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Research paper

Development of a Low-Cost Colorimeter Based on LED Light Sources

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Abstract

The spectrophotometric and colorimetric methods are the most widely used methods in various scientific fields, such as physics, materials science, chemistry, biochemistry, and molecular biology. They are based on an application of the Beer and Lambert law. However, the currently available instruments for spectrophotometry and colorimetry mostly use a light source, grating disc, and a silicon photocell. Unfortunately, the use of all these components in combination increases the device costs. The proposed system was developed with a low-cost material, a light emitting diodes (LED) as the light source, and an RGB Sensor. Two types of LEDs having different wavelengths were selected for each solution. The USB serial (through a USB cable) and wireless Bluetooth (the Bluetooth module) were the two alternative communication methods used to control the system and view the results. The measurement range was 0.02 to 30.0 ppm. The colorimeter was successfully used to detect nitrate and fluoride concentrations with an average R^2 of 0.99 when compared with the concentrations obtained by using a spectrophotometer (Optizen POP QX, Mecasys, South Korea). The material cost was less than $75.

Keywords: *Microcontroller, Spectrophotometric, Low-cost Colorimeter, Light Emitting Diodes.*

1. Introduction

Light emitting diodes (LEDs) were first applied for chemical analysis three decades ago [1]. LEDs are often used as alternative light sources to conventional incandescent lamps due to their small size, longer life time, higher brightness, high stability, low heat production, low power consumption, low cost, flexible configuration, enhanced special purity, and scope of spectral range (those with a spectral range of 210–1550 nm are commercially available). Thus, LEDs are often preferred as the radiation sources for photometric detection in analytical chemistry, especially in the near infrared to UV range. The use of LEDs, which mostly emit a narrow wavelength, eliminates the need for a monochromator and thus simplifies the creation of devices [2, 3].

The development of LED–based analytical devices was first presented by Barnes in 1970, Anfalt et al. in 1976, Betteridge et al. in 1978, Johnson et al. in 1983, and Trozanowicz in 1984 (as stated by Dasgupta et al. [2]. Most of the reported devices based on LEDs are low-cost alternatives to the commercial instruments. Since the emergence of the use of LEDs in analytical devices, more devices have been developed. These include instruments for absorbance measurements in cuvettes, flow injection detection systems, HPLC detection, and capillary electrophoresis. Commercial products are also available either in the form of portable or bench-top devices [4].

Commercial spectrophotometers usually employ prisms or diffraction grids as radiation dispersers to divide light into a spectrum for “spectra-scanning” purposes. Consequently, most spectrophotometers are bulky and expensive because of their optical assemblies [5]. Furthermore, computers are used to acquire and store the data needed to control the spectrophotometers. As they require computers, traditional spectrophotometers are rarely used for outdoor measurement applications. For a sample whose composition has been determined, a narrow-band of incident light, rather than a wide range of wavelengths, is needed to determine the concentration of the sample. To induce photon absorption and transmission, the main wavelength of the narrow-band light and its peak energy must match the specific characteristics under consideration [6].

In this article, a low-cost colorimeter based on the LED light sources is presented for the preliminary analysis of a solution. Two LED light sources with different wavelengths were attached facing a cuvette in a holder while an RGB sensor was set up in the opposite direction toward the cuvette as the detector. The selected LED wavelengths were dependent on the specific solutions that were placed in the cuvette. The small effective bandwidth of an LED and its low power consumption make it adequate as a monochromatic light source and a substitute for the sensitive optical components in traditional spectrophotometers. Thus, the built device is referred to as a colorimeter rather than a spectrophotometer.

2. Method and Experiment

Device development was divided into two parts: hardware and software configuration, and use of the colorimetric method.

2.1. Hardware and Software Configuration

The configuration of the hardware consisted of input, output, a processing unit, a communication protocol, and a power supply, as shown in Figure 1.

