Vol. 08, No. 2 (2026) 1253-1260, doi: 10.24874/PES08.02B.014

Proceedings on Engineering Sciences

www.pesjournal.net

MICROFLUIDIC DEVICE FOR RAPID SOIL pH ASSESSMENT USING AN OPTIMIZED INDICATOR MIXTURE

H.M.C.S. Wijerathne[1]
N.D. Tissera
G. Priyadarshana
R.N. Wijesena

Received 21.12.2025
Revised 12.02.2026
Accepted 13.04.2026

Keywords:

Soil pH, Microfluidic device, Indicator mixture, Precision Agriculture, On-site monitoring

A B S T R A C T

Soil pH monitoring is critical in agriculture as it directly affects the plant nutrient absorption and microbial activity, including a number of chemical and biochemical reactions. Although various pH assessment methods exist, a clear gap remains in achieving rapid, on-site soil pH measurement with current techniques, where microfluidic devices show a remarkable impact. This study presents the development of a microfluidic pH sensor unit incorporating an optimized indicator mixture for enhanced accuracy and range. The indicator mixture is composed of five sulphonephthalein indicators, which have an improved linear response over a broad range from pH 2 to 10. The prototype microfluidic pH sensing platform enables rapid, on-site, and continuous soil pH measurement, is low-cost and easy to operate, and effectively fulfills the pH monitoring requirements of precision agriculture.

1. INTRODUCTION

Soil pH is a significant soil quality parameter that regulates several chemical and biological processes that are operating within the soil. The pH of soil typically ranges from 1 to 14, with a pH value of 7 considered neutral. Values below 7 indicate acidic conditions, whereas values above 7 represent alkaline (basic) conditions. Both the acid-forming and base-forming ions affect soil pH. Soil acidity is strongly influenced by acid-forming cations such as hydrogen (H^+), aluminum (Al^{3+}), and iron (Fe^{2+}, Fe^{3+}), whereas soil alkalinity is governed by base-forming cations including calcium (Ca^{2+}), potassium (K^+), and sodium (Na^+)(Jackson & Thomas Meetei, 2018). Soils exhibiting alkaline pH values typically contain elevated levels of these basic cations, along with carbonates and bicarbonates derived from soil minerals or irrigation water.

In regions with low precipitation, reduced leaching of base cations further contributes to elevated pH values above 7. Conversely, acidic soils are commonly found in high-rainfall environments or in areas where the parent material is rich in silicic minerals. Increased precipitation enhances the leaching of base cations, thereby lowering soil pH (Jackson & Thomas Meetei, 2018). Moreover, soil pH is affected by crop growth, the use of fertilizers, acid rains, and oxidative weathering. Soil acidity and alkalinity can be adjusted through the application of appropriate soil amendments. Soil acidity is commonly reduced (soil pH increased) by incorporating alkaline materials such as finely ground limestone (calcium

[1] Corresponding author: R.N Wijesena
Email: ruchiraw@itum.mrt.ac.lk

carbonate), industrial-grade calcium oxide, or wood ash, all of which supply base-forming cations and neutralize excess hydrogen ions in the soil solution. On the other hand, soil alkalinity can be decreased (soil pH lowered) by applying acidifying amendments. These include nitrogen-based fertilizers such as ammonium nitrate or urea, which release hydrogen ions during nitrification, as well as acidic organic matter. Elemental sulfur is also widely used; upon microbial oxidation, it forms sulfuric acid, effectively lowering soil pH(Odutola Oshunsanya, 2019). According to the classification system of the United States Department of Agriculture (USDA), Natural Resources Conservation Service, soil pH is categorized into distinct ranges. Soils with pH values below 3.5 are considered ultra-acidic, while those between 3.5 and 4.4 fall into the extremely acidic class. pH levels from 4.5 to 5.0 are termed very strongly acidic, and values between 5.1 and 5.5 are regarded as strongly acidic. The range of 5.6 to 6.0 is classified as moderately acidic, whereas soils with a pH of 6.1–6.5 are slightly acidic. A pH of 6.6–7.3 is defined as neutral. On the alkaline side, soils with pH values of 7.4–7.8 are slightly alkaline, those between 7.9 and 8.4 are moderately alkaline, and soils with pH 8.5–9.0 are strongly alkaline. Values exceeding 9.0 are categorized as very strongly alkaline (Burt, 2014).

