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Low-cost portable photometer using wi-fi-enabled microcontroller and silicon photodiode for iron and phosphorus determination

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Abstract

A low-cost and portable photometer was developed based on the ESP32 microcontroller integrated with a BPW34 silicon photodiode for the colorimetric determination of iron (Fe) and phosphorus (P) in fertilizer samples. The BPW34 sensor provided broad spectral responsivity in the 400–1100 nm range, rapid response (<100 ns), and low dark current (<2 nA), making it well suited for visible-light detection in colorimetric assays. Calibration studies showed linear responses for Fe(II)–phenanthroline and phosphomolybdate blue complexes within the ranges of 1.14–10.0 mg L⁻¹ and 0.085–1.0 mg L⁻¹, with coefficients of determination (R²) of 0.981 and 0.9966, respectively. The limits of detection (LOD) were 0.34 mg L⁻¹ for Fe and 0.025 mg L⁻¹ for P. Validation against standard methods showed good agreement between the developed photometer and the reference spectrophotometer, with Bland–Altman mean bias 0.00 mg L⁻¹ for Fe and –2.25 mg L⁻¹ for P, along with acceptable spike recoveries of 93–105% (Fe) and 90–112% (P). These results confirm that the developed photometer offers reliable analytical performance and practical applicability for quantitative colorimetric determination of nutrients in fertilizer samples, representing an affordable alternative to conventional spectrophotometric instruments.

Keywords: BPW34 sensor, Colorimetric analysis, ESP32 microcontroller, Fertilizer testing, Iron, Phosphorus

1. Introduction

Iron (Fe) and phosphorus (P) are essential elements with critical roles in environmental monitoring, agriculture, food processing, and water quality control. Both nutrients are central to sustainable agricultural productivity and ecological balance. Iron deficiency can impair chlorophyll synthesis and plant metabolism, while excess iron may contaminate water supplies and cause ecological harm [1,2]. Similarly, phosphorus is vital for energy transfer and root development, yet excessive phosphate fertilizers contribute to eutrophication and aquatic ecosystem degradation [3]. Consequently, accurate determination of iron and phosphorus concentrations is crucial in applications such as fertilizer formulation, soil assessment, and water treatment.

In many developing regions and small laboratories, there is an urgent demand for accessible and affordable analytical tools capable of delivering reliable results without the cost and complexity of conventional instruments. Traditional techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma optical emission spectrometry (ICP-OES), and UV-Visible spectrophotometry provide high sensitivity and accuracy [4–6]. For iron, colorimetric assays with 1,10-phenanthroline are widely employed [7], while phosphorus is typically measured by the molybdenum blue method [8]. Despite their robustness, these methods rely on expensive, bulky equipment that requires skilled operators, regular calibration, and stable power sources—limitations that restrict their use outside

well-equipped laboratories. There is growing interest in compact, low-cost photometric devices capable of field-ready analysis using simplified electronics and open-source platforms.

Several laboratory-made portable spectrophotometric systems based on microcontrollers and light-emitting diodes (LEDs) have been reported as cost-effective and field-deployable alternatives to conventional benchtop instruments. Laganovska et al. [9] developed a portable, open-source, wireless spectrophotometer consisting of a white LED, a miniature spectrometer chip, an Arduino Nano microcontroller, and a Bluetooth module for wireless data transfer to a smartphone application, achieving absorbance measurements across the 450–750 nm range with performance comparable to a commercial UV–Vis spectrophotometer. Shin and Choi [10] demonstrated an Arduino-based wireless spectrometer by integrating microcontroller hardware with a conventional optical grating instrument, yielding a cost-effective solution for analytical laboratory applications. Di Nonno and Ulber [11] reported Portuino, a portable Arduino-controlled photo- and fluorimeter employing LEDs as excitation sources and a phototransistor as the detector, which was successfully validated for the determination of phosphate in water samples. These works collectively confirm the feasibility of constructing reliable, low-cost portable photometric devices using commercially available microcontrollers and optical components; however, none of these systems incorporated wireless network connectivity or were specifically designed for simultaneous multi-analyte determination in agricultural matrices.

Building upon these advances, the availability of affordable microcontrollers and optoelectronic components has facilitated the development of compact analytical instruments. The ESP32 microcontroller has gained attention due to its high processing capability, integrated Wi-Fi and Bluetooth connectivity, low power consumption, and sensor compatibility [12]. For optical detection, the BPW34 silicon PIN photodiode offers a cost-effective solution, featuring broad spectral response (400–1100 nm), high quantum efficiency ($\sim 0.65 \text{ A W}^{-1}$ at 850 nm), and rapid temporal response ($< 100 \text{ ns}$). Its low dark current ($< 2 \text{ nA}$) results in high signal-to-noise ratio even under low-light conditions [13]. Programmable light sources such as the WS2812B addressable RGB LED enable controlled emission of specific wavelengths, making them suitable for colorimetric assays [14]. By integrating these components, it is possible to design a functional photometric device for reliable determination of iron and phosphorus concentrations in low-resource environments.

