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DESIGN OF A MICROFLUIDIC DEVICE FOR COLORIMETRIC ESTIMATION OF SOIL PH USING AN OPTIMIZED INDICATOR MIXTURE

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ABSTRACT: Soil pH is a critical parameter in soil analysis, influencing nutrient availability, microbial activity, and overall soil health. Although several methods exist for measuring soil pH, many of them face limitations in terms of continuous monitoring, including the need for laboratory infrastructure, trained personnel, or expensive instrumentation. Consequently, there is a growing need to develop novel approaches that are rapid, low-cost, user-friendly, and suitable for on-site applications. In this study, a colorimetric detection method was developed using an optimized mixture of pH indicators integrated into a microfluidic device (MFD) for the determination of soil pH. This approach enables farmers and field workers to directly assess soil pH in the field across a broad range of pH values (2–10). The indicator mixture, consisting of bromocresol green, bromothymol blue, bromophenol blue, phenol red, and thymol blue, was designed to produce distinct colour transitions over a wide pH spectrum. A linear and visually discernible response was achieved across two key pH intervals: an acidic range from pH 2.0 to 6.0 (covering 4.0 pH units) and an alkaline range from pH 7.0 to 12.0 (covering 5.0 pH units), demonstrating the suitability of the method for practical soil monitoring applications.

Keywords: colorimetry, indicator- mixture, microfluidic technologies, soil pH

1 INTRODUCTION

1.1 Background

Soil pH is a critical parameter that influences a wide range of soil properties and agricultural productivity. It affects the chemical form and availability of essential nutrients, microbial activity, and the behaviour of toxic elements (Dewangan et al., 2023). Maintaining optimal soil pH is vital for healthy plant growth and sustainable agricultural practices. Therefore, routine monitoring of soil pH is essential for informed decision-making in agriculture, especially in the context of precision farming. Traditional methods for soil pH determination, such as glass electrode pH meters or colorimetric test kits, often require sample preparation, reagent handling, and interpretation by trained personnel. These techniques, while accurate under laboratory conditions, may be impractical for on-site or rapid assessment, particularly in resource-limited or field-based settings. Additionally, pH meters can be sensitive to environmental conditions and require frequent calibration and maintenance (Lu et al., 2020; Sansalvador et al., 2016). These limitations highlight the need for alternative, user-friendly approaches that offer rapid, reliable, and cost-effective soil pH measurement directly at the point of use (Dudala et al., 2020).

1.2 Significance of using a microfluidic device and a colorimetric detection technique

Recent advancements in microfluidics and sensor technologies offer promising alternatives for on-site soil analysis. Microfluidic devices, also known as lab-on-a-chip systems, enable precise fluid handling at the microliter scale and facilitate rapid analysis with minimal reagent consumption (Lu et al., 2020). When integrated with colorimetric detection systems, microfluidics provides a platform for simple, low-cost, and portable sensing solutions (Dudala et al., 2020). Potentiometric methods commonly used for pH measurement are reliable only within specific conditions, typically between 278–323 K in temperature, 0.1 MPa pressure, and ionic strengths below 0.1 mol/kg of water. These limitations arise due to the instability of the reference electrode and uncertainties in the liquid junction potential under extreme conditions. In contrast, spectroscopic (or colorimetric) methods offer an alternative approach, using pH-sensitive dyes that exhibit colour changes corresponding to the solution's pH (Lin & Liu, 2000; Raghuraman et al., 2006a). In this study, we present a colorimetric approach for soil pH estimation using an optimized mixture of pH indicators integrated into a microfluidic device. The indicator mixture was designed to provide a smooth and distinguishable colour gradient across the target pH range. The microfluidic platform allows efficient sample-reagent interaction and visual detection without the need for advanced instrumentation. Using an optimized indicator mixture for soil pH determination provides a broader detection range with sharper colour transitions compared to conventional pH paper, which often gives only approximate values. In contrast, pH papers are less reliable for soil testing due to colour fading, overlapping shades, and interference from soil turbidity or colored extracts, leading to reduced precision. This work addresses key limitations in current soil pH testing methods by offering a low-cost, rapid, and user-friendly solution, particularly suited for applications in precision agriculture and resource-limited settings.

