

The results of the power obtained when passing a polarized beam through different solutions at different concentrations are analyzed, and a correlation between the amount of sugar contamination and the received power was determinate.

The application is based on Angular framework and has a settings tab where the current angle of the polarizer is displayed, buttons to start or stop a measurement, as well as text boxes where parameters for measurements can be configured, such as the direction of rotation and the angular speed of the polarizer. It has various functionalities for graphing the stored data and comparing them, as well as some visualization tools. It also allows viewing a time series with real-time measurements and a section to manage stored data.

Keywords: Mobile Application, Polarimetry, Fiber optic, ESP32, Cloud, IoT, Automatization, Sugar.

1. INTRODUCTION

Precision in measuring the concentration of substances in solutions is crucial across various scientific and industrial fields, such as quality control in food and beverage production and drug formulation in the pharmaceutical industry. Traditional methods, including spectroscopy, chromatography, and reflectometry, can be expensive, complex, and time-consuming. In this context, studying optical properties, such as light polarization, presents a promising alternative. Substances like sugar can rotate the plane of polarized light—a phenomenon known as optical activity—which can be correlated with their concentration in a solution [1,2].

Visible light typically oscillates in multiple directions perpendicular to the direction of propagation. Light is said to be polarized when its waves are restricted to oscillate in a single plane. This can occur through polarizing filters [1] that only allow light whose oscillation is aligned with the filter to pass through (see Figure 1).

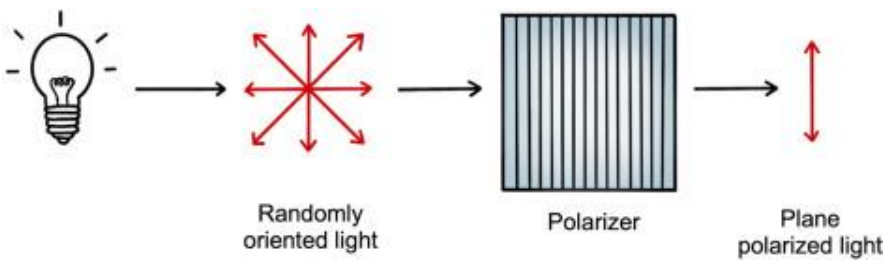

Figure 1 Functioning of a polarizer

Optical activity is the ability of a substance to rotate the plane of polarized light that passes through it. This phenomenon occurs due to the relationship with the chirality of the molecules. Chirality is a property of molecules that have an asymmetric structure, making them non-superimposable with their mirror image. When polarized light passes through a solution containing a chiral substance, the molecules in the substance interact with the light in a way that rotates the plane of polarization. The direction and angle of this rotation depend on the nature of the molecules and the concentration of the substance in the solution [3].

Understanding and applying optical activity in practical scenarios can significantly enhance the efficiency and accuracy of concentration measurements. By leveraging the simplicity and effectiveness of polarization-based methods, this study aims to provide a modern approach for measuring and analyzing sugar concentrations in various solutions.

2. METHODS

The experiment was designed to assess how varying sugar concentrations and types influence the polarization of light, providing insights into the utility of polarimetric techniques for concentration measurement. It was conducted using a setup that included the following components:

-Laser: A 633 nm wavelength laser was used as the light source. The laser emitted a beam of coherent light necessary for polarimetric measurements.

-Polarizers: Two polarizers were employed in the experiment. The first polarizer was fixed, while the second polarizer was mounted on a stepper motor allowing it to rotate.

-Container: Solutions of varying sugar concentrations were placed in a container through which the laser beam passed. The concentrations tested included 40%, 50%, 60%, and 70%, with distilled water used as a reference. The container has 0.125dm of optical path.

-Stepper Motor and ESP32: The stepper motor, controlled by an ESP32 microcontroller, rotated the second polarizer with high precision. A system of 3D-printed gears was employed to achieve the desired rotational movement. Specifically, a small gear made six complete revolutions for every single revolution of the larger gear.

-Light Condenser: Positioned after the second polarizer, the light condenser focused the beam onto the photodiode.