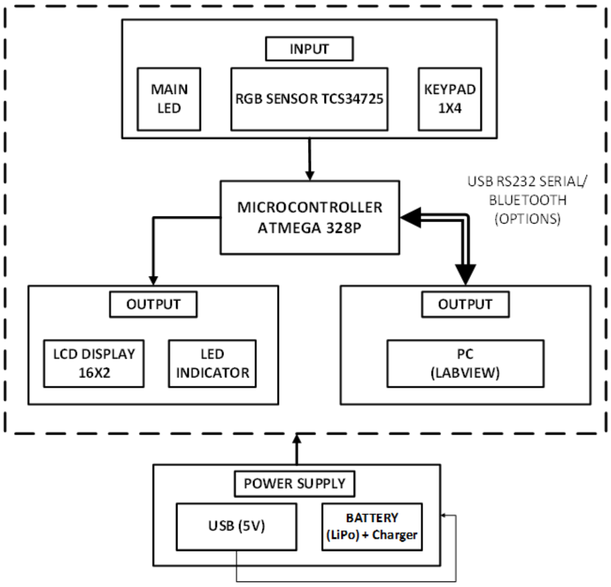

Fig.1: Block diagram of the low-cost colorimeter system.

The system was composed of a set of input modules (LED, RGB Sensor, and keypad), a processing unit (microcontroller Atmega328P), an output module (LCD display, indicator LED, and interface software), and a power and communication module (RS232, Bluetooth, Lipo battery, and charger). A microcontroller was installed and connected to control the light sources and the detector. The main program was installed in the microcontroller. An interface program was also designed to communicate with the device using both the Bluetooth and the RS232 protocol, to display data and perform analyses. The installed battery package with built in chargers and a Bluetooth communication protocol for the device enable portable measurement in the field. Without a complicated optical design, this colorimeter has the advantages of being lightweight and inexpensive for basic industrial inspection or as an educational instrument in experimental courses on spectrophotometric/colorimetric devices. The 3D Case was designed in SOLIDWORKS 2018 and printed using a black PLA material. Figures 2 and 3 show the developed device.

Fig. 2: Appearance of the built colorimeter device (top view)

Fig. 3: Appearance of the built colorimeter device (front view)

2.2. Colorimetric Method

Colorimetric analysis is a method of determining the concentration of a chemical element or chemical compound in a solution with the aid of a color reagent. Thus, for chemical analysis, a color reagent must be added to detect changes in the solution's color intensity. Two kinds of chemical substances were selected for this study.

2.2.1. Fluoride and SPADNS Method

Fluoride is an important chemical substance that should be present in water. In excess amounts, it will cause dental fluorosis, while its unavailability can cause dental caries. It has been reported that ideally, a fluoride amount of 0.8–1.0 mg/L is substantial in drinking water.

In the SPADNS colorimetric method, a preformed color is bleached by the fluoride ion. The preformed color is formed when zirconium is added to SPADNS dye, depending upon the method used. The intensity of the color produced will be reduced if the amount of zirconium present is decreased. The fluoride ion combines with the zirconium ion to form a stable complex, ZrF. The concentration of the complex, which is proportional to the fluoride concentration, tends to bleach the dye, which therefore becomes progressively lighter as the fluoride concentration increases.

2.2.2. Nitrate and Chromo-Tropic Acid Method

In surface water, nitrates generally occur in small quantities, but their concentrations are higher in some groundwater samples. It has been demonstrated that fresh wastewater contains trace amounts, but in the effluent of nitrifying biological treatment plants, the concentration of nitrates may be as high as 30 mg/L. In high concentrations, nitrates can cause an illness known as methemoglobinemia in infants.

The chromotropic acid high range nitrate method involves the reaction of the nitrate ion in a strong acid medium with chromotropic acid. The final reaction mixture is contained in a screw-capped vial. This method can be used to detect 0.2–30 mg/L of nitrate ions. In the chromotropic acid test, a sample is added to a vial containing sulfuric acid. This sample/sulfuric acid mixture is used to zero the spectrophotometer. Chromotropic acid is then added with a powder reagent. Two moles of nitrate react with one mole of chromotropic acid to form a yellow reaction product within 10 min, which exhibits maximum absorbance at 410 nm and is stable for 48 h (see Figure 4).

