

# Development of an Optofluidic System for Concentration Measurement of Colorimetric Based Solution Targeted For Water Quality Assessment

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**Abstract** - Concentration measurement of a solution based on colorimetric method is normally performed using a commercial and bulky device such as colorimeter and spectrometer. This approach has several drawbacks: the sample needs to be manually taken, transported and tested in laboratory, as well as it requires large volume of analyte and reagent. Such problem can be overcome by having a small and compact system such as optofluidic based device with the capability of carrying out colorimetric measurements with better operational processes. Therefore, this research focuses on the development of a smaller optofluidic based system to measure the concentration of colorimetric based solutions. The system consists of a microfluidic platform combined with a light emitting diode (LED) and a light-dependent resistor (LDR) as its optical source and detector, respectively. Based on Beers law principles, different concentration of coloured solution produces different voltage signal and absorbance effect, which is then being processed and manipulated to produce the concentration measurement. The optofluidic system was then tested on colorimetric solution between 0.1M to 1M and gives linearity coefficient,  $R^2$  of 0.9977 and 0.9979 for its voltage and absorbance, respectively. The proposed optofluidic system is targeted to be able to measure the concentration of particles in colorimetric solution and to be implemented for colorimetric based water quality assessment.

**Keywords:** optofluidic, colorimetric, Beer's Law, concentration, absorbance

## 1. Introduction

Water quality assessment has become one of the main processes conducted in water related industries to observe and monitor the condition of watery environments [1]. The assessment task is very important in many industrial applications such as aquaculture, agriculture, wastewater management, water distribution and others [2]. In wastewater management for example, there are three types of water quality assessment techniques that are normally used which are whole effluent toxicity (WET), whole effluent assessment (WEA) and direct toxicity assessment (DTA) [3-5]. Conventionally, the water quality was assessed by means of laboratory-based measurements such as through the use of spectrometer and colorimeter [6, 7]. In doing that, the samples are normally collected using a manual sampling procedure and transported to the lab for measurement purpose [8]. As an example, the samples with excessive fluoride from the countryside needed to be sent by the authorities' health centres to the laboratories in the cities [9]. Laboratories testing shown that it required more time to obtain the result. This traditional method also leads to unreliable outcomes as there may be chemical and physical responses involving the samples due to time-consuming operation [10]. It is also mentioned in [9] that the charges for the estimation of the fluoride concentration per sample is quite high. Studies from [11] also showed that all available in situ instruments that can observe various parameters are restricted from their use due to their bulky size and high energy consumption. All these issues such as sample degradation or chemical changes, time-consuming operation, high cost, bulky size and high energy consumption [12] thus pose a challenge in assessing the water quality in different areas of application. The need to have a device capable of determining these water quality parameters for in situ application is thus crucial to improve the way the assessment is performed.

On the other hand, optofluidics is the enabling technology that can be adapted to overcome this issue [13]. Optofluidics is the combination of microfluidics and optics, which offers a potential optical platform for handling and analysing fluid samples [14] in real time. In a simple word, optofluidics describes the interaction of light and fluids on a single chip. There are many major components in the optofluidic device such as an optofluidic laser, a prism, a switch and a lens. Each component represents a different working principle of the optofluidic device. Optofluidic platform development also can be

extended for more added features in water quality assessment activities such as by integrating the Internet of Things(IOT) and artificial intelligence capabilities.

This work aims to develop a sensing system that can be used for in situ measurement of water quality parameter based on optofluidic approach and light absorbance principles. Absorbance is defined as the amount of light a solution can absorb which is also known as optical density [15]. Absorbance is also related with the Beer-Lambert Law or known as Beer’s Law where the characteristics of the medium through which light is moving will affect how much light is attenuated [16].

The system is expected to be able to serve as a preliminary work for in situ sensing platform development can improve the water quality assessment process. The scope of this work is on the measurement of concentration of orange-based solution prepared in our laboratory. The colour of the solution can mimic the actual colorimetric solution produced by combining heavy metal ions such manganese (Mn) with its colorimetric reagent. With the development of such system, different concentrations of manganese can then be rapidly measured.