-Photodiode: A FDSP625 photodiode was used. It was implemented in a reverse-biased circuit. The photodiode was used to measure the intensity of light passing through the setup. This measurement was recorded for each degree of rotation of the second polarizer.

-Data Analysis Software: Software was utilized to process and analyze the recorded data, including calibration, data fitting, and error analysis.

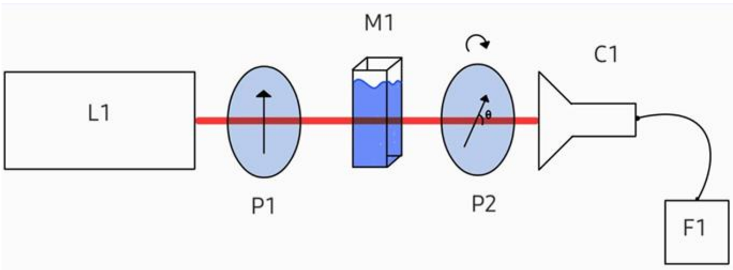

Figure 2. Experimental Setup. L1: 633 nm Laser, P1: Polarizer, M1: Sample Container, P2: Polarizer/Analyzer, C1: Light Collector, F1: Photodiode

For the preparation of the samples, three types of sugar were selected: standard sugar, refined sugar, and brown sugar. An initial mixture with a 30% sugar concentration was prepared for each type. The mixture was heated on an electric stove at a very low power setting and stirred vigorously until all the sugar was dissolved.

Subsequent samples were prepared by adjusting the concentration through evaporation. For each target concentration (40%, 50%, 60%, and 70%), the amount of water to be evaporated was calculated. After reaching the desired concentration, a small sample was taken. This process was repeated for each concentration level. Finally, all samples were allowed to rest for 24 hours to ensure they reached room temperature before measurements were taken. This was done to ensure that temperature variations did not affect the measurements [4]. This method ensures accuracy by accounting for factors such as water evaporation and sample loss during preparation.

3. PROGRAM DESCRIPTION

3.1 Project Name

PolarView

3.2 Objective

To develop an automated polarimetry measurement tool via IoT, which includes functionalities for sample measurement, data management, data visualization, and microcontroller parameter configuration.

3.3 Functional Scope

To achieve the functionalities outlined in the objective, four modules were created. A configuration module to manage the microcontroller parameters, another module for real-time sample measurement, a third module for handling and grouping the received data, and finally, a data visualization module where the phase shift can be analyzed.

3.3.1 Configuration Module

In this module, the initial parameters of the microcontroller are obtained, including a specific measurement value and the device name. The user can modify the parameters for Revolutions per Minute, Degrees per Turn, Laps to Rotate, and Points per Degree as needed. The description of each parameter and button is listed below, referring to figure 3:

-Sensor Value: This field receives the value obtained from measuring the laser power. For this project, the raw ADC value from the ESP32, ranging from 0 to 4095, was used.

-Degree: This field receives the sexagesimal degree at which the measurement was taken.

-Device ID: This is a string that represents the ID with which the device was registered in Azure IoT Hub.

-Revolutions per Minute: This field can be modified by the user; represents the revolutions per minute that the motor will perform during rotation. In this case, the motor used only accepts values from 0 to 17.

-Degrees per Turn: This field can be modified by the user; represents the sexagesimal degrees the motor will move when pressing one of the buttons (<-) or (->).

-Laps to Rotate: This field can be modified by the user; represents the number of laps the motor will perform when pressing the “Rotate” button and the “Start” button of the measurement module (see figure 4).

-Points per Degree: This field can be modified by the user; represents the number of readings the microcontroller will send to the application per sexagesimal degree during measurements.

-Button (<-): Performs a small turn to the left based on the parameter adjusted in “Degrees per Turn.”

-Button “Rotate”: Performs one or more laps based on the parameter “Laps to Rotate.”

-Button (->): Performs a small turn to the right based on the parameter adjusted in “Degrees per Turn.”