2 METHODOLOGY

2.1 Reagents and materials

The pH indicators utilized in this study comprised Bromophenol Blue (BPB), Bromothymol Blue (BTB), Bromocresol Green (BCG), Thymol Blue (TB), and Phenol Red (PR), all of which were used as received without any further purification. Additional reagents, including ethanol, hydrochloric acid (HCl), and sodium hydroxide (NaOH), were of analytical grade. All solutions were prepared using distilled water. A matrix solution containing 0.001 M buffer(s) and 0.05 M NaCl was employed to maintain consistent pH and ionic strength. Three types of buffers, Tris [tris(hydroxymethyl) aminomethane], citric acid, and boric acid, were selected based on their effective pH ranges (Lin & Liu, 2000). The pH of the solutions was precisely adjusted to the target values using 0.1 M HCl or 0.1 M NaOH, and measurements were conducted with an Onyx Aqua Farm digital pH meter with an accuracy of ±0.01 pH units. Spectral measurements were made using an Evolution 201 UV-Visible spectrophotometer (Thermo Scientific), with the indicator solutions analyzed in quartz cuvettes having a 10 mm optical path length. The microfluidic device employed for visualizing soil pH levels was fabricated from Poly (methyl methacrylate) (PMMA) using a laser micromachining technique. (All experiments were performed at 293 K) (Raghuraman et al., 2006b).

2.2 Preparation and spectroscopic analysis of indicator mixture

For the spectroscopic analysis of the indicators, separate solutions of each indicator were prepared. Then, according to their individual behaviour, concentrations of each indicator were optimized, which are then used in the mixture. Optimized concentration of each indicator was BPB: BCG: BTB: TB: PR, 0.05:0.1:0.2:0.15:0.05. The absorption spectra of each indicator were recorded from 250 nm to 750 nm at acidic (pH 2.02), neutral (pH 7.10), and alkaline (pH 11.21) conditions. The behaviour of the indicator mixture at different buffer solutions from pH 2-10 was studied using the UV-Visible spectrophotometer. For the visual illustration of the indicator mixture for soil sample testing, a colour chart was developed so that it can be easily used in field-level applications for pH determination.

2.3 Soil pH determination using the Microfluidic device

The capillary breaching technique was used to introduce the soil solution and reagent mixture to the MFD. Then the pH was determined using the developed color chart.

3 RESULTS AND DISCUSSION

Colorimetric pH determination relies on the change in absorbance of an indicator with pH. A single indicator is effective only within a narrow range of about two pH units ($pK_a \pm 1$). Outside this range, absorbance changes are minimal, leading to greater measurement error. One method to broaden the dynamic range for pH measurement is to use multiple indicators. This is illustrated in Figure 1(a), which shows the response for different indicators (BPB, BCG, BTB, PR, and TB) and a mixture of indicators with different pK_a. The normalized absorbance response to pH for individual indicators and a mixture of multiple indicators is shown. Calculations assume absorbance is measured at a wavelength where only the basic form of each indicator absorbs, and that the concentrations in the mixtures are adjusted to produce equal maximum absorbance. Solid lines represent the responses of single indicators, while dashed lines depict the combined response of indicator mixtures. It is clearly shown that the dynamic range for pH measurement is broadened by using a mixture of indicators, and it has a linear response over a broader pH range from 2 to 10.

Although the base forms of the indicators differ in colour, as BPB (purple), BCG (blue), BTB (blue), TB (blue), and PR (red), their absorption spectra are relatively close. As shown in Figure 1(b), the ideal measurement wavelength lies between points A and B, where the spectra of indicators intersect. Selecting a wavelength in this region, specifically 570 nm, ensures that the absorbance values of the indicators are comparable, allowing balanced contributions from each dye in a mixed indicator solution. Figure 1(c) displays the absorbance of the dye measured at 525 nm, while Figure 1(d) displays the absorbance of the dye measured at 570 nm across varying pH levels. The data show a strong linear correlation at two wavelengths, 525 nm and 570 nm, within the pH range of 2 to 12, indicating a consistent and predictable response of the dye in this interval.

The developed MFD is reusable, and when combined with a set of capillaries sufficient for 15 tests, the total cost is approximately LKR 650.00. This highlights the economic feasibility of the device for routine soil pH assessment, offering a low-cost alternative to conventional laboratory-based methods.