## 2. Methodology

### 2.1 Optical Sensing Circuit

#### 2.1.1 Circuit Simulation

The optical circuit simulated by using an open-source simulation software, TinkerCAD in order to test and verify the working principles of the proposed system as shown in Fig. 1.

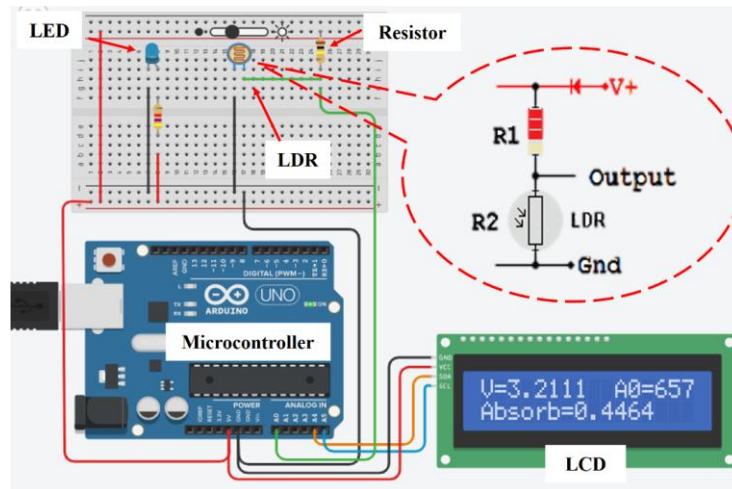


Fig. 1: Simulated circuit using TinkerCAD with enlarged dark activated detection configuration

As in Fig. 1, the schematics of the circuit consist of four main components which are the microcontroller, LDR, LED and LCD display. The type of detection scheme that was used in this circuit simulation is dark activated configuration, whereas more light is absorbed as it travels from the light source to the LDR, the higher/lower output voltage will be. This in turn gives an output voltage that corresponds to the degree of absorbance of liquid/material between light source and absorbance. The resistor is used as a voltage divider to act as the dividing factor for the detected voltage [17].

In this simulation, certain tests were done to observe the absorbance effect from LED to LDR. The absorbance was calculated based on the voltage produced for different brightness levels of the simulated light as given in Equation 1[18].

$$A = -\log \frac{(V_{sample} - V_{zero})}{(V_{solvent} - V_{zero})} \quad (1)$$

An Arduino Uno microcontroller was used to read the value of the LDR voltage detected from the analog pin for different brightness levels. A code was developed to perform analog-to-digital conversion (ADC), and to convert the signal into absorbance value before being displayed in the serial monitor as well as the LCD display. By putting an ideal assumption of the  $V_{zero}$  and  $V_{solvent}$ , the conversion from voltage into absorbance was verified to ensure the developed code executes a correct conversion task.

### 2.1.2 Hardware Development

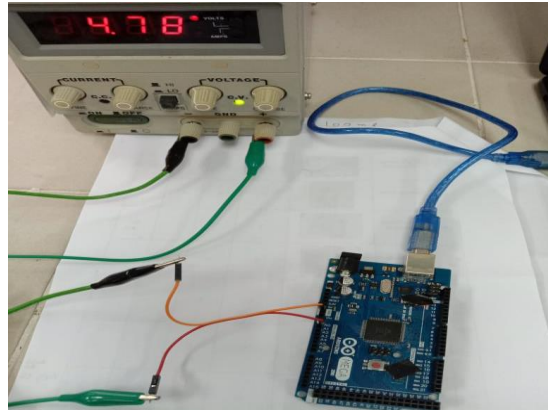


Fig. 2: ADC conversion setup (schematic diagram)

Based on the simulation results, the circuit was then developed according to Fig. 2. The ADC behaviour were tested by injecting a range of voltages from 0 to 5 V at 0.5 V intervals and comparing them to the output voltage read by the controller. It is expected that for every voltage injected, the same value of voltage will be read which ensures that no ADC error occurs that could cause any inaccuracy of measurement.