-Button “Upload”: Sends an update of the parameters to the microcontroller. It is essential to press this button every time changes to the parameters are made. The parameters revert to their initial configuration each time the device is restarted.

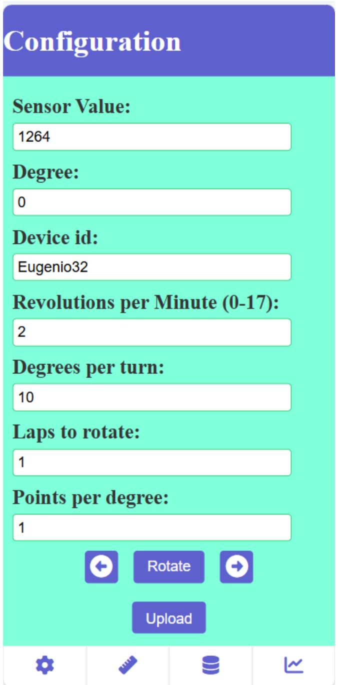

Figure 3. Configuration Module with standard setup.

3.3.2 Measurement Module

Within this module, real-time measurements of samples are performed. You can define the name under which the graph will be saved. Below is the description of each button in FIGURAMED:

-Button "Start": This button initiates a new measurement with the parameters defined for "Laps to Rotate" and "Points per Degree" (see FIGURACONFIG).

-Button "Stop": Stops the readings sent by the microcontroller, although the motor will continue to rotate until it completes the laps defined in its configuration.

-Button "Reset": Clears all previously graphed data. It does not affect the motor, or the readings sent by the microcontroller.

-Button "Save": Saves the graph in the database with the name defined in the "Plot Name:" field.

-Button "Free Mode": Allows the microcontroller to send readings without moving the motor. Readings continue until the user clicks the "Free Mode" button again. This option is ideal for the initial calibration of the laser to ensure proper alignment.

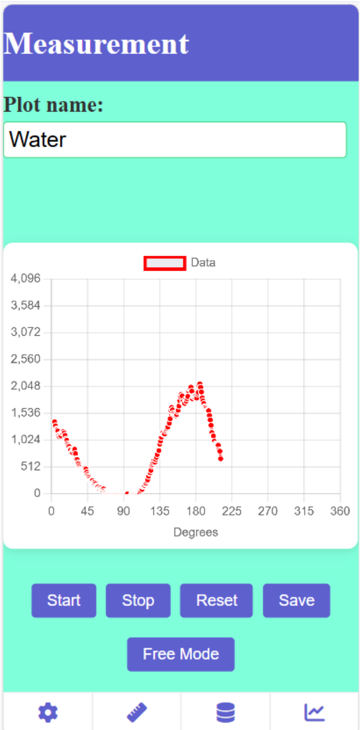

Figure 4. Measurement Module measuring real time data.

3.3.3 Management Module

In this module, the obtained graphs are managed. It includes options to delete saved graphs and to create a group of graphs. Each group has a name and a reference graph to be used in the visualization module. You can select as many graphs as needed, and they will be displayed within the application (see figure 5).

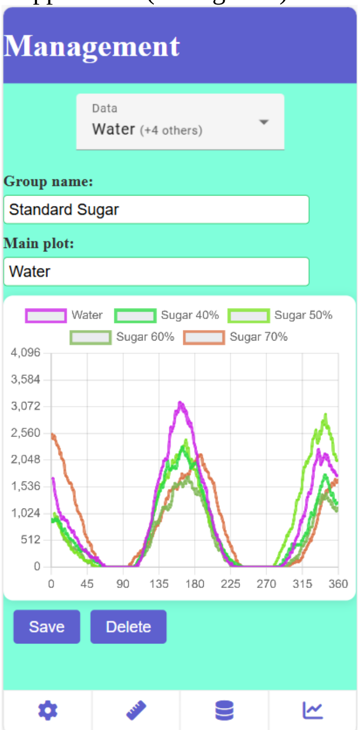

Figure 5. Management Module with a group of Standard Sugar.