This study presents a portable, low-cost photometer based on the ESP32 microcontroller and BPW34 photodiode for quantitative determination of both iron and phosphorus using colorimetric methods. The device integrates a WS2812B RGB LED as a programmable light source and is designed to be compact, user-friendly, and suitable for laboratory and field applications. Performance was evaluated by comparing results with those from a commercial spectrophotometer, demonstrating the feasibility of using open-source hardware to create reliable and affordable alternatives to traditional analytical instruments.

2. Materials and methods

2.1 Development of photometer and data acquisition system

The photometer was developed using an ESP32 microcontroller with a detection system that incorporated a BPW34 silicon PIN photodiode as the sensor and a WS2812B addressable RGB LED as the light source. The complete circuit comprised three functional sections: power management, photodetection, and wireless communication as shown in Figure 1. Experimental data were transmitted via Wi-Fi to the data acquisition software for real-time visualization and analysis.

The power management circuit was designed to regulate and distribute electrical power to the photometer. A lithium polymer battery served as the primary energy source, providing an average output of 3.7 V and 1 A of maximum current. The battery was recharged via a micro-USB charger module, which incorporated a regulator to step up the voltage from 3.7 V to 5 V. For optimal ESP32 operation, which requires 7–12 V, a 12 V regulator module was employed to step up the voltage from 5 V to 12 V.

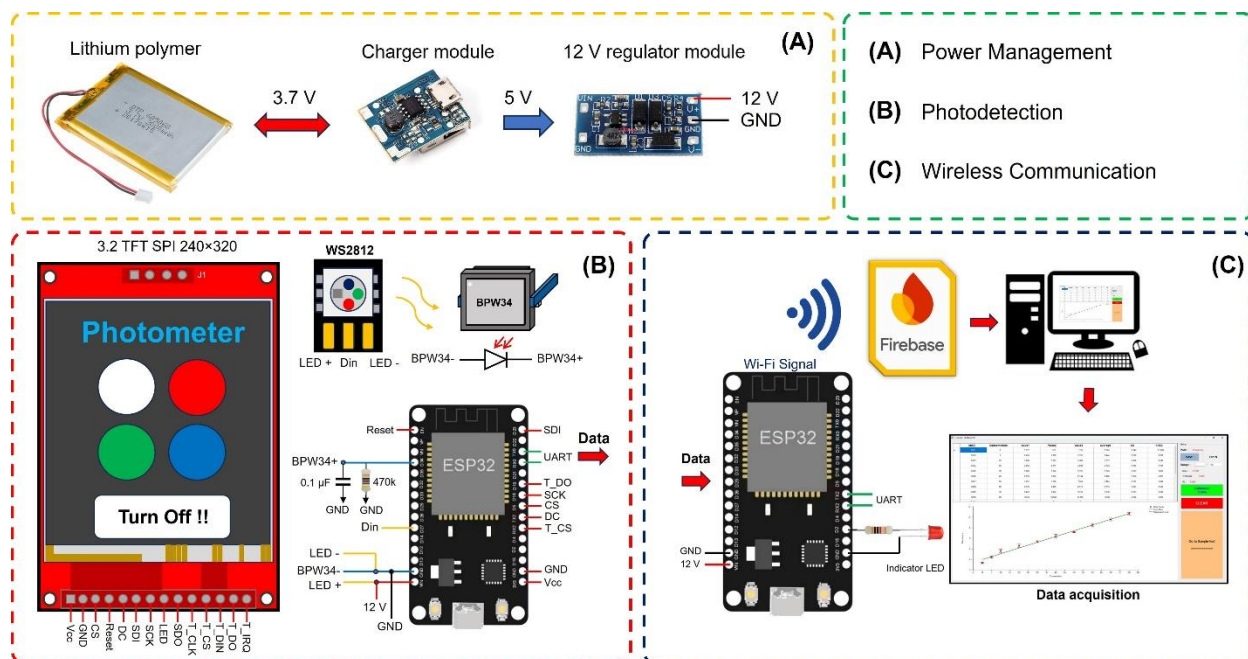


Figure 1 Circuit diagram of the developed photometer, comprising (A) the power management circuit, (B) the photodetection module with electrical components and wiring, and (C) the wireless communication circuit with the data acquisition system.

The photodetection module integrated multiple electronic components. The ESP32 microcontroller was programmed for three main functions: (i) controlling the TFT touchscreen for user interaction via the Serial Peripheral Interface (SPI) protocol, (ii) controlling the WS2812B RGB LED light source (WorldSemi, China) to select the desired excitation wavelength—Red: 620–630 nm (typ. 625 nm), Green: 515–525 nm (typ. 520 nm), and Blue: 465–475 nm (typ. 470 nm), per manufacturer specifications [14], and (iii) detecting light intensity measurements from the photodiode. In operation, the user selects the light color—red, green, blue, or white—through the TFT screen. Once the standard or sample solution is placed in the detection position, the photodiode measures the light intensity as a corresponding voltage signal related to the solution concentration. The small current generated by the photodiode is converted to voltage using a 470 kΩ resistor and stabilized by a 0.1 μF capacitor to enhance sensitivity and stability. The resulting voltage was digitized by the ESP32's analog-to-digital converter (ADC) and transmitted to the wireless communication module via the Universal Asynchronous Receiver/Transmitter (UART) protocol.

