

Article

Universal Analytical Framework Coupling Open-Source Platforms with Colorimetry for On-Site Water Quality Assessment

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Abstract

Various analytical methods for water quality monitoring have been standardized to date; however, implementation of these techniques necessitates considerable skill or expensive equipment, which impacts their use. In this study, a pragmatic strategy that employs an open-source Arduino platform coupled with visible-spectrum colorimetry for water quality assessment is proposed. Validation procedures demonstrate satisfactory application of the developed system to determine free residual chlorine (frCl) and ammonia-nitrogen (NH₃-N) in collected water samples. The detection limits achieved, i.e., 0.04 and 0.03 mg L⁻¹ for frCl and NH₃-N, respectively, are considerably lower than the concentration levels recommended by regulations; thus, the proposed technique has sufficient detection capability for common use. Moreover, on-site water quality assessment can be achieved using a compact configuration, as the system weighs less than 100 g and is powered by a laptop. Remarkably, the system constructed in this study is more cost-effective than commercially available spectrophotometers, at approximately USD 35 per system.

Keywords: water quality; open source; colorimetry; visible spectrum; on-site assessment

1. Introduction

Ancient civilizations originated in large river basins with plenty of water, indicating the central importance of water to human survival. Throughout history, water quality and quantity have critically impacted human well-being, as appropriate resources can provide stable supplies of drinking water and facilitate irrigation water for agricultural production. Even though human civilization has flourished, many problems regarding water quality and supply remain [1]. Therefore, in 2012, the “Future We Want” Declaration of the United Nations (UN) Conference on Sustainable Development (Rio + 20) reaffirmed the human right to safe drinking water and sanitation, and stated that this right should be progressively realized for all populations with full respect for national sovereignty [2]. Moreover, “The 2030 Agenda for Sustainable Development” launched in 2015 by the UN Member States included the following aim: to “ensure availability and sustainable management of water and sanitation for all” [3].



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Because access to water resources is closely related to human welfare, relevant authorities regulate water-supply quality, including its color, turbidity, and odor [4–6]. To date, various analytical methods have been standardized for water quality monitoring. However, these methods involve modern instrumentation with considerable equipment costs or require skilled operation, which form huge obstacles to widespread use. Although the problems described above can be avoided through the commission of suitable organizations to perform water quality monitoring, the associated expenditure is high, as considerable testing fees typically apply to frequent analyses of real-time water quality information. Furthermore, the time from work delivery to result reporting impacts the task timeliness. Over the past few decades, miniaturized techniques involving microfluidic chips [7–11] and paper-based devices [12,13] have attracted much attention. In spite of significantly improving device portability and reducing operation difficulty, such techniques still require the use of sophisticated electronic accessories to collect the measured signals in most cases [7,14,15]. Although some studies have successfully used smartphones as substitutes for sophisticated detection modules, the fact that most signal acquisition parameters cannot be configured manually introduces uncertainty regarding the reliability of repeated measurements [16–18]. To date, many suppliers have devoted considerable effort to bridge the gap [19,20]. Nevertheless, compatibility issues between different brands such as proprietary instrument interfaces and brand-specific test strips still limit their applicability. Therefore, a comprehensive analytical strategy for water quality assessment is urgently required.

In the 1970s, open-source software began to circulate within academic and research institutions. This early practice of freely sharing knowledge and resources in the field of software development established the foundation of the open-source movement [21,22]. In the following years, this concept was extended to hardware domains in accordance with similar principles [23,24]. Under the hardware-focused open-source concept, designs for physical components are freely accessible and broader innovation and customization are enabled. A significant factor in the widespread adoption of this concept is the decreasing component cost, which has made prototyping and experimentation accessible to a wider audience. Currently, various open-source software/hardware platforms such as Arduino [25–28], Raspberry Pi [29,30] and so on have been successfully launched, and customized boards can be seamlessly adopted with other software and hardware systems to support a diverse range of applications. Even so, most research still focuses on developing individual instrumentation rather than establishing a broadly applicable analytical framework.

In this study, a pragmatic analytical framework for water quality assessment based on open-source software/hardware platforms with colorimetry is developed. The analytical system, which includes a microcontroller board, a color sensor and, publicly available program codes built on the Arduino platform. By coupling chromogenic agents with appropriate selectivity, information on target analytes are readily accessed by the constructed system.