Maintaining an optimal soil pH is fundamental for ensuring healthy plant growth, efficient nutrient uptake, and long-term agricultural productivity. Soil pH influences the chemical form and availability of essential macro and micronutrients, affects microbial activity, and governs the mobility of potentially toxic elements (Kumar et al., 2023).Even slight deviations from the optimal pH range can lead to nutrient deficiencies or toxicities, ultimately reducing crop yield and quality. Therefore, regular soil pH monitoring is a key component of evidence-based land management, enabling farmers to select appropriate amendments, fertilizers, and crop varieties. This practice has become even more critical with the expansion of precision agriculture, where site-specific soil information guides real-time management decisions to enhance sustainability and resource-use efficiency (Najdenko et al., 2024).

1.1 Soil pH monitoring

Conventional methods used for measuring soil pH present several limitations when applied to precision agriculture systems. Common and traditional soil pH measurement methods include laboratory slurry analysis, portable electrochemical pH meters, and colorimetric test kits. In the lab-based slurry method (Merl et al., 2022), a soil sample is mixed with distilled water or a $CaCl_2$ solution (in ratios such as 1:2.5 or 1:5), and a calibrated glass-electrode pH meter is used to obtain very accurate and precise measurements widely regarded as the gold standard (Eldeeb et al., 2023). Portable pH meters, which use glass or solid-state electrodes, allow for rapid on-site readings but require frequent calibration and careful maintenance (e.g., rinsing, temperature compensation). Colorimetric kits use pH-sensitive dyes or strips that change color when mixed with a soil-water extract; they are easy to use, but less precise than electrode-based methods (Song et al., 2012; Vivaldi et al., 2021).

Advanced technologies are enabling faster, higher-resolution, and more scalable soil pH monitoring platforms suited to precision agriculture. In-situ electrochemical pH sensors are capable of continuous, direct soil measurements without extensive sample preparation, offering real-time profiles of pH. Another approach is using Optical pH optodes that provide an alternative by measuring pH non-invasively through pH-sensitive dyes and imaging, which is especially useful for heterogeneous or partially saturated soils (Merl et al., 2022). Highlight a major drawback of the electrochemical sensors, in continuous pH monitoring, for example, electrode drift, calibration drift, fouling, and ion interference. Electrochemical probes measure only a tiny contact zone around the electrode, etc.

Microfluidic approaches, including paper-based and lab-on-chip colorimetric devices, miniaturize reagent use and combine rapid chemical reactions with digital image analysis or smartphone readouts for low-cost, field-deployable pH assays (Chanu et al., 2020). When these sensors are networked via IoT architectures, they enable continuous, remote monitoring and integration with decision-support systems for site-specific management at larger scales.

Despite these advances, many of the existing technologies remain inaccessible to the farmers due to their high initial costs, technical complexity, and the need for specialized expertise in deployment and data interpretation. As a result, such methods have not gained widespread adoption among farmers, particularly in smallholder and resource-limited settings. This gap highlights the need for a practical, affordable, and user-friendly solution that can support routine soil pH monitoring without sophisticated instrumentation. In this context, a microfluidic-based pH sensing device offers a promising alternative, providing low-cost, rapid, and field-deployable measurements that better align with the operational realities of precision agriculture. Based on the literature survey, by studying available technologies and methods for soil pH assessment, this study is focused on the development of a microfluidic-based soil detection system for rapid onsite soil pH monitoring.

1.2 Microfluidic devices (MFDs) for soil pH monitoring

MFDs, also known as lab-on-a-chip (LOC) or miniaturized total analysis systems (mTAS), are at the forefront of analytical and diagnostic technology, offering groundbreaking solutions for numerous scientific, industrial, and environmental challenges (Neethirajan et al., 2011). These devices manipulate

minute fluid volumes (microlitres10^{-6} to picolitres 10^{-12} microliters) within microchannels, enabling precise control over fluid dynamics (Solanki et al., 2020). Their ability to integrate multiple laboratory functions onto a single platform significantly reduces cost, reagent consumption, and processing time. The compact nature of MFDs allows for portability and efficient use, making them particularly suitable for applications requiring real-time analysis and rapid decision-making (Kim et al., 2016; Neethirajan et al., 2011).