The wireless communication module utilized a dedicated ESP32 microcontroller to transmit experimental data to the data acquisition software via Firebase, a cloud-based real-time database platform. A separate ESP32 was employed to avoid multitasking errors, as the primary ESP32 managed photodetection, ADC sampling, LED control, and user interface tasks. Specifically, this dual-MCU architecture was implemented to mitigate ADC sampling jitter and timing conflicts that typically occur when the Wi-Fi stack is active on a single processor. Since the ESP32's Wi-Fi radio tasks operate with high priority, they can introduce non-deterministic latency in ADC sampling loops. Furthermore, the use of two MCUs bypasses the hardware limitation where ADC2 cannot be utilized while Wi-Fi is enabled. This decoupling ensures that high-speed photodetection and signal processing remain stable and unaffected by wireless transmission, maintaining a consistent signal-to-noise ratio. The limited flash memory of the ESP32 can reduce efficiency when executing large program files with multiple libraries. By delegating wireless communication to a second ESP32, system reliability and performance were enhanced, ensuring stable data transmission. The Firebase integration supports seamless real-time communication, reliable data acquisition, future integration with mobile or web-based monitoring tools, and multi-user collaboration.

The developed data acquisition (DAQ) software comprises two interface windows: standard calibration and sample analysis, as shown in Figure 2. In the calibration window, experimental data from standard solutions are displayed in the DataGrid view, where three replicate measurements are recorded. The software automatically calculates the average, standard deviation (SD), and relative standard deviation (%RSD). The user enters the concentration of each standard solution to generate the calibration curve by pressing the 'Calibration Curve' button. The plotted curve,

including data points, error bars, and linear regression line, is displayed in the chart window. Key regression parameters, including slope, y-intercept, and coefficient of determination (R^2), are calculated and displayed. The plot range can be adjusted by modifying values in the 'Range' text box. All data can be saved as a text file using the 'Save' button, while previously saved data can be reloaded using the 'Open' button. After completing calibration, the user can initiate sample analysis by selecting the 'Go to Sample Test' button, which opens the sample analysis window (Figure 2(B)).

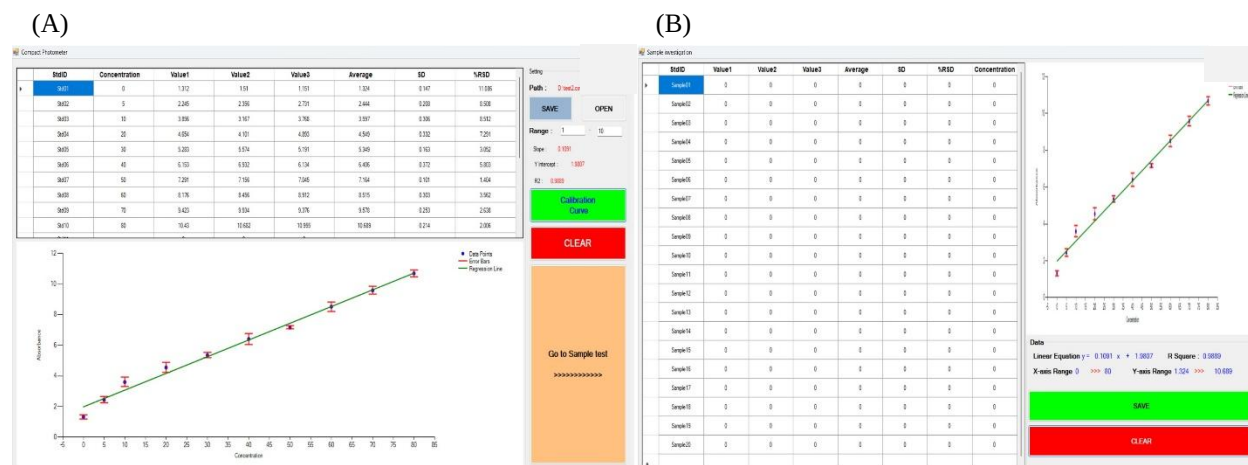


Figure 2 Interface of the data acquisition software illustrating (A) the standard calibration process, including visualization of the calibration curve and data, and (B) the analysis of sample measurements with real-time concentration analysis.

When the sample analysis window is opened, the calibration curve is displayed along with the corresponding regression data, including the linear equation, coefficient of determination (R^2), and data range. A DataGrid view is provided to receive and display the experimental data from samples. Once the data are recorded in the table, the software automatically calculates the average, SD, and %RSD. The calculated average value is then used to determine the sample concentration via the linear equation and is displayed in real time. All results can be saved as a text file for further analysis or for inclusion in reports.