2. Experimental Section

2.1. Reagents and Materials

All chemicals were of analytical reagent grade and used as received unless otherwise stated. High-purity water was obtained via a Milli-Q apparatus (Millipore, Bedford, MA, USA). Ammonium chloride (NH_4Cl , $\geq 99.5\%$), phenol ($\geq 89\%$ in H_2O , solution), and sodium nitroferricyanide dihydrate ($\text{Na}_2[\text{Fe}(\text{CN})_5\text{NO}] \cdot 2\text{H}_2\text{O}$, $\geq 99\%$) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Ammonium hydroxide (NH_4OH , 28–30%), and sulfuric acid (H_2SO_4 , 95–97%) were purchased from Honeywell-Fluka (Seelze, Germany). Sodium citrate dihydrate ($\text{HOC}(\text{COONa})(\text{CH}_2\text{COONa})_2 \cdot 2\text{H}_2\text{O}$, granular), sodium hydroxide (NaOH),

and sodium hypochlorite solution (NaClO , 5% available chlorine) were obtained from J. T. Baker (Phillipsburg, NJ, USA). Ethanol (95% purity) was obtained from Uni-Onward (New Taipei City, Taiwan). Food-grade coloring agents (ponceau 4R (red), tartrazine (yellow) and brilliant blue FCF (blue)) were purchased from You-Ci (New Taipei City, Taiwan). Commercial N,N-diethyl-p-phenylenediamine (DPD) free chlorine reagent powder pillows (Permachem[®], Hach, Loveland, CO, USA) were used as the chromogenic reagent.

Colored solutions ranging from 25 to 350 mL L⁻¹ were prepared by stepwise dilution of the food-grade coloring agents using high-purity water. The phenol solution was prepared by mixing 11.1 mL of phenol with ethanol to 100 mL. A sodium nitroprusside solution was prepared by mixing 0.5 g $\text{Na}_2[\text{Fe}(\text{CN})_5\text{NO}] \cdot 2\text{H}_2\text{O}$ with high-purity water to 100 mL. An oxidizing solution was prepared by mixing 100 mL of alkaline citrate solution (0.68 M $\text{HOC}(\text{COONa})(\text{CH}_2\text{COONa})_2 \cdot 2\text{H}_2\text{O}$ /0.25 M NaOH) with 25 mL of 5% NaClO.

2.2. Construction of Analytical System

A schematic and photographic image of the developed system, which includes a detection unit, a microcontroller, and a personal computer (PC), is shown in Figure 1.

The detection unit comprised a commercially available color sensor module (GY-31 TCS3200 color sensor; Taiwan Internet of Things Technology Co., Ltd., Tainan City, Taiwan) and a mounting case constructed in-house. The module integrated a light-to-frequency converter and 64 configurable photodiodes arranged in an 8 × 8 array, including 16 photodiodes with red (R) filters, 16 with green (G) filters, 16 with blue (B) filters, and 16 without filters. Additionally, four white light-emitting diodes (LEDs), which served as the illumination source for the measurements, were adopted into the module and positioned around the photodiodes. For the color sensor module, a mounting case was designed using geometric modeling software (AutoCAD 2024, Autodesk Inc., Sausalito, CA, USA). Then, the designed pattern was machined onto poly(methyl methacrylate) (PMMA) substrates (Pu Te Acrylic Ltd., New Taipei City, Taiwan) using a laser engraver (EBF-090060-60R, Laser Life Co., Ltd., Taipei, Taiwan). Figure S1 illustrates the layout of the proposed mounting case. The mounting case was assembled using black opaque PMMA substrates to isolate possible interference light from the environment.

To realize programmable control, the mounted converter was connected to a microcontroller (Arduino[®] Uno Rev3, Microchip Technology, Chandler, AZ, USA) via a Dupont line (Jin Hua Electronic Co., Ltd., Taipei City, Taiwan). The program was written in free integrated development environment (IDE) software (Arduino[®] IDE software 2.3.2). The full code is publicly available on Zenodo under the MIT License with a persistent DOI: <https://doi.org/10.5281/zenodo.21199640>. A PC equipped with an Intel Core i5-6198DU processor, 8 GB RAM, and NVIDIA GeForce 930MX running a 64-bit Windows 10 operation system was connected to the Uno Rev3 microcontroller via a USB B cable. The PC was used for data acquisition and serial communication. General size information of parts of the developed system is summarized in Table S1.

White polypropylene screw caps for glass vials (G13550-28571, 20 mL, 61 × 28 mm o.d., Dogger Scientific Co., Ltd., Taipei City, Taiwan) were used as sample holders due to their ease of access. In this study, optical detection was performed using a reflection-mode configuration. Specifically, the white LEDs and photodiode array were positioned on the same side of the sample. The sample vial was placed directly under the sensor module and inside a black opaque mounting case; this setup ensured a fixed relative geometry between the illumination source, sample, and detector. The TCS3200 color sensor outputs a square-wave signal (50% duty cycle) with a frequency that was directly proportional to the incident light intensity. The Arduino microcontroller measured the output-signal pulse width via the pulseIn() function. It is worth noting that, because the pulse width was inversely

proportional to the output frequency, a lower light intensity yielded a wider pulse width. Data acquisition was performed using the Arduino IDE, which provided a real-time display of the sensor output through a serial monitor. The datasets were subsequently exported to graphing software (OriginPro 2021; OriginLab Co., Northampton, MA, USA) for further processing and graphical representation. Throughout this study, all measurements were conducted at room temperature in triplicate. All calibration curves showed adequate linearity, with the F-tests indicating significant regression ($p < 0.05$). Figure 2 shows a schematic illustration involving signal acquisition and data processing.