Recent advances in microfluidic technology have enabled highly miniaturized, reagent-efficient, and real-time pH sensing systems. Lu et al., 2020 developed an online microfluidic pH detection platform that immobilizes m-cresol purple within a PVA membrane, achieving an exceptionally broad dynamic range from extremely acidic (5 M [H^+], ~pH 3) to highly alkaline conditions (2 M [OH^-], ~pH 14) with strong reversibility, long-term stability, and Artificial Neural Networks (ANN) -based non-linear signal processing for accurate real-time readout (Lu et al., 2020). Complementing these extreme-range systems, Perez de Vargas Sansalvador et al., 2016 introduced a portable, autonomous microfluidic pH sensor that integrates low-cost LEDs, photodiodes, and optimized multi-dye reagent chemistry. Their device achieves a linear detection range from pH 4 to 9, high reproducibility (RSD ≤1.8%), excellent reagent stability (over 8 months), and successful validation in real-water samples, demonstrating suitability for long-term field monitoring(Perez De Vargas Sansalvador et al., 2016). For marine applications requiring very high accuracy, Rérolle et al.,2013 miniaturized the spectrophotometric method into a microfluidic PMMA flow cell using a tri-wavelength LED and thymol-blue chemistry, enabling autonomous seawater pH measurements with precision of 0.001 pH units, accuracy within 0.004 units of certified buffers, and extremely low reagent consumption during month-long shipboard deployments (Rérolle et al., 2013). Collectively, these platforms demonstrate that microfluidics can deliver highly stable, low-power, and field-deployable pH sensors with performance ranging from broad-range chemical robustness to oceanographic-grade accuracy.

Although a wide range of microfluidic pH sensing platforms has been developed for environmental, biomedical, and aquatic applications, microfluidic devices specifically designed for soil pH detection remain extremely limited in the literature. Most reported systems focus on aqueous samples, seawater, or controlled laboratory microchannels, while only a small number attempt direct integration with soil matrices, as discussed in the previous examples. Soil presents unique challenges, including heterogeneous texture, variable moisture content, suspended particulates, and complex buffering chemistry, which make direct microfluidic adaptation difficult. As a result, soil-specific microfluidic pH sensors are rare, with only a few emerging studies demonstrating colorimetric or electrochemical microfluidic approaches for soil analysis. This scarcity highlights a clear research gap and underscores the need for microfluidic platforms that can accommodate complexities of real soil samples while maintaining high accuracy, low reagent consumption, and field deployability (Abdullah et al., 2025; Eldeeb et al., 2023).

Given these challenges and the key role of soil pH in controlling nutrient availability and plant health, the need for rapid, onsite, and continuous monitoring has become increasingly important, particularly within precision agriculture systems that rely on real-time data for informed decision making. Traditional laboratory measurements cannot meet the spatial or temporal resolution required in the field, highlighting a clear technological gap. In response, the present study proposes a microfluidic device designed for rapid onsite soil pH assessment, utilizing an optimized mixture of indicators to achieve broad-range, high-sensitivity detection within a compact lab-on-chip platform. This work aims to advance soil chemical sensing by providing a practical and scalable solution that supports next-generation precision soil monitoring. To achieve this aim, the study focuses on the design and fabrication of a compact microfluidic device for rapid onsite soil pH measurement, together with the development and optimization of an indicator mixture based colorimetric sensing system capable of providing high sensitivity and reliable detection across a broad pH range. In addition, the work evaluates the analytical and operational performance of the proposed device in terms of sensitivity, and measurement accuracy, while demonstrating its practical applicability for precision soil monitoring and environmental assessment under real-world conditions.

2. METHODOLOGY

2.1 Reagents and materials

The pH indicators used in this study included 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, citric acid, boric acid, and Tris [tris(hydroxymethyl)aminomethane], 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.

pH measurements were conducted with an Onyx Aqua Farm digital pH meter, which had 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 used for determining soil pH levels was fabricated from Poly (methyl methacrylate) (PMMA) using a laser micromachining technique.

All experiments were performed at room temperature.

2.2 Preparation and Spectrophotometric Characterization of the Indicator Mixture

Individual stock solutions of the selected pH indicators Bromophenol Blue (BPB), Bromothymol Blue (BTB), Bromocresol Green (BCG), Thymol Blue (TB), and Phenol Red (PR) were initially prepared for subsequent spectrophotometric analysis. In spectrophotometric pH measurements employing acid–base indicators, both the protonated (acidic) and deprotonated (basic) forms exhibit distinct absorbance characteristics at specific wavelengths. Although absorbance can theoretically be measured at shorter wavelengths corresponding to the acidic form or at longer wavelengths corresponding to the basic form, the latter is generally preferred. This is because the molar absorptivity of the basic form is significantly higher at longer wavelengths, where the yellow-coloured acidic form exhibits minimal absorption(Lin & Liu, 2000). Consequently, spectral overlap between the two species is reduced, improving the sensitivity and precision of pH-dependent absorbance measurements.