3.3.4 Visualization Module

In the visualization module, tools are provided to better understand the obtained data. The first step is to select a group created in the administration module (see figure 5), and the graphs of that group will be loaded (see figure 6). The "Fit" button adjusts the graphs to a sinusoidal function using the Levenberg-Marquardt method (see figure 7).

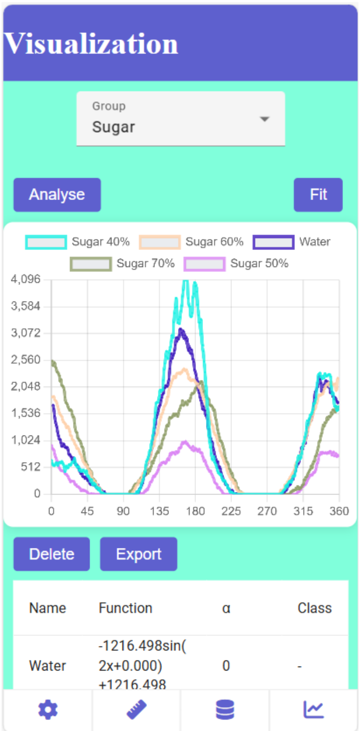

Figure 6. Visualization Module with raw data.

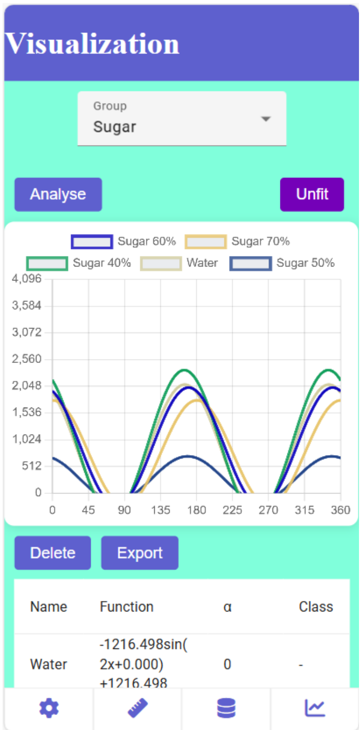

Figure 7. Visualization Module with fit data.

On the other hand, the "Analyse" button normalizes the data with respect the reference (see figure 8) and loads a table with the name, mathematical function, phase shift relative to the reference, and the measured classification of each graph in the group (see figure 9). Additionally, a button is available to delete a group and to download the graphs in CSV format.

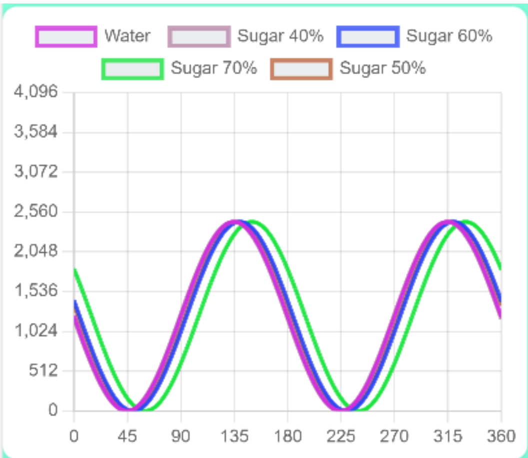

Figure 8. Normalized Group

Name	Function	α	Class
Water	-1216.498sin(2x+0.000) +1216.498	0	-
Sugar 40%	-1216.498sin(2x+0.023) +1216.498	1.307	40%
Sugar 60%	-1216.498sin(2x-0.165) +1216.498	9.442	60%
Sugar 70%	-1216.498sin(2x-0.522) +1216.498	29.884	70%
Sugar 50%	-1216.498sin(2x-0.125) +1216.498	7.148	50%

Figure 9. Table with the phase shift and classification.

3.4 Technical Scope

The application architecture is based on a distributed client-server infrastructure that leverages the power of Azure cloud and IoT technology (see figure 10). The data flow starts with the capture of light polarization through a photodiode connected to the ESP32 and ends on the user's mobile device.