The external housing of the photometer was manufactured by 3D printing using fused filament fabrication (FFF) with black PLA filament. The device dimensions are $100 \times 205 \times 80$ mm (Figure 3(A)). The upper section comprises a control and display unit consisting of a 3.2-inch TFT LCD (ILI9341, Ilitek, Taiwan) mounted on an inclined panel to facilitate viewing and operation. The touchscreen functions both as a display and user interface for command input. Adjacent to the display is the sample compartment, equipped with a sliding cover to prevent ambient light interference during measurements. Inside the compartment, a slot accommodates a rectangular cuvette ($12 \times 12 \times 45$ mm), allowing light to pass through the sample solution. Transmitted light is detected by an array of eight BPW34 photodiodes, which convert light intensity into electrical signals. The use of an array of eight photodiodes was adopted to increase the effective light-sensitive area of the detection module, thereby capturing a greater fraction of the transmitted light and improving the signal-to-noise ratio, particularly at low analyte concentrations. Additionally, the array provides spatial averaging across the beam cross-section, reducing the effect of any non-uniformity in the light distribution from the LED source. These signals are processed by the ESP32 to compute absorbance values, which are then displayed on the screen (Figure 3(B)). At the rear, an LED indicator shows the Wi-Fi connection status, and a momentary push-button is provided for system reset (Figure 3(C)). Although PLA was used for the prototype's housing, it should be noted that its chemical resistance to concentrated acids is limited. For future long-term field applications, using more robust materials such as ABS or PETG, or applying chemical-resistant coatings, is recommended to enhance the device's durability against reagent vapors.

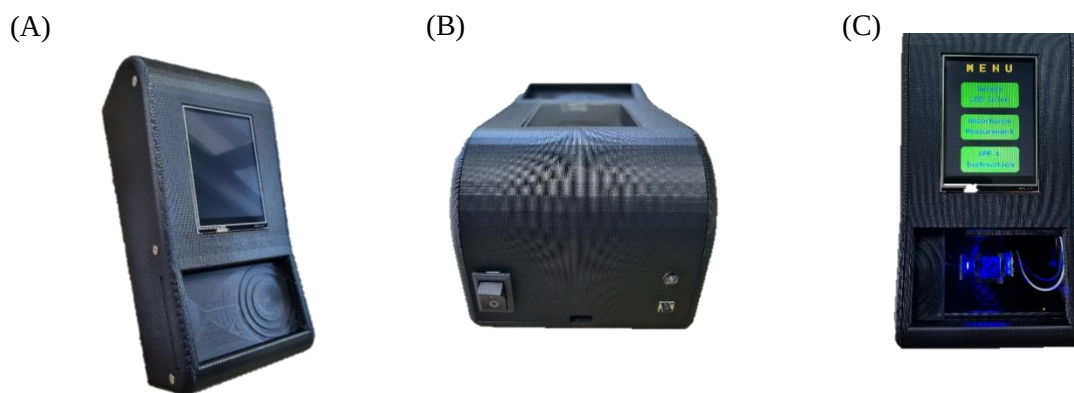


Figure 3 The developed photometer: (A) front view, (B) rear view, (C) during operation.

2.2 Application to analysis of fertilizer samples

The developed photometer was employed to determine phosphorus and iron in chemical fertilizer samples by the molybdenum blue method and 1,10-phenanthroline method, respectively. The results were validated against two standard spectrophotometric methods: the 1,10-phenanthroline method (APHA Standard Method 3500-Fe B) [15] for iron determination and the ascorbic acid–molybdenum blue method (APHA Standard Method 4500-P E) [15] for phosphorus determination.

2.2.1 Preparation of reagents and standards

All solutions were freshly prepared with deionized water and analytical-grade chemicals in accordance with APHA Standard Methods 3500-Fe B and 4500-P E [15]. A stock standard solution (1000 mg L^{-1}) of Fe(II) was prepared by dissolving 1.7726 g of ferrous ammonium sulfate hexahydrate $((\text{NH}_4)_2\text{Fe}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O})$, KemAus, Australia) in water containing 0.1% v/v concentrated sulfuric acid (H_2SO_4 , RCI Labscan, Thailand). Working standard solutions ($1.14\text{--}10 \text{ mg L}^{-1}$) were prepared daily by diluting the stock solution with ammonium acetate buffer. The ammonium acetate buffer (pH 4.2) was prepared by dissolving 1.665 g of ammonium acetate ($\text{CH}_3\text{COONH}_4$, KemAus, Australia) in approximately 800 mL of deionized water, adding 4.49 mL of glacial acetic acid (CH_3COOH , RCI Labscan, Thailand), and diluting to 1 L. The pH was adjusted to 4.2 using glacial acetic acid or ammonium hydroxide (NH_4OH) as required. A 0.1% w/v phenanthroline reagent was prepared by dissolving 0.101 g of 1,10-phenanthroline monohydrate ($\text{C}_{12}\text{H}_8\text{N}_2 \cdot \text{H}_2\text{O}$, KemAus, Australia) in deionized water and diluting to 100 mL. A 0.1% w/v ascorbic acid solution was prepared by dissolving 0.100 g of ascorbic acid ($\text{C}_6\text{H}_8\text{O}_6$, Loba Chemie, India) in deionized water and diluting to 100 mL as the reducing agent.