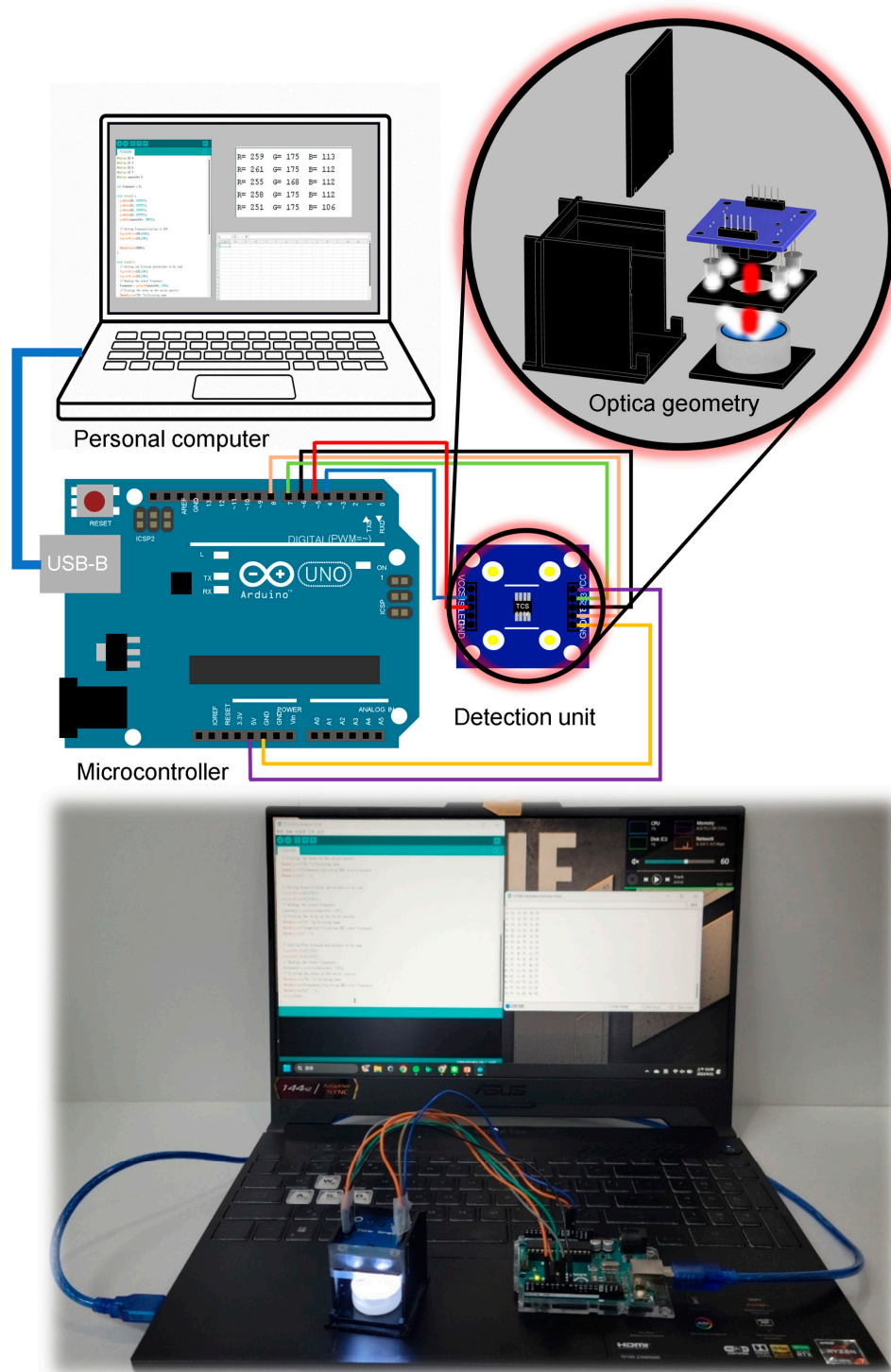


Figure 1. Schematic and photographic image of developed analytical system.