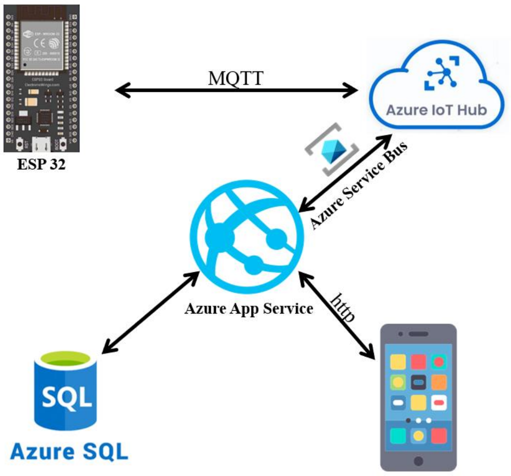

Figure 10. Architecture of the project.

For the development of the application, a series of technologies and services have been chosen to ensure an efficient and versatile solution. Each technical component used is described in detail below:

Mobile Application:

- Framework: Angular 16.1. The choice of Angular is due to its ability to create hybrid web-mobile applications, providing versatility and compatibility with various devices and platforms.

Backend Server:

- Framework: Spring Boot 3.2.5. This framework has been employed to implement the backend server, leveraging its robust capabilities for application development.
- Language: Java 17. The choice of Java 17 ensures compatibility with the latest language features and improvements in performance and security.
- Hosting: Azure App Service. The backend is hosted on Azure App Service, providing a managed and scalable platform for deploying and maintaining the application.

Microcontroller:

- Model: ESP32. The ESP32 was selected for its cost-benefit ratio and its capability to integrate with necessary tools and protocols for developing an IoT device. This microcontroller includes advanced functionalities and support for wireless connectivity, making it ideal for real-time data capture applications.

IoT Communication:

- Device Management Service: Azure IoT Hub. Azure IoT Hub is used to manage communication between the ESP32 and the backend server, facilitating data reception and routing.
- Messaging Service: Azure Service Bus. Azure Service Bus is used for messaging between the IoT Hub and the backend, providing an additional layer of asynchronous and decoupled communication that ensures message delivery and processing.

Database:

- Service: Azure SQL Database. A SQL Server database hosted on Azure SQL Database is used to efficiently store and manage the processed data. The data is stored in the database based on the entity-relationship diagram shown in Figure 11.

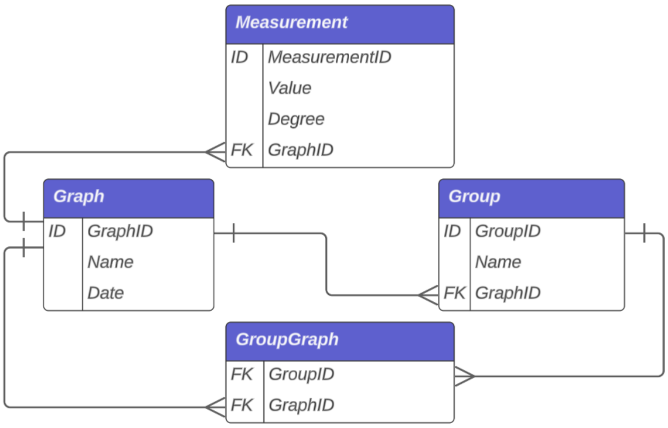

Figure 11. Entity-Relationship diagram.

3.5 Components

The table 1 outlines the components and programs of the project, providing a clear structure of the various modules involved. Each component is designed to address specific aspects of the project, from configuration to data visualization. The table includes the name of each module and the associated programs.

Table 1. List of the components of each module.