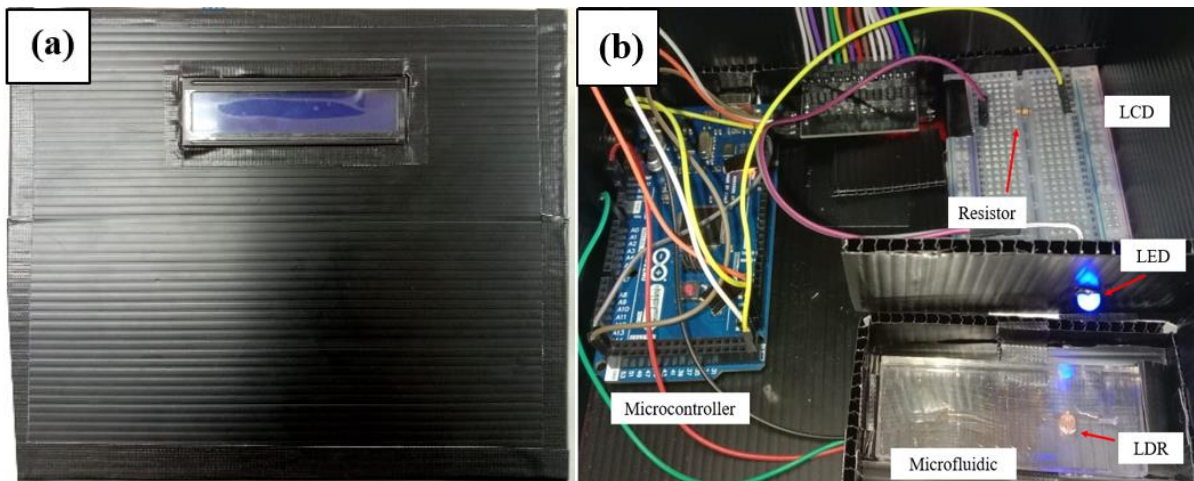


Fig. 3: Optical circuit system (a) external view (b) internal view

The optical circuit was then integrated and assembled inside a black box enclosure to form the final optical system as illustrated in Fig. 3. All of the connections are based on the TinkerCAD simulation. The components were placed inside the black box to minimize the external light that can influence the result of the absorbance detected from the LDR. In this setup, the placements of LED and LDR are directly aligned to ensure the LDR will get maximum detection from the LED.

## 2.2. Microfluidic Device

The microfluidic device was based on our previously developed microfluidic chip. This device is manufactured through micro milling process at the Faculty of Mechanical Engineering's laboratory. The fabrication technique can be summarized by two main processes. The first step is to use any computer-aided design (CAD) to produce the finished devices. It can be done using any CAD models such as AutoCAD. During this process, the size and dimension is properly drawn to get the exact size in actual form. Then, micro milling process was executed by using the computer numerical control (CNC) machine facilities. Fig. 4 shows the microfluidic design of the created from the 3DuF website which is an environment specialized for designing microfluidics. This design contains two inlets with Y-type connection to the five turns of a mixer, an outlet and a detection area.

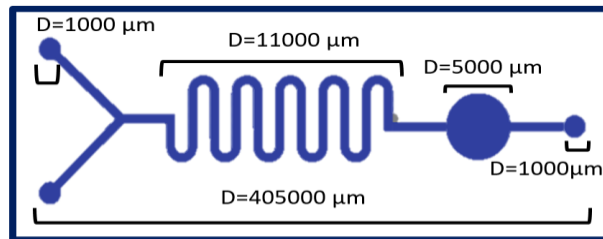


Fig. 4: Microfluidic design

In order to make sure whether the device can sustain the sample without leakage, a microfluidic test was performed. Coloured solution was used during the test conducted in order to identify and rectify any potential leakage that could occur during fabrication process. A portable USB digital camera microscope was used to visually check the leakage possibility. The zoom detail can be viewed from the desktop camera. Fig. 5 shows the overall view of the microfluidic under digital camera zoom and the zoomed part for microchannel and detection area.