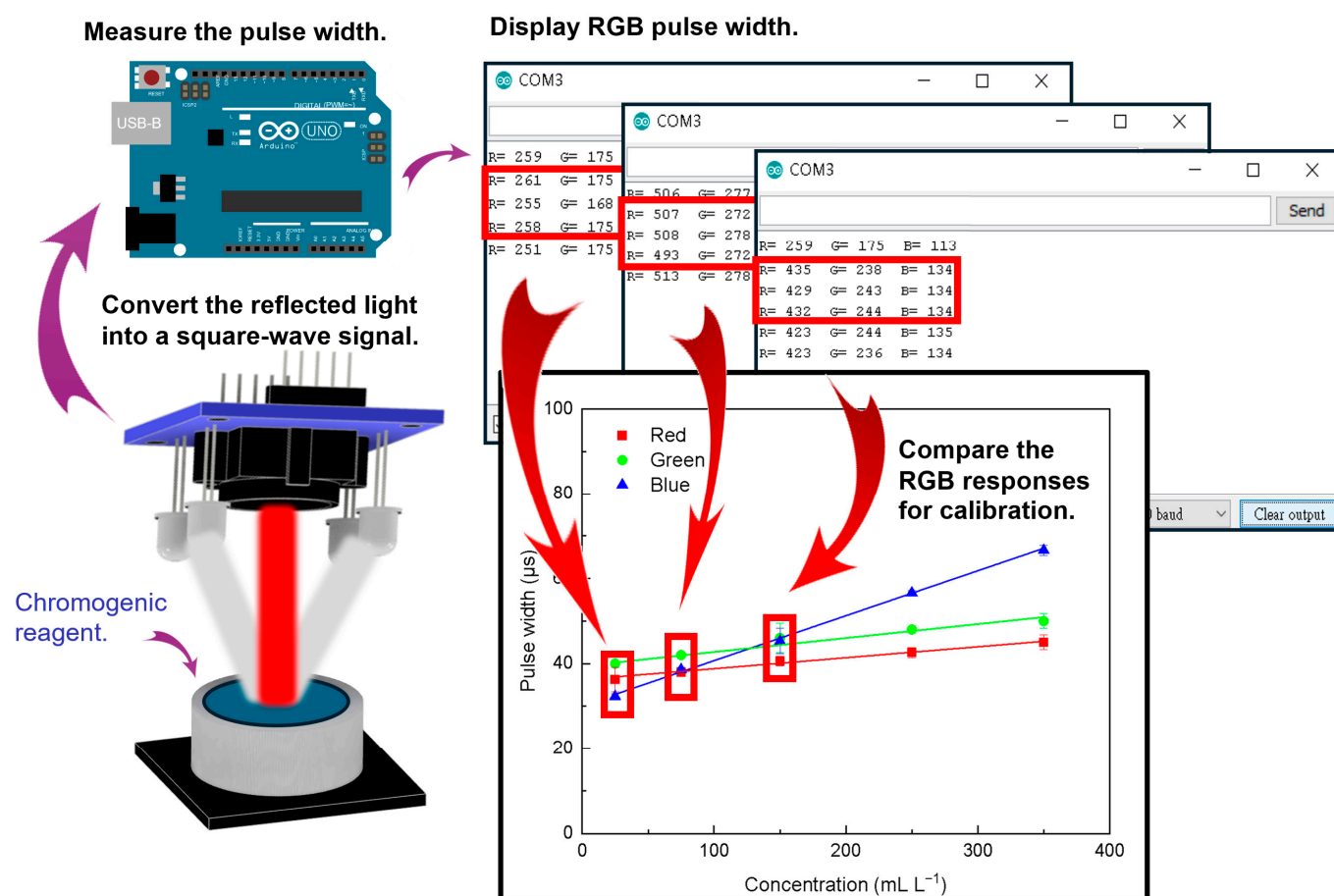


Figure 2. Schematic illustration of signal acquisition and data processing.

2.3. Determination of Free Residual Chlorine (frCl) Content

In this study, frCl content was determined based on the formation of the magenta Würster dye [31]. Initially, 10 mL of a standard solution/collected sample was individually mixed with the DPD reagent powder pillow and incubated for 1 min. For calibration, working standards ranging from 0.2 to 2.00 mg L⁻¹ were prepared daily through stepwise dilution of a stock solution (5% available chlorine) with high-purity water. The frCl contents of the standard solutions/collected samples were estimated using the analytical device developed in this study and, also, a commercially available spectrophotometer (characteristic absorption at 515 nm). All procedures followed the methods described by the American Public Health Association (APHA) [32].

2.4. Determination of Ammonia–Nitrogen (NH₃–N) Content

In this study, NH₃–N content was determined via the Berthelot reaction, that is, the phenate method [33]. Initially, 25 mL of a standard solution/collected sample was mixed with 1 mL of 1.12 M phenol, 1 mL of 0.02 M Na₂[Fe(CN)₅NO]·2H₂O, and 2.5 mL of the oxidizing solution. Incubation was then performed for 1 h. For calibration, working standards ranging from 0.2 to 1.40 mg L⁻¹ were prepared daily through stepwise dilution of a stock solution containing 2000 mg L⁻¹ NH₄Cl with high-purity water. The NH₃–N contents of the standard solutions/collected samples were estimated using the analytical device developed in this study and a commercially available spectrophotometer (characteristic absorption at 640 nm). All procedures followed the methods described by the APHA [34].

2.5. Sample Preparation

The water samples for frCl determination were collected from a swimming pool (24°47'41.8" N 120°59'29.6" E), a sink (Department of Biomedical Engineering and Environmental Sciences, 24°47'21.3" N 120°59'29.0" E), and a water dispenser (Department of Biomedical Engineering and Environmental Sciences, 24°47'21.3" N 120°59'29.0" E) at National Tsing Hua University (Hsinchu City, Taiwan). The water samples for NH₃-N determination were collected from a sink (Department of Chemistry, 25°02'06.7" N 121°25'49.1" E) at Fu Jen Catholic University (New Taipei City, Taiwan) and the river that flows through Huajiang Riverside Park (25°02'06.1" N 121°28'56.9" E, New Taipei City, Taiwan). All the collected samples were stored at 4 °C in the dark and filtered through a poly(vinylidene difluoride) membrane (Chromafil®, 0.45 µm, 15 mm diameter.; Macherey-Nagel, Düren, Germany) prior to use. All procedures were implemented in accordance with the methods described by the APHA [32,34]. When handling samples with substantial matrix interference, the sample pretreatment procedures recommended by the APHA standard methods can also be followed.