A stock standard solution of phosphorus (100 mg L^{-1} as P) was prepared by drying potassium dihydrogen phosphate (KH_2PO_4 , Ajax Finechem, Australia) at 105°C for 1 h, accurately weighing 0.4394 g, dissolving in deionized water, and diluting to 1000 mL. Working standard solutions ($0.085\text{--}1.0 \text{ mg L}^{-1}$) were freshly prepared by diluting the stock solution. The reagent mixture was prepared by dissolving 0.13 g of potassium antimony tartrate trihydrate ($\text{C}_4\text{H}_4\text{KO}_7\text{Sb} \cdot 3\text{H}_2\text{O}$, Loba Chemie, India) in approximately 700 mL of deionized water, adding 5.6 g of ammonium molybdate tetrahydrate $((\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O})$, Loba Chemie, India) and 70 mL of concentrated sulfuric acid (H_2SO_4 , RCI Labscan, Thailand), and diluting to 1000 mL. The combined reagent was prepared by dissolving 0.50 g of ascorbic acid in 100 mL of the reagent mixture immediately before use.

2.2.2 Sample preparation

Six fertilizer samples were prepared for the analysis of iron (Fe) and phosphorus (P). For Fe determination, 5 g of each fertilizer sample was accurately weighed, dissolved in deionized water, and diluted to 100 mL. For P determination, 0.75 g of each fertilizer sample was weighed, dissolved in deionized water, and diluted to 100 mL. The solutions were thoroughly mixed until complete dissolution was achieved and then transferred into pre-cleaned sample bottles, which were properly labeled with detailed sample information for subsequent analysis. Prior to analysis, sample solutions were diluted appropriately to bring the analyte concentrations within the calibrated linear ranges of

the method (Fe: 1.14–10 mg L⁻¹; P: 0.085–1.0 mg L⁻¹). The reported concentrations were calculated by multiplying the measured values by the corresponding dilution factors.

2.2.3 Analytical procedure

The quantitative determination of iron (Fe) and phosphorus (P) was carried out using both the developed photometer and a commercial UV–Visible spectrophotometer for method validation.

For phosphorus analysis, 50 mL of each sample was transferred into a beaker and one drop of phenolphthalein indicator was added. If a red color appeared, concentrated H₂SO₄ was added dropwise until the color disappeared. Subsequently, 10 mL of the combined reagent was added, mixed thoroughly, and allowed to stand for 10 minutes but not more than 30 minutes before measurement. The absorbance of the resulting phosphomolybdenum blue complex was measured at 880 nm following APHA Standard Method 4500-P E [15], using the UV–Visible spectrophotometer (UV9100B, LabTech, USA). In parallel, the same samples were analyzed using the developed photometer, in which the red LED of the WS2812B module was selected as the light source and the transmitted intensity was detected by the BPW34 photodiode.

For iron analysis, 2 mL of each sample solution was pipetted into a 50 mL beaker followed by the addition of 2 mL of acetate buffer (pH 4.2), 2 mL of 0.1% w/v ascorbic acid solution, and 2 mL of 0.1% w/v 1,10-phenanthroline solution. The mixtures were thoroughly mixed and allowed to stand for 10 minutes to form the orange-red Fe(II)–phenanthroline complex, following APHA Standard Method 3500-Fe B [15]. The absorbance was then measured at 510 nm using the UV–Visible spectrophotometer. The same procedure was simultaneously performed with the developed photometer, using the green LED of the WS2812B module as the excitation source and BPW34 photodiode as the detector.

All sample solutions were measured in triplicate ($n = 3$) from the same prepared solution. The agreement between the developed photometer and the APHA reference method was evaluated separately for each analyte. For both Fe and P, Bland–Altman analysis was performed on samples with quantifiable concentrations to evaluate the agreement between the developed photometer and the reference method, with the mean bias and 95% limits of agreement ($LoA = \text{mean bias} \pm 1.96 \times \text{SD of differences}$) reported for each analyte. To assess the accuracy and potential matrix effects in complex fertilizer samples, a spike recovery study was conducted. Three randomly selected fertilizer samples were spiked with Fe standard solution at 2.0 mg L⁻¹ and P standard solution at 0.5 mg L⁻¹, and each spiked sample was analyzed in triplicate ($n = 3$) using the developed photometer.

3. Results and discussion

The developed photometer was demonstrated for the determination of iron and phosphorus. The performance of the photometer was evaluated through calibration, sample measurements, and statistical comparison with the conventional spectrophotometric method.

3.1 Analytical characteristics of light sources

To evaluate the analytical performance and optical characteristics of the developed photometer, the responsivity of four different LEDs (red, green, blue, and white) was assessed using standard colored solutions prepared from powder food colorings (Dao brand, Thailand): a red solution from Ponceau 4R (C₂₀H₁₁N₂Na₃O₁₀S₃, E124), a blue solution from Brilliant Blue FCF (C₃₇H₃₄N₂Na₂O₉S₃, E133), an orange solution from a blend of Sunset Yellow FCF (C₁₆H₁₀N₂Na₂O₇S₂, E110) and Ponceau 4R, and a green solution from a blend of Tartrazine (C₁₆H₉N₄Na₃O₉S₂, E102) and Brilliant Blue FCF, each at two concentration levels (0.01% and 0.1% w/v). Mean absorbance values, SD, and %RSD were determined to evaluate the reproducibility and stability of the photometric responses for each LED-solution combination, as summarized in Table 1.