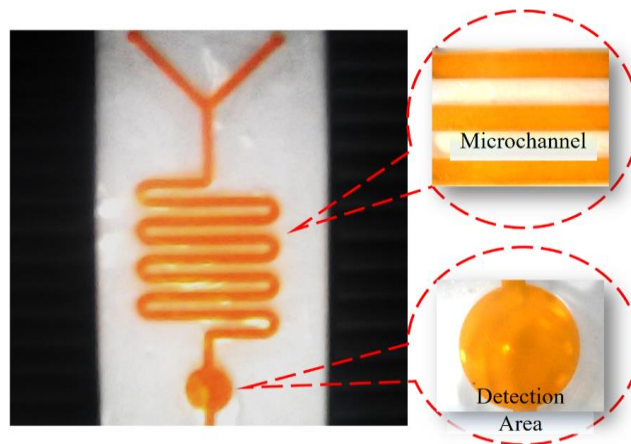


Fig. 5: Microfluidic test

Based on Fig. 5, the coloured solution injected inside the microchannel seems to be well sustained without any leakage or air bubble associated with it, suggesting the efficiency of this fabrication process.

## 2.3 Final System Setup

The final system consists of the integration between the two major parts which are the optical system and microfluidic device as in Fig. 6.

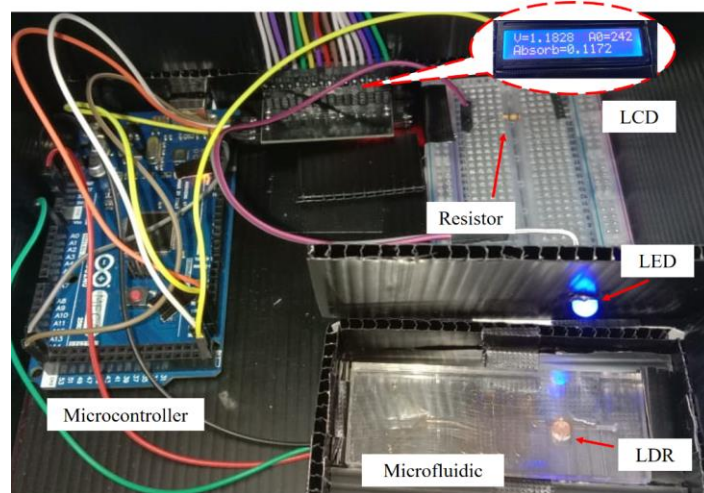


Fig. 6: Final system consists of microfluidic device and optical system

In order to test and verify the system functionality and capability, sample solutions were prepared using food coloured solution. The orange-coloured solution which mimics the colorimetric solution of a manganese solution was chosen in this test. According to the demonstration of the spectrophotometric complementary colour wheel [19], a blue LED was chosen as it can get the highest absorbance from the orange-coloured solution.

The sample solutions were prepared at range from 0.1 M to 1.0 M and conducted in the laboratory with correct procedure. Fig. 7 shows the different concentrations of the prepared sample ranging from 0.1 M to 1.0 M.