3. Results and Discussion

3.1. Optimization of Operating Conditions

To optimize the analytical performance of the constructed system, the effects of certain parameters were examined: the selected color channel, stray light, and light path length.

3.1.1. Effect of Color Channel

In contrast to general spectrometric methods (e.g., analyses based on fluorescence and ultraviolet radiation), which require sophisticated instrumentation, an alternative strategy involving visible-spectrum colorimetry and based on the Arduino platform was adopted in this study. A commonly used color coordinate RGB color space was employed to quantify the color compatible with the Arduino platform [35]. Figure 3 shows the analytical features of the constructed system for different color channels and the three colored solutions. Further, characteristic spectra corresponding to the colored solutions are shown in Figure S2. As summarized in Table 1, better results in terms of calibration sensitivity and calibration curve linearity were obtained in the G, B, and R channels for the red, yellow, and blue solutions, respectively. The calibration sensitivity is defined as the slope of the constructed calibration curve [36]. The observed phenomenon can be explained in terms of color wheel theory because complementary colors typically provide a strong contrast, which aids observation [35,37].

Table 1. Analytical features of constructed system for different color channels.

Colored Solution	Color Channel ^a	Linear Equation ^b	R ² ^c
ponceau 4R (red)	R	y = 0.029x + 37	0.950
	G	y = 0.121x + 46	0.993
	B	y = 0.054x + 33	0.911
tartrazine (yellow)	R	y = 0.026x + 36	0.987
	G	y = 0.031x + 40	0.952
	B	y = 0.105x + 30	0.999
brilliant blue FCF (blue)	R	y = 0.091x + 55	0.995
	G	y = 0.059x + 49	0.979
	B	y = 0.018x + 32	0.949

^a The image in the RGB color space could be separated into three color channels, i.e., red (R), green (G), and blue (B). ^b x represents the concentration of target analyte, and y represents the pulse width. ^c Coefficient of determination.