The red LED (peak emission 620–630 nm, typ. 625 nm) demonstrated high responsivity toward green and blue solutions, which possess absorption characteristics complementary to its emitted wavelength. Absorbance values ranged from 0.3905 to 0.4070 at 0.01–0.1% concentration levels, while no measurable signal was obtained for the orange solution due to spectral overlap with the LED emission. Excellent reproducibility was achieved, with %RSD values between 0.09 and 0.77%, indicating stable and reliable performance. These results confirm the suitability of the red LED for colorimetric detection of analytes exhibiting complementary colors, such as phosphomolybdate blue complexes.

Table 1 Absorbance values, standard deviations (SD), and relative standard deviations (%RSD) for different LED light sources measured against colored solutions at 0.01 and 0.1%w/v concentrations.

LED Color	Colored solution (%w/v)	Absorbance $\pm$ SD (n = 10)	%RSD
Red	Orange (0.01%)	0.0000 $\pm$ 0.0000	-
	Green (0.01%)	0.0827 $\pm$ 0.0004	0.48
	Blue (0.01%)	0.3905 $\pm$ 0.0030	0.77
	Orange (0.1%)	0.0000 $\pm$ 0.0000	-
	Green (0.1%)	0.4045 $\pm$ 0.0003	0.09
	Blue (0.1%)	0.4070 $\pm$ 0.0030	0.74
Green	Red (0.01%)	0.3472 $\pm$ 0.0055	1.60
	Orange (0.01%)	0.2460 $\pm$ 0.0064	2.61
	Blue (0.01%)	0.0530 $\pm$ 0.0015	2.74
	Red (0.1%)	0.3800 $\pm$ 0.0063	1.67
	Orange (0.1%)	0.3587 $\pm$ 0.0022	0.61
	Blue (0.1%)	0.2362 $\pm$ 0.0022	0.94
Blue	Red (0.01%)	0.3316 $\pm$ 0.0053	1.61
	Orange (0.01%)	0.3292 $\pm$ 0.0060	1.83
	Green (0.01%)	0.2127 $\pm$ 0.0014	0.67
	Red (0.1%)	0.3629 $\pm$ 0.0150	4.15
	Orange (0.1%)	0.3619 $\pm$ 0.0008	0.22
	Green (0.1%)	0.3448 $\pm$ 0.0014	0.41
White	Red (0.01%)	0.0000 $\pm$ 0.0000	-
	Orange (0.01%)	0.0000 $\pm$ 0.0000	-
	Green (0.01%)	0.0000 $\pm$ 0.0000	-
	Blue (0.01%)	0.0000 $\pm$ 0.0000	-
	Red (0.1%)	0.0051 $\pm$ 0.0024	46.65*
	Orange (0.1%)	0.0000 $\pm$ 0.0000	-
	Green (0.1%)	0.0820 $\pm$ 0.0009	1.05
	Blue (0.1%)	0.0577 $\pm$ 0.0009	1.64

* %RSD not interpretable; calculated from a near-zero absorbance signal (mean = 0.0051 AU), making the relative value statistically unreliable.

The green LED (peak emission ~525 nm) exhibited strong absorbance responses toward red and orange solutions, with values ranging from 0.2460 to 0.3800, while blue solutions yielded weak signals due to spectral overlap. Reproducibility was generally satisfactory, with %RSD values between 0.61 and 2.74%; optimal precision was achieved for the orange solution at 0.1% concentration (%RSD = 0.61%). These observations indicate that the green LED is well-suited for the detection of red or orange-colored analytes that absorb in the 520–550 nm range, such as the Fe(II)–phenanthroline complex, making it suitable for iron determination applications.

The blue LED (peak emission ~470 nm) provided strong absorbance signals for red and orange solutions (Abs = 0.3292–0.3629) and moderate responses for green solutions (Abs = 0.2127–0.3448). The system demonstrated good overall reproducibility with %RSD values between 0.22 and 1.83%, except for the red solution at 0.1% concentration, where higher variability was observed (%RSD = 4.15%). The blue LED is therefore suitable for the analysis of orange to red-colored species absorbing in the 440–480 nm region.

In contrast, the white LED, which exhibits broad spectral emission spanning 400–700 nm, showed the weakest signal response performance among all LEDs evaluated. No measurable absorbance was observed for red, orange, or green solutions at 0.01% concentration, and only minimal response was detected for the red solution at 0.1% (Abs = 0.0051). Significantly, the white LED exhibited very poor reproducibility, with %RSD of 46.65 for the only measurable signal. This high measurement uncertainty is attributed to the broadband nature of the white LED emission and weak spectral overlap with the absorption bands of the test solutions. Consequently, the white LED is unsuitable as a primary light source for colorimetric applications, although it may be applicable for general illumination purposes or instrument alignment.

3.2 Calibration curves and linear responses

The calibration curve for iron was constructed by plotting the absorbance of the Fe(II)–1,10-phenanthroline complex against Fe^{2+} concentration using a green LED as the light source. Measurements were performed over the linear working range of 1.14–10.0 mg L⁻¹ (LOQ–10.0 mg L⁻¹). The calibration was constructed from 6 standards with three replicates per point (n = 3), and SD_blank was calculated from n = 10 replicate blank measurements. The calibration curve followed the equation $y = 0.0088x + 0.0015$ ($R^2 = 0.981$), with residuals across the working range of -0.004 to +0.006 absorbance units showing no systematic trend, confirming the appropriateness of the linear model. The limit of detection (LOD) and limit of quantification (LOQ), calculated as $3 \times \text{SD_blank/slope}$ and $10 \times \text{SD_blank/slope}$, were 0.34 mg L⁻¹ and 1.14 mg L⁻¹, respectively. The R^2 of 0.981, while below the ≥ 0.995

criterion typical for monochromator-based spectrophotometric methods, is consistent with LED-based portable photometers reported in the literature, where the broader emission bandwidth of the LED source introduces greater photometric variation than a monochromator.