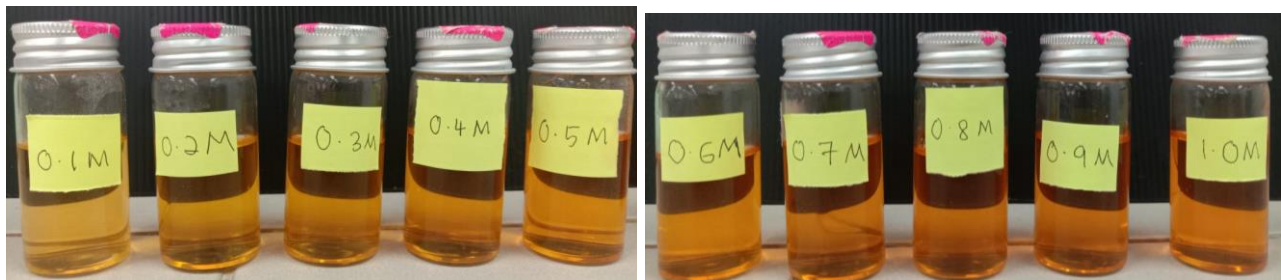


Fig. 7: Samples with different concentration

From Fig. 7, it is observed that the coloured solutions gradually change from light orange to darker orange as the concentration gets higher. These solutions were treated as stock solutions for microfluidic testing.

## 2.4. Data Collection

For each test, the coloured solution was injected into the microfluidic inlet using a syringe as in Fig. 8 until the orange-coloured solution covered each area all the way to the outlet.

Next, the microfluidic device with coloured solution was inserted into the testing black box. It is crucial to ensure that the microfluidic detection area, blue LED and LDR sensor are vertically aligned to optimise the sensing efficiency. After covering all components with the black box, reading from the LDR sensor can be observed from the serial monitor displayed on the laptop and LCD display located on top of the black box. The readings for voltage and absorbance were observed, collected and tabulated in a table for analysis. Lastly, the coloured solution in the microfluidic was extracted from the outlet using syringe. All steps were repeated for all different concentrations.

The collected data were then analysed to observe the performance of the built measurement system. Linearity and error analysis was used to verify the system.

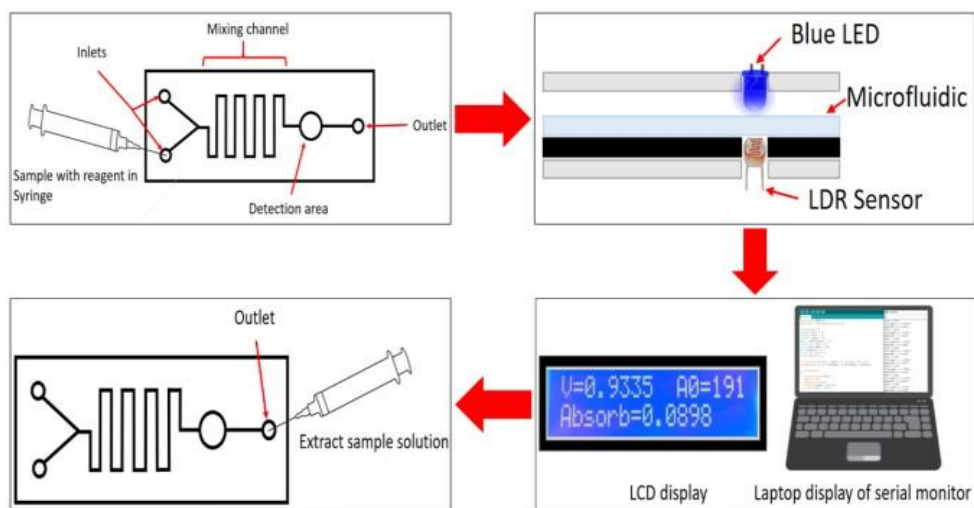


Fig. 8: Testing process flow

### 3. Results and Discussion

The developed system is successfully developed by displaying the parameter of interests i.e., voltage and absorbance on the LCD display. Several tests have been performed to verify the functionality of the developed optical measurement system. The conversion from voltage reading to its respective absorbance was verified through calculation as in Equation 1. The test was also performed in order to ensure the correct ADC conversion. The ADC test gives an error of less than 5%, verifying the validity of our coding to convert the value of LDR into voltage. For performance measurement, both voltage and absorbance were used to represent the concentration of the prepared samples.