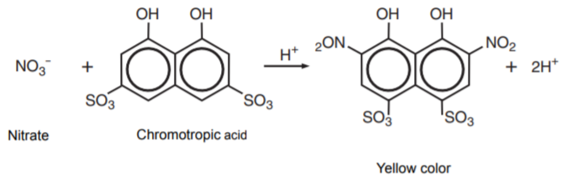

Fig.4: Reaction of the nitrate ion with chromotropic acid

3. Results and Discussion

3.1. Colorimeter Specifications

After meeting the initial specification design, the overall build cost of the colorimeter with all its components was $72. Figure 5 shows the circuit of the colorimeter when the top cover was removed.

Fig. 5: The appearance of the colorimeter circuit

A colorimeter can be used to test and estimate the concentrations of several kinds of chemical substances. Two kinds of inorganic chemical substances in water were selected owing to their significant effects and appearance in ground/surface water. A fluoride solution with the SPADNS reagent and a nitrate solution with a chromotropic acid reagent were selected to examine the performance of the colorimeter in estimating the concentration of a chemical substances. Table 1 shows the brief specifications of the built colorimeter.

Table 1: Specifications of the built colorimeter

Parameters	**Specification**
Manufacturing Cost	**< US$ 75**
Chemical Substances to be observed	Fluoride LR, Nitrate HR,
Method	Between two kinds of chemical substances:
	Fluoride: SPADNS,
	Nitrate: Chromotropic Acid
Parameter Measurement Range	Nitrate 0.2–30 mg/L
	Fluoride 0.05–2.00 mg/L
Absorbance Range	-1 to 3 AU
Accuracy	0.05 ppm
Resolution	0.05 ppm
Wavelength	570 nm and 410 nm.

The colorimeter was designed and was successfully able to detect the two chemical substances, i.e., fluoride and nitrate, with a 570 nm and 410 nm LED, respectively, in the absorbance range from -1 to +3 absorbance units.

3.2. Colorimeter Software

The software for the colorimeter consisted of a data collection part that was installed into the ATMEGA328P microcontroller to control LEDs and the sensor, and an interface part that was used to retrieve and display the data. This PC program was built using LABVIEW 2018, as shown in Figure 6.

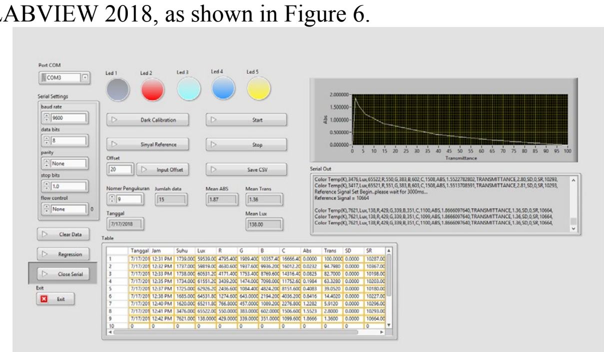

Fig. 6: Screen shot of PC interface software

3.3. Colorimeter Measurement Performance

3.3.1. Fluoride Measurement

An experiment was performed to measure the concentrations of different fluoride solutions, which were prepared with a sodium fluoride (MW = 41.98817) standard solution of 1000 mg/L diluted with distilled water. The following different concentrations were prepared: 0.02, 0.05, 0.10, 0.20, 0.50, 1.00, and 2.00 mg/L. A sample of each solution was poured into a reaction tube containing the SPADNS reagent to form a colorless solution to obtain absorbance and transmittance data utilizing a 570 nm LED. The obtained values were compared with those obtained with the commercial spectrophotometer Optizen QX.
The absorbance values showed that the colorimeter with a 570 nm LED was able to detect fluoride concentrations from as low as 0.05 mg/L to as high as 2.00 mg/L. The R2 of correlation coefficient between the absorbance (y-axis) of the colorimeter device and the concentration(x-axis) was 0.9974, while the R2 of the correlation of the Optizen QX Spectrophotometer was 0.9984, as shown in Figure 7.