PolarView
Configuration
Retrieve the Current Configuration Data from the ESP32
Upload Changes in Configuration
Rotate the polarizer
Measurement
Manage Measurement (Start, Stop and reset Measurement)
Save Measurement
Free mode
Management
Obtain Stored Graphs
Display Graphs
Save Group
Delete Graph
Visualization
Obtain Stored Groups
Display Group
Fit Graphs of the Group
Normalize Graphs
Display Analyzed data
Graph Classification

3.6 Results

A software was developed that accurately measured over 60 time series, allowing for automatic adjustment of the experimental design and efficient data analysis. The incorporation of cloud technologies has also provided a scalable and cost-effective solution, making it straightforward to apply this technology to significantly larger systems.
Previously, the manual measurement process required approximately 15 minutes to perform only 36 measurements per round. However, thanks to the implementation of an automated system based on a mobile application and IoT technology,

this time has been drastically reduced to just 3 minutes with 360 measurements per round. Moreover, configuration options allow for a time reduction of up to 30 seconds with more than 3,600 measurements per round.
It is now much easier to control, monitor, and store measurements from anywhere in the world via a smartphone, allowing for high accessibility and flexibility. Additionally, the automation of the process has significantly increased the accuracy of measurements, minimized human errors and ensured the consistency of the collected data.

4. DATA

For data collection during the experiment, the Measurement module of the application was used (see Figure N). Once the data is received by the photodiode, the ESP32 sends the readings to the application, where they are plotted in real-time. The photodiode is implemented in a reverse-biased circuit, which includes a potentiometer that can be adjusted to refine the device's sensitivity. Due to variations in power when creating denser mixtures and the slight misalignment caused each time the cell changed substances, it was decided to take the raw ADC value from the ESP32 rather than convert it to a voltage equivalent, as the dimensions between the same graphs may differ due to sensitivity adjustments. Additionally, during measurements, graphs meeting the following two criteria were discarded:
-Several maximum points exceed the ESP32's resolution of 4095. These graphs had very high sensitivity, resulting in incomplete sinusoids (see Figure 12).
-A connection issue occurred during data transmission from the ESP32 to the device. This could cause the order of the points to be altered (see Figure 13), resulting in unreliable data.

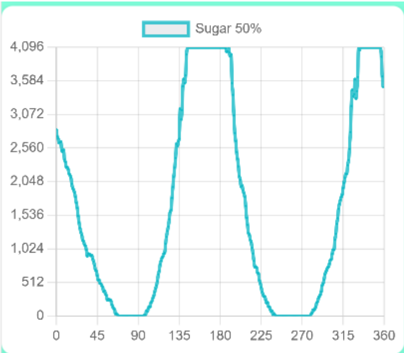

Figure 12. Incomplete sinusoidal wave at maximum points.

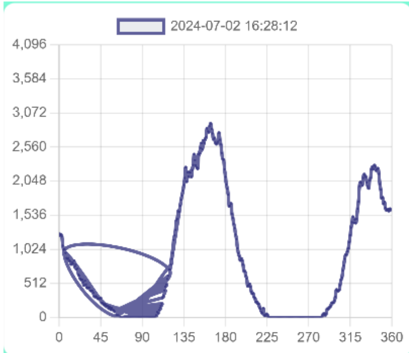

Figure 13. Data order lost due to internet disconnection.

To analyze the samples, it was decided to measure the same sample multiple times (see Figure N), ensuring a minimum of 5 measurements for each of the 4 concentrations (40%, 50%, 60%, 70%) with the 3 types of sugar (refined, standard, brown). This was done to evaluate the efficiency of the software, the repeatability of the data, and to obtain training data for the classification algorithm.

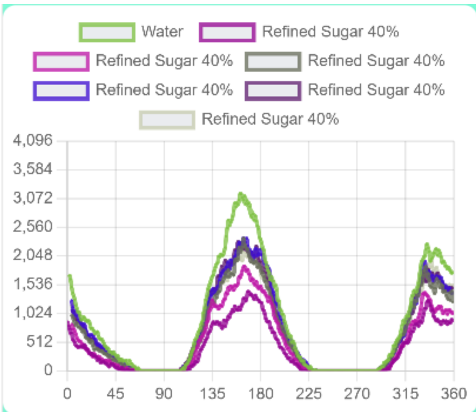

Figure 14. Group with 6 different plots of Refined Sugar at 40% of concentration of sugar.