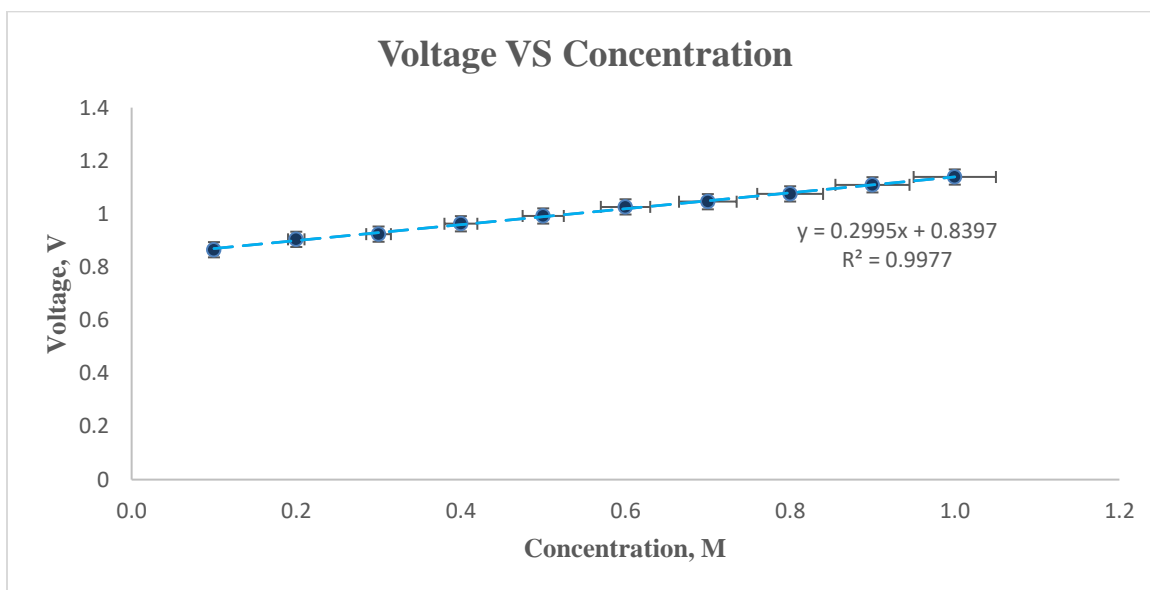


Fig. 9: Voltage vs concentration

Fig. 9 shows the relationship between voltage and concentration ranging from 0.1 M to 1.0 M. It is found that when the concentration of the sample increases, the value of the voltage obtained also increases, showing its linearity relationship with the coefficient of determination,  $R^2$  is 0.9977. Since  $R^2$  is approximately very near to 1, it can be said that the system is most

likely accurate with low percentage of error. In terms of measurement tolerance, all the points lie within 5% error plot as compared to the fitted line. Positive linear relationship also indicates that in this circuit configuration, as concentration get higher, less light is detected by LDR, which in turn increases the voltage.

Meanwhile, Fig. 10 shows the relationship between absorbance and concentration with the coefficient of determination,  $R^2$  is 0.9979, which is also very close to 1, as expected. This is aligned with our hypothesis, since the absorbance was a direct conversion from the voltage reading. This plot also produced a low percentage error where all the points are within 5% error plot compared to the fitted line.