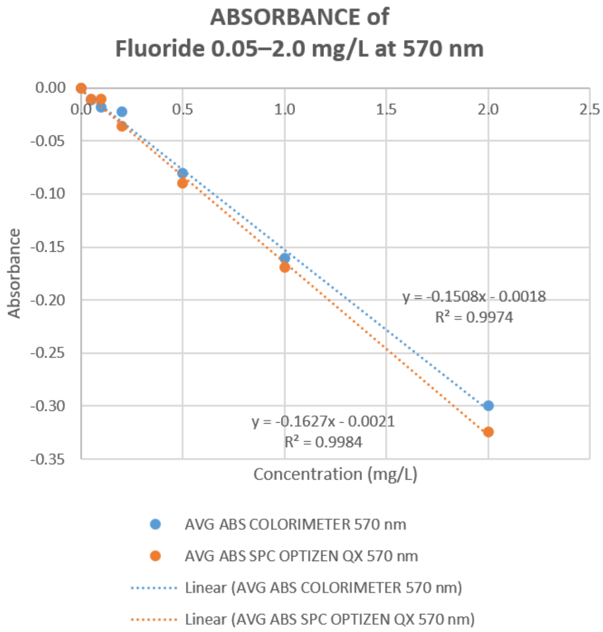

Fig. 7: Absorbance of fluoride measured with the colorimeter at 570 nm and compared with that of the commercial spectrophotometer.

3.3.2. Nitrate Measurement

A second experiment was performed to measure the absorbance of a nitrate solution, which consisted of a sodium nitrate (MW = 84.9947) standard solution of 1000 mg/L diluted with distilled water to achieve the following concentrations: 0.2, 1.0, 3.0, 5.0, 10.0, 20.0, and 30.0 mg/L. The nitrate solutions were each poured into a reaction tube containing a chromotropic reagent for the nitrate ion (HR) to get the absorbance and transmittance data utilizing a 410 nm UV LED, which were then compared with those obtained with the commercial spectrophotometer Optizen QX.
The absorbance values revealed that the colorimeter with a 410 nm LED was able to detect nitrate concentrations from as low as 0.2 mg/L to as high as 30.0 mg/L. The correlation coefficient between the absorbance (y-axis) of the colorimeter device and the concentration(x-axis) was 0.9913, while the correlation value of the Optizen QX Spectrophotometer was 0.9908, as shown in Figure 8.

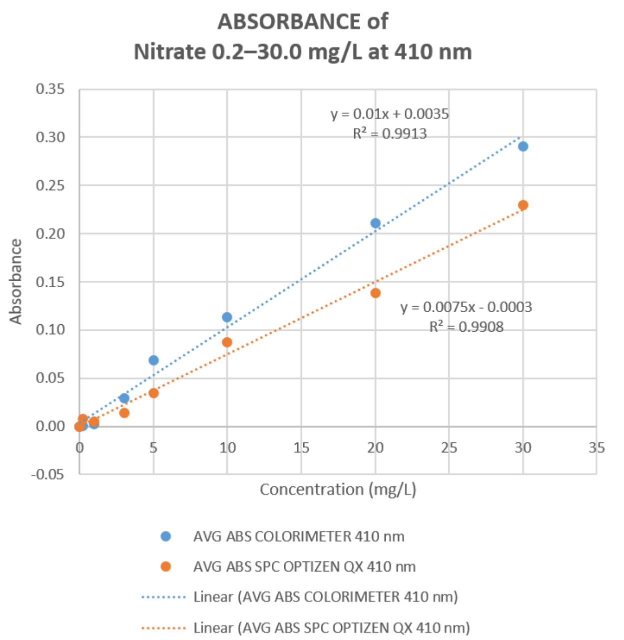

Fig. 8: Absorbance of nitrate measured with the colorimeter at 410 nm and compared with that of the commercial spectrophotometer.

Owing to its low build cost and comparable results, the built colorimeter device can be used as an affordable alternative to the commercial spectrophotometer/colorimeter. The built colorimeter can also be applied in further research to detect other chemical substances with the minimal cost of adding an additional LED whose wavelength will correspond to the device's reagent system.

4. Conclusion

A low-cost colorimeter having an overall manufacturing cost of US$ 72 was successfully built. The device was built with a PC interface and a direct interface for portable measurement. The colorimeter, which mainly utilizes a microcontroller, a specific wavelength LED, and an RGB sensor, was able to detect and measure the absorbance and transmittance of a nitrate (410 nm) and fluoride solution, and its readings had an average correlation value of 0.99435 with those obtained with the Optizen QX Spectrophotometer, which is a commercial spectrophotometric/colorimetric-based device. The built colorimeter is comparable to the commercial device.

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