Assuming the predominance of the basic form of the indicators, spectral scans were performed in the wavelength range of 300–850 nm to determine the optimal absorbance wavelength and appropriate concentration ratios for the indicator mixture. Based on these results, an indicator mixture (In-mix) was prepared using the selected concentration ratios. The spectral response of the mixture was subsequently recorded across a pH range of 2–10. Then, the normalized absorbance responses of the individual indicators and the multi-indicator mixture were analysed to evaluate linearity and assess the suitability of the system for extending the measurable pH range.

Calibration data were obtained from three consecutive spectral scans. The mean absorbance at the optimum wavelength, identified through the correlation analysis, was used as the representative value, while the corresponding standard deviation was employed to indicate the measurement reproducibility.

2.3 Fabrication of the microfluidic device (MFD) and the reagent storage chamber

The microfluidic device employed for visualizing soil pH levels was fabricated from Poly methyl methacrylate (PMMA) using a laser micromachining technique. A capillary-based reagent storage chamber was fabricated using polytetrafluoroethylene (PTFE, Teflon) tubing, which provides excellent chemical inertness and low surface adhesion. The chamber was subsequently sealed using a polymer packaging layer to prevent reagent leakage and evaporation, ensuring stability and compatibility with the microfluidic system.

2.4 Soil sample collection and pH testing

Several real samples were sourced from different locations (S1 -6°17'20.00"N, 80°46'18.04"E, S2- 7°18'14.31"N, "80°9'41.90" E, S3- 6°10'7.36"N, "80°10'44.98" E, S4- 8°10'14.57"N, 80°18'35.27" E, S5- 7°22'45.12"N, 80°21'22.53" E, S6- 6°20'50.03"N, 80°53'17.24" E, S7- 7°29'52.71"N, 80°37'18.42" E, S8- 6°56'44.33"N, 81°7'58.11" E, S9- 6°50'16.23"N, 80°0'32.52" E, S10- 7°55'44.09"N, 81°2'50.99" E) in Sri Lanka, and they were analysed using a calibrated pH meter, and the developed microfluidic device. Soil samples were collected following the standard soil testing protocols recommended by the Department of Agriculture, Sri Lanka. Representative samples were obtained by collecting 20 subsamples per 1–3-acre plot in a zigzag pattern from the plough layer (approximately 15 cm depth), after removing surface residues; the subsamples were thoroughly mixed, and a composite sample of about 1000 g was air-dried and prepared for analysis. For pH analysis, a 1:5 soil-to-water ratio was employed, and the filtered soil–water extract was used for pH determination. Breaching technique was used to introduce the soil sample along with the optimized indicator mixture to the microfluidic device.

3. RESULTS AND DISCUSSION

3.1 Spectrophotometric Characterization of the Indicator Mixture

Spectrophotometric pH determination relies on the pH-dependent absorbance shift of one or more indicators. Typically, a single indicator provides a useful measurement range of only about two pH units around its pK_a value ($pK_a \pm 1$). Outside this interval, the absorbance varies only slightly with pH, leading to significant measurement inaccuracies. If a linear response is required, the effective range becomes even narrower, approximately one pH unit ($pK_a \pm 0.5$)(Lin & Liu, 2000). These constraints result in a limited dynamic range and a non-linear response, both of which restrict the practical utility of optical pH sensors based on individual indicators. One method that can be used to overcome this limitation is using an indicator mixture instead of using a single indicator. Therefore, during this study, an indicator mixture was used to develop the pH determination system for soil pH monitoring.

Figure 1 illustrates the absorbance responses of individual indicators with different pKa values (BPB, BCG, BTB, PR, and TB) across varying pH levels, as well as the combined response of their optimized mixture. The normalized absorbance response to pH for individual indicators and a mixture of multiple indicators is shown in the figure. 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 pH 2 to 10.