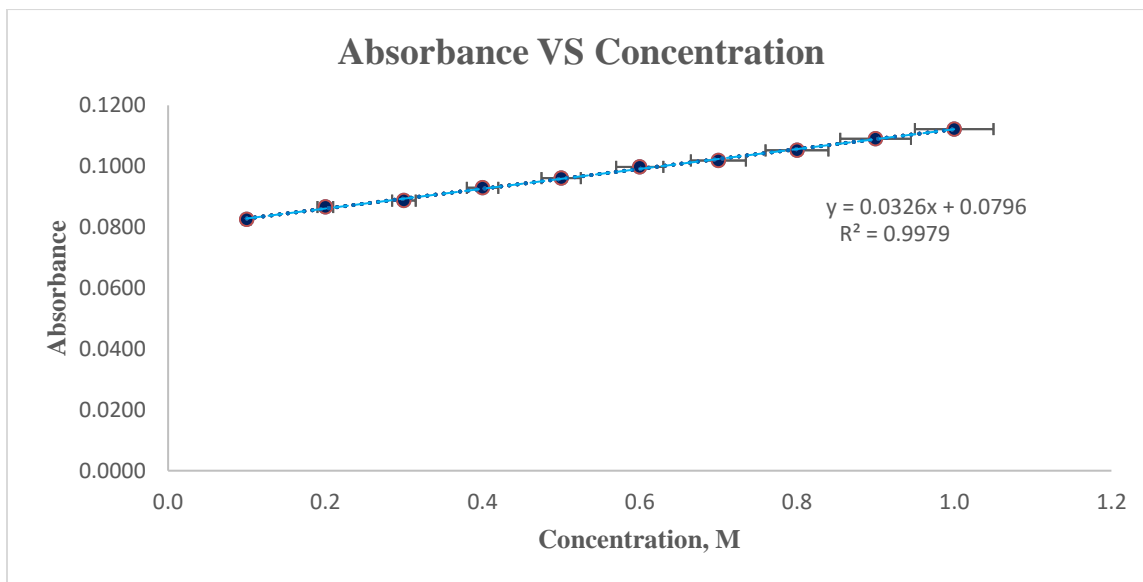


Fig. 10: Absorbance vs concentration

Both plots thus indicate the ability of the system to be used for measuring the concentration of the prepared solution within the range of interests. The obtained voltage and absorbance reading can be further manipulated to be used as a calibration curve for predicting the unknown concentration.

#### 4. Conclusion

It is concluded that the optofluidic system for concentration measurement of colorimetric based solution is successfully developed in this work. In achieving the targeted objectives, many crucial steps are required. In terms of its performance, the system has low percentage of error for the concentrations ranging from 0.1 M to 1.0 M. With  $R^2$  value for both voltage and absorbance plots against the concentration of the prepared samples are close to unity, it shows that the development and experimental setup is convincing. This system makes matters easier as it is small, compact and easily operated. Hence, this system is easier to use and more effective compared to the conventional bulky system. Last but not least, for future work, further tests will be carried out for the actual implementation purposes such as the measurement of any colorimetric solution in different area of application. Water quality testing is one of our target applications in future whereas the parameter can be normally measured using colorimetric techniques. In the near future, we plan to implement this system for heavy metal measurement such as in manganese (Mn) detection due to the orange colour reaction it produced is similar to our test samples.