To classify the sugar concentration of new samples, it was decided to use only the standard sugar data for training. This approach aimed to study the differences or similarities with respect to the other two types of sugar. The algorithm chosen was the K-Nearest Neighbors (KNN). To implement it, the 4 most similar phase shifts for each concentration percentage

(40%, 50%, 60%, 70%) of standard sugar were obtained in relation to the distilled water sample. The results of this process are shown in Table 2.

Table 2. Phase shifts obtained of each concentration with respect distilled water.

Concentration of Standard Sugar	Phase shifts
40%	[4.281,1.878,1.519,1.535]
50%	[6.258,6.988,8.53,8.978]
60%	[9.7, 9.708, 10.773, 10.668]
70%	[18.126, 16.171,22.353, 17.062]

5. RESULTS

Standard Sugar

Standard sugar samples were the most used and measured among these three types. This sugar was used as a reference for the classification algorithm due to its high usage in the industry. Additionally, the increase in phase shift at higher sugar concentrations was clearly observed (see Table 3), and its high level of purity allowed for highly repeatable data, achieving an average standard deviation of 1.36 degrees.

Table 3. Mean and standard deviation of the samples for each concentration percentage of standard sugar.

Percentage	Mean	Standard Deviation
40%	2.104	1.103
50%	7.5804	1.014
60%	10.0582	0.5501
70%	17.5072	2.8076

Brown Sugar

The results obtained with brown sugar (see Table 4) were not satisfactory, as no conclusive data showing its optical activity could be obtained. It appears that the impurity level of this sugar affects not only the purity but also the optical activity, although further studies are required to confirm this claim. On the other hand, it also seems that the designed polarimeter is quite sensitive to sample contamination, as an average standard deviation of 4.124 degrees was obtained, which is higher than that of the other two types, although it is worth noting that it was especially high only at the 60% concentration.

Table 4. Mean and standard deviation of the samples for each concentration percentage of brown sugar.

Percentage	Mean	Standard Deviation
40%	16.0792	4.291
50%	20.0218	1.4058
60%	15.1125	9.0653
70%	19.5492	1.7342

Refined Sugar

Table 5 illustrates the increase in phase shift as the sugar concentration percentage rises. Among the types of sugar tested, refined sugar showed the lowest standard deviation, averaging 0.69 degrees, which indicates a high level of repeatability in the results. This high repeatability is likely due to the refined sugar's superior purity.

Table 5. Mean and standard deviation of the samples for each concentration percentage of refined sugar.

Percentage	Mean	Standard Deviation
40%	1.335	0.1547
50%	14.0847	1.339
60%	17.3584	0.7361
70%	19.8642	0.5546

Classification algorithm

To test the classification algorithm, it was decided to use some measurements from each percentage of sugar and to include both refined sugar and standard sugar. The algorithm successfully classified all the standard sugar samples correctly; however, it did not accurately classify those of 50% and 60% refined sugar, resulting in an accuracy of 75%. This result can be observed by analyzing the means of the 50% and 60% concentrations (see table 3 and table 5) of both sugars, as they differ by a few units from each other.

6. CONCLUSION

The development of the software and its integration with IoT and cloud technologies have led to a significant improvement in the efficiency of the measurement process. Automation has drastically reduced the time required to perform measurements, increasing analytical capacity and reducing human errors. The developed technological solution provides a scalable and effective tool for applications in larger and more complex systems.

Regarding the samples, the high repeatability in the measurements of standard sugar, with an average standard deviation of 1.36 degrees, underscores the effectiveness of the system in obtaining consistent and reliable data. The low standard deviation observed in refined sugar (0.69 degrees) confirms that the purity of the sugar has a positive impact on measurement accuracy. On the other hand, the results with brown sugar were inconclusive and revealed a high standard deviation (4.124 degrees). It appears that brown sugar, due to its higher level of impurities, presents significant challenges in obtaining precise and consistent measurements. These results suggest the need for further studies to understand how impurities affect optical activity and measurement accuracy.

Finally, the classification algorithm proved effective in identifying standard sugar samples but struggled to correctly classify 50% and 60% refined sugar samples, achieving an overall accuracy of 75%.

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