For phosphorus analysis, the calibration curve was constructed by measuring the absorbance of the phosphomolybdate complex produced in the molybdenum blue reaction using a red LED. A strong linear correlation was observed over the linear working range of 0.085–1.0 mg L⁻¹ (LOQ–1.0 mg L⁻¹), established from *n* = 10 replicate blank measurements, according to the equation: $y = 0.1182x + 0.0026$ ($R^2 = 0.9966$). The calculated LOD and LOQ values were 0.025 mg L⁻¹ and 0.085 mg L⁻¹, respectively, demonstrating the suitability of the method for detecting low phosphorus concentrations.

3.3 Determination of iron and phosphorus in fertilizer samples

The developed photometer was applied to the quantitative determination of iron and phosphorus in fertilizer samples using standard colorimetric methods—the 1,10-phenanthroline method for Fe(II) and the molybdenum blue method for phosphorus, respectively. The colored products generated from these reactions were measured using both the proposed photometer and a reference spectrophotometer to compare analytical performance. The analytical results are shown in Tables 2 and 3.

For Fe determination, three of the six samples (samples 1, 2, and 5) yielded concentrations above the LOD; the remaining samples (3, 4, and 6) are reported as ND. For the three quantifiable Fe samples, concentrations from the photometer and reference spectrophotometer agreed closely: Sample 1 (3.6 vs. 3.5 mg L⁻¹), Sample 2 (1.8 vs. 1.7 mg L⁻¹), and Sample 5 (4.8 vs. 5.0 mg L⁻¹), with relative differences of 2.9%, 5.9%, and 4.0%, respectively. Given *n* = 3, Pearson's correlation was not applied. Bland–Altman analysis yielded a mean bias of 0.00 mg L⁻¹ (LoA: -0.34 to +0.34 mg L⁻¹), indicating no systematic difference between the two methods for Fe determination.

For P determination, all six samples yielded quantifiable concentrations. Bland–Altman analysis revealed a mean bias of -2.25 mg L⁻¹ (LoA: -8.67 to +4.17 mg L⁻¹), indicating that the photometer systematically underestimates P concentration relative to the reference method. The wide limits of agreement are driven primarily by Samples 3 and 4, which showed large negative differences (-5.7 and -5.3 mg L⁻¹, respectively). When these two samples are excluded, the mean bias narrows to -0.63 mg L⁻¹ (LoA: -5.91 to +4.66 mg L⁻¹), suggesting that method agreement is substantially better in samples without pronounced matrix interference. The discrepancy in Samples 3 and 4 is attributed primarily to matrix effects, such as competing chromophores or high ionic strength in these specific fertilizer matrices, rather than to wavelength mismatch alone. Although operating at 625 nm instead of the molybdenum blue λ_{max} (880 nm) reduces molar absorptivity, the acceptable spike recovery (90–112% for P) in controlled matrices confirms that wavelength mismatch does not produce bias of this magnitude. Future device iterations could incorporate a near-infrared LED (e.g., 850 nm) to better match the λ_{max} and reduce matrix sensitivity.

Furthermore, the accuracy of the method was validated through recovery experiments on spiked fertilizer samples. The recovery percentages ranged from 93–105% for Fe and 90–112% for P, which are within the acceptable range for colorimetric methods at the respective concentration levels, indicating acceptable method accuracy in complex fertilizer matrices.

Table 2 The results of iron determination in fertilizer samples analysis using the developed photometer compared with a spectrophotometric method. Iron determination in fertilizer samples Fe.

Sample	Found Fe (mg L ⁻¹)		Found Fe (mg g ⁻¹)	
	Photometer*	Spectrophotometer*	Photometer*	Spectrophotometer*
1	3.6 ± 0.2	3.5 ± 0.1	0.072 ± 0.004	0.070 ± 0.002
2	1.8 ± 0.2	1.7 ± 0.1	0.036 ± 0.004	0.034 ± 0.002
3	ND	ND	ND	ND
4	ND	ND	ND	ND
5	4.8 ± 0.3	5.0 ± 0.2	0.096 ± 0.006	0.100 ± 0.004
6	ND	ND	ND	ND

* Mean of triplicate measurements; ND = Not Detectable; Fe content (mg g⁻¹) calculated as $C \text{ (mg L}^{-1}) \times 0.02 \text{ L g}^{-1}$ (5 g / 100 mL)

Table 3 The results of iron determination in fertilizer samples analysis using the developed photometer compared with a spectrophotometric method. Iron determination in fertilizer samples P.