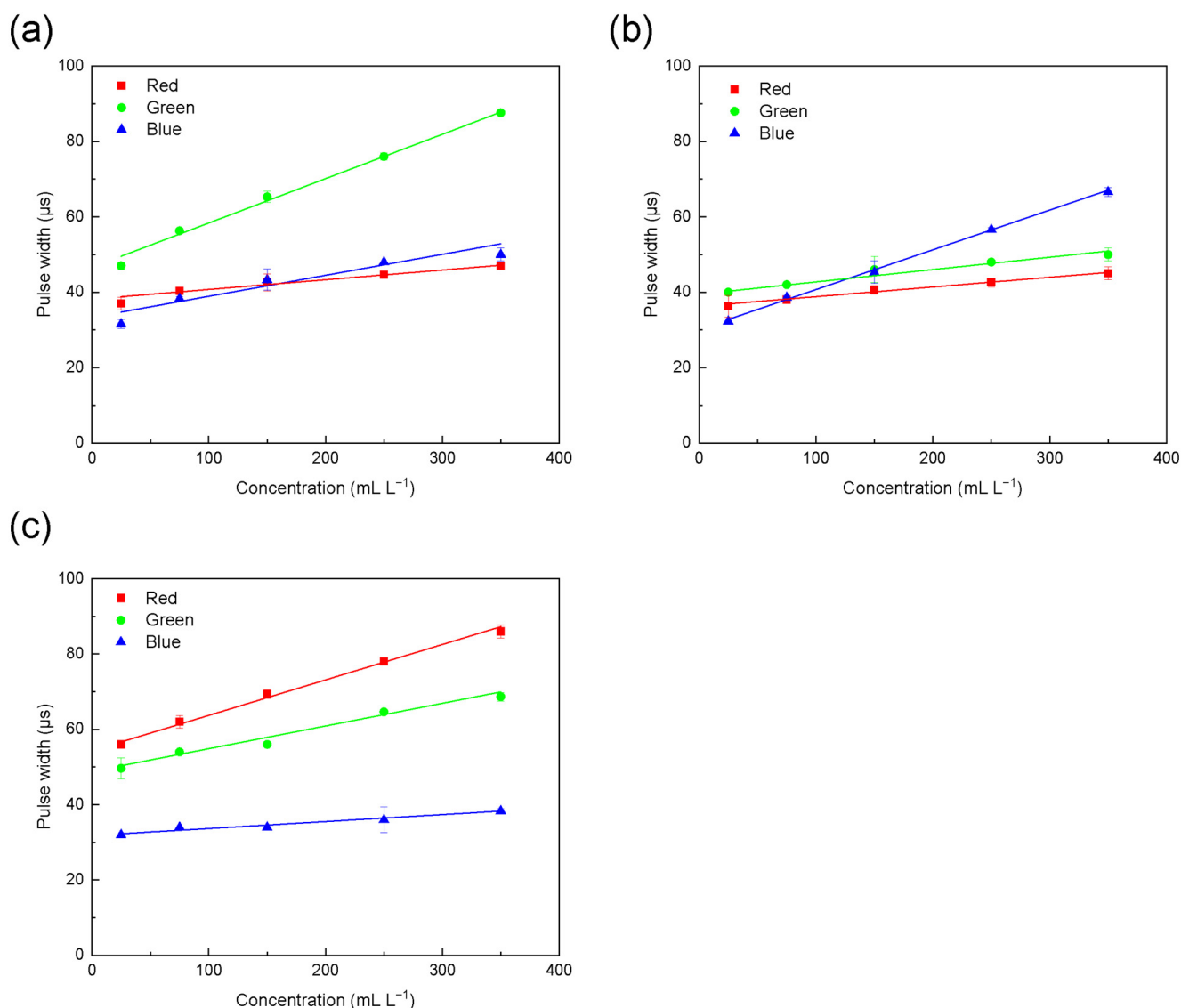


Figure 3. Analytical features of the constructed system in different color channels for three colored solutions: (a) ponceau 4R (red), (b) tartrazine (yellow), and (c) brilliant blue FCF (blue). Uncertainty for each point shown by the error bar is expressed as standard deviation when $n = 3$. All measurements were conducted at room temperature.

3.1.2. Effect of Stray Light

It is widely accepted that stray light from the environment can easily interfere with colorimetric methods based on visible-light detection [38]. Thus, the use of an opaque case to block possible light interference is practical for effective detection. Taking the blue solution as a representative example, Figure 4 illustrates the analytical features of the constructed system with and without shielding. To ensure consistent operating conditions, a mounting case comprising transparent PMMA substrates was employed to simulate the system without shielding. As indicated in Figure 4, although acceptable calibration curve linearity was achieved for each configuration, significantly greater variation was observed among the repeated analyses for the system without shielding. In other words, the issue of ambient light entering the instrument has indeed been effectively controlled. Therefore, the configuration with shielding was employed in the subsequent experiments.

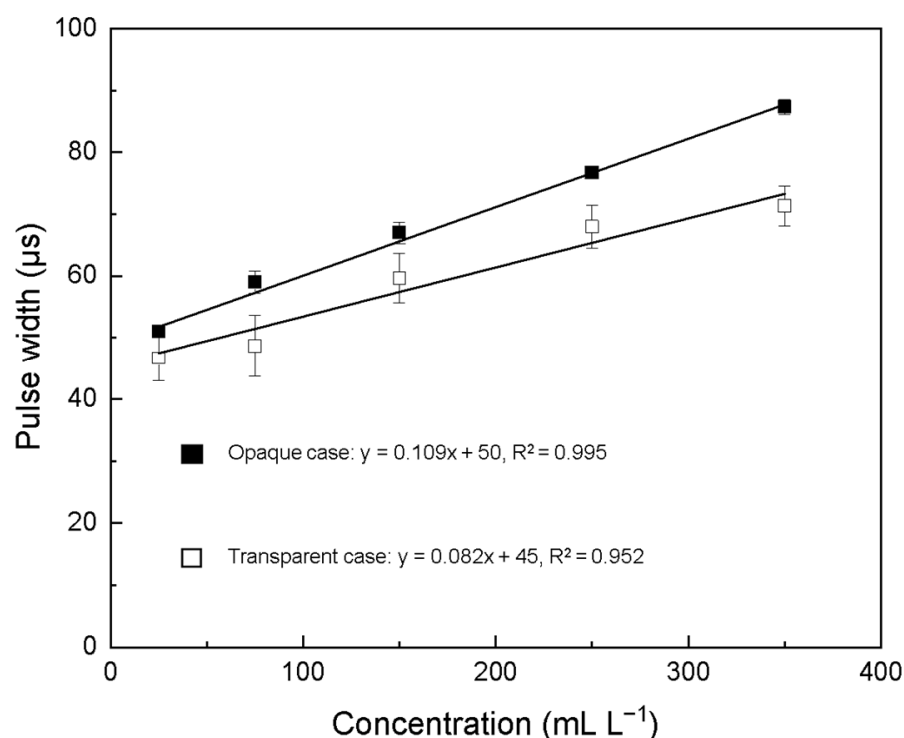


Figure 4. Analytical features of the constructed system with and without shielding, taking the blue solution as representative. A mounting case comprising transparent PMMA substrates was employed to simulate the system without shielding. Uncertainty for each point shown by the error bar is expressed as standard deviation when $n = 3$. All measurements were conducted at room temperature.