Figure 2(a) shows an image of the fabricated MFD, and Figure 2(b) depicts how the optimized indicator mixture is visualized within the microfluidic device, highlighting its interaction and response under specific pH conditions.

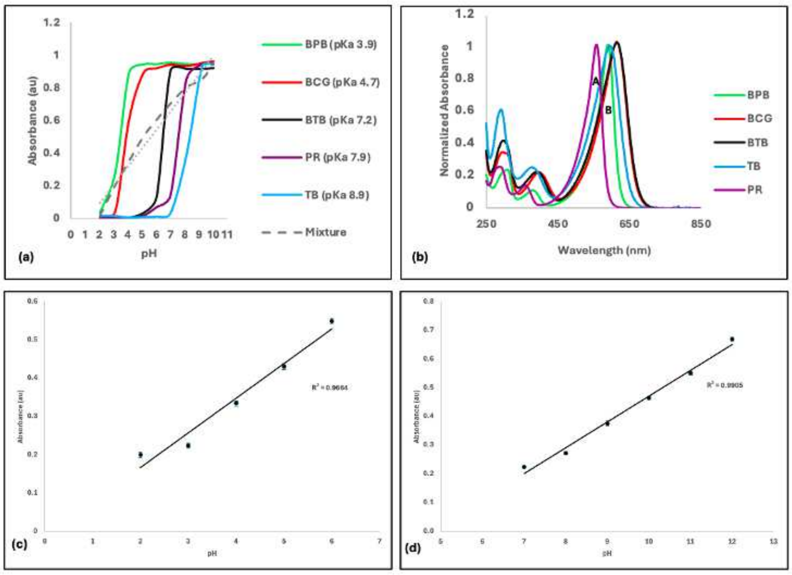

Figure 1. (a) Absorbance response to pH of single indicators and indicator mixture (b) Normalized spectra of the base form of the five indicators(BPB, BCG, BTB, TB, PR) (c) Absorbance at 525 nm as a function of pH, The line shows the linear fit at the linear range pH 2-6, R2 =0.9985 (d) Absorbance at 570 nm as a function of pH, The line shows the linear fit at the linear range pH 7-12, R2 =0.9948

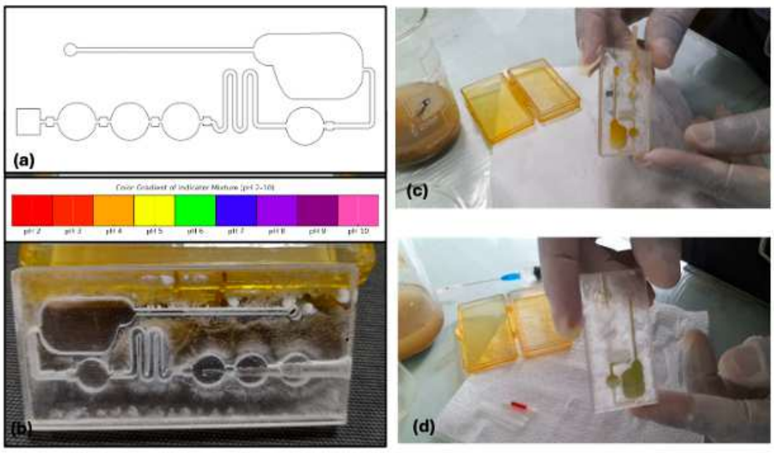

Figure 2. (a) CAD design of the microfluidic device with the developed colour chart. Photograph of the prototype microfluidic sensor chip: (b) before use, and (c), (d) after exposure to two different soil samples with different pH, showing the visible colour change following the reaction.

4 CONCLUSION

The developed colorimetric method for soil pH estimation, utilizing an optimized mixture of pH-sensitive indicators embedded in a microfluidic device, offers a practical, low-cost, and field-deployable solution for rapid soil analysis. The indicator mixture provided a visually distinct and linear response across a wide pH range (2–10), with enhanced resolution in both acidic (pH 2.0–6.0) and alkaline (pH 7.0–10.0) intervals. The integration of this system into a portable microfluidic platform demonstrates its potential for empowering farmers and agricultural stakeholders with on-site soil pH monitoring, thereby contributing to precision agriculture and informed soil management practices.

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