Sample	Found P (mg L ⁻¹)		Found P (mg g ⁻¹)	
	Photometer*	Spectrophotometer*	Photometer*	Spectrophotometer*
1	23.7 ± 0.3	22.2 ± 0.1	3.16 ± 0.04	2.96 ± 0.01
2	6.1 ± 0.2	9.3 ± 0.2	0.81 ± 0.03	1.24 ± 0.03
3	2.5 ± 0.2	8.2 ± 0.1	0.33 ± 0.03	1.09 ± 0.01
4	2.1 ± 0.2	7.4 ± 0.1	0.28 ± 0.03	0.99 ± 0.01
5	33.9 ± 0.2	32.0 ± 0.2	4.52 ± 0.03	4.27 ± 0.03
6	55.5 ± 0.3	58.2 ± 0.1	7.40 ± 0.04	7.76 ± 0.01

* Mean of triplicate measurements; P content (mg g⁻¹) calculated as C (mg L⁻¹) × 0.1333 L g⁻¹ (0.75 g / 100 mL).

3.4 Comparison with previous work

The instrumental features of the developed photometer were compared with those of four recently reported laboratory-made portable photometric devices (Table 4) [9,11,16,17]. As shown, the present device offers three key advantages: (i) multi-analyte capability for both Fe and P determination using a single WS2812B RGB LED with selectable emission wavelengths (R: 620–630 nm, G: 515–525 nm, B: 465–475 nm); (ii) real-time wireless data transmission via ESP32 built-in Wi-Fi, extending its suitability for remote field monitoring; and (iii) an estimated component cost of approximately USD 35, which is among the lowest reported for comparable portable photometric instruments. The LODs and linear ranges obtained are appropriate for Fe and P concentrations typically encountered in agricultural water samples.

Table 4 Comparison of instrumental features of selected laboratory-made portable photometric devices.

Feature	Laganovska et al. [9]	Di Nonno & Ulber [11]	Pal et al. [16]	Fernandes et al. [17]	This work
Illumination source	White LED	LED (590 nm)	Single LED	RGB LED	WS2812B RGB LED
Transducer / Detector	Hamamatsu C12880MA micro spectrometer	Phototransistor (SFH300)	Silicon photodiode	TCS34725 RGBC color sensor	BPW34 silicon PIN photodiode
Signal processor	Arduino Nano	Arduino	Arduino	ESP32	ESP32
Connectivity / Readout	Bluetooth (smartphone app)	USB (PC)	Bluetooth + IoT	Wi-Fi/Bluetooth	Wi-Fi (web interface)
Dimension (LxWxH mm)	90 × 85 × 58	90 × 93 × 95	110 × 60 × 60	NR	100 × 205 × 80
Est. component cost (USD)	~ 265	NR	~ 35	~ 88	~ 35
Analyte	Vitamin B12, P, H ₂ O ₂	Protein, P	P, NO ₂	Fe ²⁺	Fe, P (multi-analyte)
Linear range	Vitamin B12: 3-24 mg L ⁻¹ ; P: 0.2–2 mg L ⁻¹ ; H ₂ O ₂ : 22-264 µM	Protein: 0.0-1.0 mg L ⁻¹ ; P: 0.0-1.0 mg L ⁻¹	P: 0.31-3.10 mg L ⁻¹ ; NO ₂ : 0.23-1.38 mg L ⁻¹	Fe: 0-1 mg L ⁻¹	Fe: 1.14–10 mg L ⁻¹ ; P: 0.085–1.0 mg L ⁻¹
LOD	Vitamin B12: 2.7 mg L ⁻¹ ; P: 0.2 mg L ⁻¹ ; H ₂ O ₂ : 1.9 µM	Protein: 0.0086 mg mL ⁻¹ ; P: 0.058 mg L ⁻¹	P: 0.074 mg L ⁻¹ ; NO ₂ : 0.06 mg L ⁻¹	Fe: 0.008 mg L ⁻¹	Fe: 0.34 mg L ⁻¹ ; P: 0.025 mg L ⁻¹

NR = Not Reported

4. Conclusion

A portable photometer integrating an ESP32 microcontroller, BPW34 photodiode, and WS2812B RGB LED was successfully developed for colorimetric determination of iron and phosphorus. The device demonstrated acceptable linearity and reproducibility, with LOD values of 0.34 mg L⁻¹ for Fe and 0.025 mg L⁻¹ for P. Bland–Altman analysis confirmed good agreement between the photometer and APHA reference methods for Fe (mean bias = 0.00 mg L⁻¹, n = 3) and acceptable agreement for P (mean bias = -2.25 mg L⁻¹, n = 6), with spike recoveries of 93–105% and 90–112%, respectively, demonstrating its analytical suitability for routine determination of Fe and P in fertilizers, soils, and water samples. The BPW34 photodiode's broad spectral response ensured reliable light detection across the required wavelength ranges. This affordable photometer shows promise for routine nutrient analysis in resource-limited settings, with future applications potentially including cloud-based monitoring and multi-parameter environmental sensing.

5. Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used Claude AI in order to assist with ESP32 microcontroller programming and code development. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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7. Author Contributions

Kanna, M.: Data curation, Formal analysis, Methodology, Validation, Writing – original draft; Permwong, W.: Software, Visualization; Somnam, S.: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing

8. Conflicts of Interest

The authors declare no conflicts of interest.

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