3.1.3. Effect of Light Path Length

Due to the inherent nature of light scattering, the effect of the distance between the targeted object and the detector, i.e., the length of the light path, on the analytical performance was examined. Table 2 lists the analytical features of the constructed system with respect to the light path length, using the blue solution as a representative example. As reported in Table 2, similar results in terms of calibration sensitivity and calibration curve linearity were observed within a distance range of 55–75 mm, and the decrease was more apparent when the light path exceeded 75 mm. To achieve optimum calibration sensitivity and calibration curve linearity within sufficient operating space, a 75 mm light path length was selected for the subsequent experiments.

Table 2. Analytical features of constructed system with respect to light path length. The blue solution was selected as a representative example.

Light Path Length ^a (mm)	Linear Equation ^b	R ² ^c
55	$y = 0.373x + 362$	0.989
65	$y = 0.555x + 612$	0.989
75	$y = 0.617x + 792$	0.990
85	$y = 0.591x + 900$	0.984
95	$y = 0.512x + 1053$	0.967

^a The distance between the targeted object and the detector. ^b x represents the concentration of target analyte, and y represents the pulse width. ^c Coefficient of determination.

3.2. Analytical Characteristics

To further demonstrate the utility of the developed analytical framework, two targets for water quality assessment, frCl and NH₃-N, were examined. Water chlorination is a disinfection method that is widely employed in water treatment systems. Thus, frCl level

monitoring serves as an effective proxy for validating the operational performance efficiency of the employed water treatment infrastructure. Meanwhile, $\text{NH}_3\text{-N}$ concentrations indicate whether a water source has been contaminated with domestic sewage or agricultural runoff. On the other hand, two chromogenic agents obtained through different channels, i.e., a commercial kit and common chemicals for frCl and $\text{NH}_3\text{-N}$, were deliberately adopted into the proposed analytical framework to demonstrate its broad applicability. Table 3 lists the analytical features of the constructed system when operating under optimum conditions. As reported in Table 3, satisfactory linearities in the region of 0.20–2.00 and 0.20–1.40 mg L^{-1} were observed for frCl and $\text{NH}_3\text{-N}$, respectively, with coefficients of determination (R^2) exceeding 0.995. The method detection limits (MDLs) for frCl and $\text{NH}_3\text{-N}$, which correspond to three times the standard deviation of seven measurements of a blank solution, were 0.04 and 0.03 mg L^{-1} , respectively. The detection limits for the investigated targets were considerably lower than the recommended concentration levels of the United States Environmental Protection Agency (USEPA) [4] and the European Union (EU) [5] regulations; thus, the proposed technique has sufficient detection capability for common use. Both the intraday and interday precisions were less than 8% of the coefficient of variation (CV), demonstrating the repeatability of the established method.

Table 3. Analytical characteristics of proposed methods.

Item	Color Channel ^a	Linear Equation ^b	Linear Range (mg L^{-1})	R^2 ^c	MDL ^d (mg L^{-1})	Intraday Precision ^e (%)	Interday Precision ^f (%)
Free residual chlorine (frCl)	G	$y = 53.4x + 151$	0.20–2.00	0.997	0.04	4.5	7.8
Ammonia–nitrogen ($\text{NH}_3\text{-N}$)	R	$y = 100.14x + 109$	0.20–1.40	0.997	0.03	4.9	5.5

^a The image in the RGB color space can be separated into three color channels: red (R), green (G), and blue (B).

^b x represents the concentration of the target analyte, and y represents the pulse width. ^c Coefficient of determination. ^d Method detection limit (MDL): sample volume = 1 mL ($n = 7$). ^e Standard concentration = 1 mg L^{-1} . Repeated determination at 1 h interval within same day ($n = 9$), expressed as coefficient of variation (CV).

^f Standard concentration = 1 mg L^{-1} . Three-day determination ($n = 3$), expressed as CV.

Because certified reference materials meeting the needs of this study were not easily accessible, an alternative approach to accuracy validation was adopted for the proposed method; that is, independent and reliable analyses were conducted for the same samples in parallel [19]. Specifically, to eliminate possible problems caused by inappropriate treatment during sampling procedures, the sample collection and performance of the independent analyses for data comparison were entrusted to authorized third parties, that is, Eurofins Tsing Hua Environment Testing Co., Ltd. (Hsinchu County, Taiwan) for the frCl samples and analyses, and Envimac Technology & Consultants Co. (Taipei City, Taiwan) for the $\text{NH}_3\text{-N}$ case. Based on the results listed in Tables 4 and 5, there were no significant differences between the values measured in this study and those obtained by the third parties; the relative percent differences (RPD) were obtained for all samples, being in the range of 2.7–13.3% [39]. Thus, the proposed method can accurately determine frCl and $\text{NH}_3\text{-N}$ concentrations in practice. In detail, the frCl content results revealed that no excessive residual levels of chlorine sanitizers occurred after the water treatment processes. Further, the absence of $\text{NH}_3\text{-N}$ in the tap-water sample revealed the effectiveness of sewage treatment by the water suppliers. Acceptable recoveries were obtained for all samples, being in the range of 92–104% and 104–110% for frCl and $\text{NH}_3\text{-N}$, respectively. These values satisfy the National Recommended Water Quality Criteria of the Association of Official Analytical Communities (AOAC) International [40], thereby affirming the high reliability of the proposed method for universal usage.