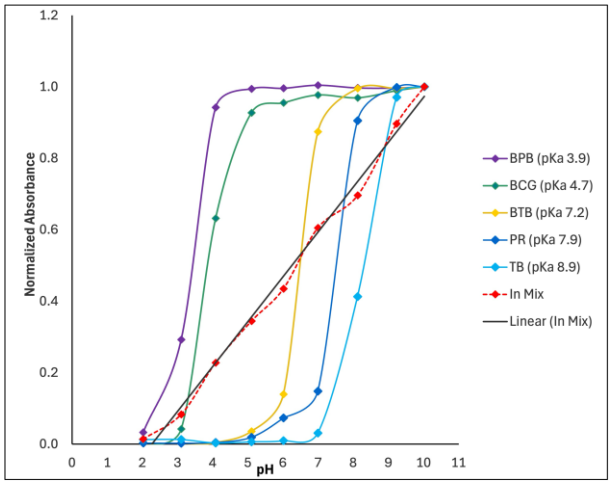

Figure 1. Normalized absorbance response to pH of single indicators (BPB, BCG, BTB, TB, and PR) and multiple-indicator mixture

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 2, the ideal measurement wavelength lies between points A and B, where the spectra of the indicators intersect. Selecting a wavelength in this region, specifically 590 nm, ensures that the absorbance values of the indicators are comparable, allowing balanced contributions from each indicator in a mixed indicator solution.

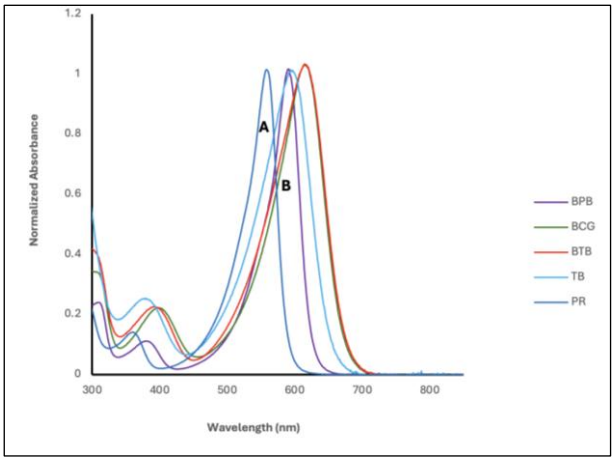

Figure 2. Normalized spectra of the base form of five indicators (BPB, BCG, BTB, TB, and PR)

Spectrophotometric analysis of the indicator mixture revealed two prominent absorbance peaks at 435 nm and 590 nm. Correlation analysis indicated that 590 nm is the most suitable wavelength for quantitative analysis. This is shown in Figure 3, while Figure 4 displays the absorbance of the indicator mixture at 590 nm plotted as a function of pH (as determined using a calibrated pH meter). A strong linear relationship is observed over the pH range of 2–10, with an excellent fit to the data (R^2 = 0.9932, n = 3).

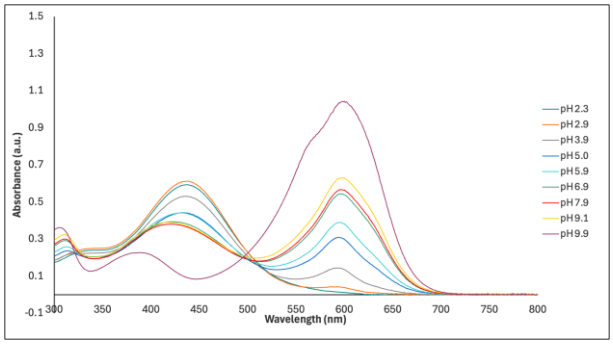

Figure 3. Spectrophotometric analysis of the indicator mixture at different pH (2.3, 2.9,3.9,5.0, 5.9, 6.9, 7.9, 9.1, and 9.9).

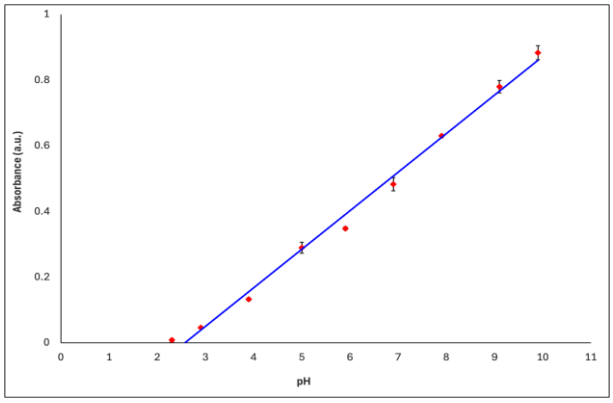

Figure 4. Absorbance of the indicator mixture at 595 nm plotted as a function of pH (R^2 = 0.9932, n = 3)

3.2 Microfluidic-based pH detection system

Integrating indicator chemistry into a microfluidic platform imposes several analytical constraints, including limited optical path lengths, reduced sample volumes, and rapid mixing dynamics. Under these conditions, single-indicator systems often fail to provide adequate sensitivity across the broad pH variations typically observed in soil extracts, where pH may span from strongly acidic to alkaline states depending on organic matter, fertilizer inputs, or geological composition. Indicator mixtures directly address these limitations by combining dyes with staggered pKa values and overlapping absorbance characteristics, producing a continuous and predictable spectral response over an extended pH domain (Raghuraman et al., 2006).