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## References

- [1] N. Yaakub, M. N. A. Raoff, M. N. Haris, A. A. A. Halim, and M. K. A. Kamarudin, “Water quality index assesment around industrial area in Kuantan, Pahang,” *Journal of Fundamental and Applied Sciences*, vol. 9, no. 2S, p. 731, Jan. 2018, doi: 10.4314/jfas.v9i2s.45.
- [2] A. P. Tom, J. S. Jayakumar, M. Biju, J. Somarajan, and M. A. Ibrahim, “Aquaculture wastewater treatment technologies and their sustainability: A review,” *Energy Nexus*, vol. 4, p. 100022, Dec. 2021, doi: 10.1016/j.nexus.2021.100022.
- [3] S. Gartiser, C. Hafner, C. Hercher, K. Kronenberger-Schäfer, and A. Paschke, “Whole effluent assessment of industrial wastewater for determination of BAT compliance. Part 2: metal surface treatment industry,” *Environmental Science and Pollution Research*, vol. 17, no. 5, pp. 1149–1157, Feb. 2010, doi: 10.1007/s11356-009-0290-6.
- [4] K. Gruiz *et al.*, “Direct toxicity assessment — Methods, evaluation, interpretation,” *Science of The Total Environment*, vol. 563–564, pp. 803–812, Sep. 2016, doi: 10.1016/j.scitotenv.2016.01.007.
- [5] B. Escher, P. Neale, and F. Leusch, *Bioanalytical Tools in Water Quality Assessment*. IWA Publishing, 2021. doi: 10.2166/9781789061987.
- [6] Z. Shi, C. W. K. Chow, R. Fabris, J. Liu, and B. Jin, “Applications of Online UV-Vis Spectrophotometer for Drinking Water Quality Monitoring and Process Control: A Review,” *Sensors*, vol. 22, no. 8, p. 2987, Apr. 2022, doi: 10.3390/s22082987.
- [7] M. Fathalla and P. R. Selvaganapathy, “Colorimetric Detection of Heavy Metal Ions Using Superabsorptive Hydrogels and Evaporative Concentration for Water Quality Monitoring,” *ACS ES&T Water*, vol. 2, no. 4, pp. 658–666, Mar. 2022, doi: 10.1021/acsestwater.2c00070.
- [8] Mir Zafarullah, “Water sampling , procedure, purpose , techniques and equipments,” Aug. 19, 2017. <https://www.slideshare.net/mirzafarullah/water-sampling-procedure-purpose-techniques-and-equipments>
- [9] Rohit, L. Kanwar, and K. Kesava. Rao, “Development of a low-cost portable colorimeter for the estimation of fluoride in drinking water,” *Sensors and Actuators B: Chemical*, vol. 149, no. 1, pp. 245–251, Aug. 2010, doi: 10.1016/j.snb.2010.05.021.
- [10] N. Wang, T. Dai, and L. Lei, “Optofluidic Technology for Water Quality Monitoring,” *Micromachines*, vol. 9, no. 4, p. 158, Apr. 2018, doi: 10.3390/mi9040158.
- [11] D. B. Senoro, K. L. M. de Jesus, R. C. Nolos, Ma. R. L. Lamac, K. M. Deseo, and C. B. Tabelin, “In Situ Measurements of Domestic Water Quality and Health Risks by Elevated Concentration of Heavy Metals and Metalloids Using Monte Carlo and MLGI Methods,” *Toxics*, vol. 10, no. 7, p. 342, Jun. 2022, doi: 10.3390/toxics10070342.
- [12] M. Gholizadeh, A. Melesse, and L. Reddi, “A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques,” *Sensors*, vol. 16, no. 8, p. 1298, Aug. 2016, doi: 10.3390/s16081298.
- [13] G. M. e Silva, D. F. Campos, J. A. T. Brasil, M. Tremblay, E. M. Mendiondo, and F. Ghiglieno, “Advances in Technological Research for Online and In Situ Water Quality Monitoring—A Review,” *Sustainability*, vol. 14, no. 9, p. 5059, Apr. 2022, doi: 10.3390/su14095059.
- [14] J. Tang, G. Qiu, and J. Wang, “Recent Development of Optofluidics for Imaging and Sensing Applications,” *Chemosensors*, vol. 10, no. 1, p. 15, Jan. 2022, doi: 10.3390/chemosensors10010015.
- [15] T. G. Mayerhöfer, A. V. Pipa, and J. Popp, “Beer’s Law-Why Integrated Absorbance Depends Linearly on Concentration,” *ChemPhysChem*, vol. 20, no. 21, pp. 2748–2753, Oct. 2019, doi: 10.1002/cphc.201900787.
- [16] R. Delgado, “Misuse of Beer–Lambert Law and other calibration curves,” *Royal Society Open Science*, vol. 9, no. 2, Feb. 2022, doi: 10.1098/rsos.211103.
- [17] W. Setya *et al.*, “Design and development of measurement of measuring light resistance using Light Dependent Resistance (LDR) sensors,” *Journal of Physics: Conference Series*, vol. 1402, p. 044102, Dec. 2019, doi: 10.1088/1742-6596/1402/4/044102.
- [18] M. R. M. Dali *et al.*, “Concentration measurement of coloured solution using optofluidic approach,” *Journal of Physics: Conference Series*, vol. 2411, no. 1, p. 012005, Dec. 2022, doi: 10.1088/1742-6596/2411/1/012005.