In contrast to conventional instrumental methods, the constructed system not only exhibits complementary analytical capabilities following coupling with appropriate chromogenic agents, but also possesses a compact configuration, as it weighs less than 100 g per system and is powered by a laptop. Remarkably, the system constructed in this study is more cost-effective than commercially available systems, at approximately USD 35 per system (see Table S2).

Table 4. Analytical characteristics of proposed method for determination of free residual chlorine (frCl).

Sample	This Study ^a		Third Party ^b	RPD ^c (%)
	Found (mg L ⁻¹)	Recovery ^d (%)	Found (mg L ⁻¹)	
Pool water	0.49 ± 0.06 ^e	104 ^f	0.56	13.3
Tap water	N.D. ^g	92 ^h	N.D.	N.A. ⁱ
Drinking water	N.D.	96 ^h	N.D.	N.A.

^a Method detection limit (MDL) = 0.04 mg L⁻¹. ^b Sample analyses were entrusted to Eurofins Tsing Hua Environment Testing Co., Ltd. The used method was based on the formation of the magenta Würster dye. MDL = 0.03 mg L⁻¹. ^c Relative percent difference (%) = |measured value in this study—measured value obtained by the authorized third party| × 100/(average of measured value in this study and that obtained by the authorized third party). ^d Recovery (%) = (concentration of spiked samples—concentration of unspiked samples) × 100/(concentration of standard spiked into samples). ^e Mean ± standard deviation (*n* = 3). ^f Spiked concentration = 0.5 mg L⁻¹. ^g Not detectable. The results obtained were below the lowest concentrations of the established calibration curves. ^h Spiked concentration = 0.5 mg L⁻¹. ⁱ Not available.

Table 5. Analytical characteristics of proposed method for determination of ammonia–nitrogen (NH₃–N).

Sample	This Study ^a		Third Party ^b	RPD ^c (%)
	Found (mg L ⁻¹)	Recovery ^d (%)	Found (mg L ⁻¹)	
Tap water	N.D. ^e	110 ^f	N.D.	N.A. ^g
River water	1.48 ± 0.02 ^h	104 ⁱ	1.44	2.7

^a Method detection limit (MDL) = 0.03 mg L⁻¹. ^b Sample analyses were entrusted to Envimac Technology & Consultants Co. The used method was based on the phenate method. MDL = 0.01 mg L⁻¹. ^c Relative percent difference (%) = |measured value in this study—measured value obtained by the authorized third party| × 100/(average of measured value in this study and that obtained by the authorized third party). ^d Recovery (%) = (concentration of spiked samples—concentration of unspiked samples) × 100/(concentration of standard spiked into samples). ^e Not detectable. The results obtained were below the lowest concentrations of the established calibration curves. ^f Spiked concentration = 0.2 mg L⁻¹. ^g Not available. ^h Mean ± standard deviation (*n* = 3). ⁱ Spiked concentration = 0.5 mg L⁻¹.

4. Conclusions

As existing water quality assessment techniques require expensive equipment and skillful operation, in this study, a cost-effective and relatively simple universal analytical framework was developed, which involves Arduino-based software/hardware platforms and colorimetry. Following optimization of the operating conditions, the analytical features of the constructed system, including the MDL and interday/intraday precision, were carefully evaluated. Two targets, frCl and NH₃–N, which are frequently used in water quality assessment, were employed to demonstrate the utility of the proposed analytical framework. Reasonable agreement was obtained between the values measured in this study and those reported by authorized third parties. Thus, the proposed method can accurately determine frCl and NH₃–N concentrations in practice, even two chromogenic agents obtained through different channels. Remarkably, the constructed system not only exhibits satisfactory analytical capabilities, but also possesses a compact configuration that facilitates on-site water quality monitoring.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/w18151884/s1>: Figure S1: Layout of the in-house-built mounting case; Figure S2: Characteristic spectra corresponding to the colored solutions (ponceau 4R (red), tartrazine (yellow) and brilliant blue FCF (blue)); Table S1: Dimensions and specifications of the system components; Table S2: Component costs of the developed analytical system.

Author Contributions: C.-Y.W.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing—review and editing; Y.-C.T.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation; J.-H.C.: Project administration, Supervision, Writing—review and editing; Y.-R.K.: Project administration, Supervision, Writing—review and editing; C.-C.C.: Visualization, Writing—review and editing; X.-Y.C.: Visualization, Writing—review and editing; J.-L.T.: Validation, Writing—review and editing; T.-T.S.: Funding acquisition, Resources, Writing—original draft, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data generated or analyzed during this study are included in this manuscript and Supplementary Information. The full Arduino source code is publicly available on Zenodo under the MIT License with a persistent DOI: <https://doi.org/10.5281/zenodo.21199640>.

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Conflicts of Interest: The authors declare no conflicts of interest.

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