Raghuraman et al., 2006 demonstrated that optimized multi-indicator formulations can preserve monotonic, chemically resolvable absorbance changes across wide pH intervals, even when constrained by short optical

pathlengths in microchannels, enabling robust spectral deconvolution and high-accuracy pH estimation in complex matrices (Raghuraman et al., 2006). Lin and Liu (2000) further established the theoretical basis for such mixtures, showing that dyes with $\Delta pK_a \leq 1.7$ can produce a quasi-linear response over 3.5–4.5 pH units, which is particularly advantageous for microfluidic systems that rely on simple, calibration-stable transfer functions (Lin & Liu, 2000).Their findings highlight that mixtures ensure uniform sensitivity, reduce nonlinearity, and minimize error propagation across the sensor's full operational pH range. For microfluidic soil analysis, these characteristics are essential. Soil solutions contain high ionic strength, variable buffering capacity, and suspended particulates that can shift indicator equilibria or distort optical measurements. Using an indicator mixture therefore improves sensor resilience by distributing the response across multiple dye species, reducing dependence on a single equilibrium and enhancing spectral stability. As a result, optimized multi-indicator systems significantly improve the precision, reliability, and range of microfluidic pH sensing, enabling accurate soil chemical characterization within compact, low-reagent, field-deployable lab-on-chip devices.

An optimized indicator mixture was used to determine the pH using the microfluidic device. Figure 5 shows a schematic illustration of the pH-sensing microfluidic platform and the reagent storage chamber.

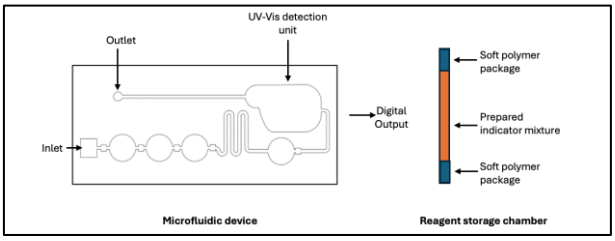

Figure 5. Schematic illustration of the design of the microfluidic device and the reagent storage chamber

The breaching technique is used to introduce the soil sample and the indicator mixture to the device. Then, the pH of the sample is determined spectrophotometrically using the device.

3.3 Soil pH determination using the microfluidic system

Soil samples were collected from multiple locations across Sri Lanka, and their pH values were measured using the developed microfluidic device. For reference and validation, the pH of each sample was also determined using a standard calibrated laboratory pH meter. The sampling sites are shown in Figure 6 while Table 1 summarizes the measured pH values along with the corresponding relative error calculated for each sample. The relative error is calculated with reference to the standard pH measurement. The measured pH values show that the developed prototype platform shows close values to the reference values, minimizing the relative error.

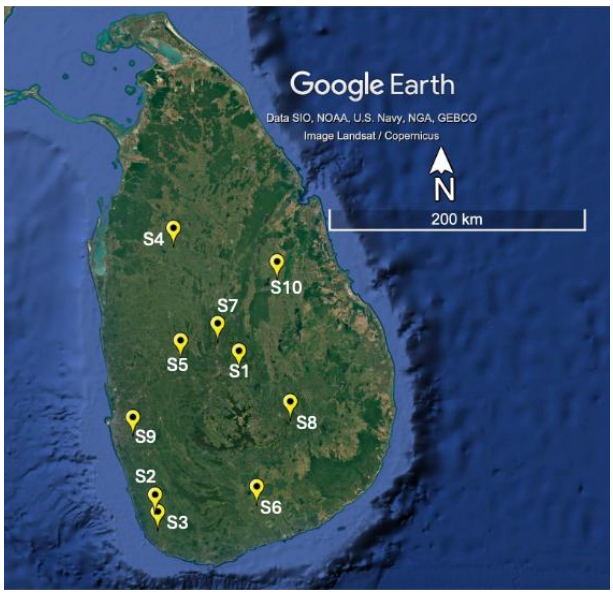

Figure 6. Sample collection locations across Sri Lanka

Table 1. Soil pH measurements from the reference pH meter and the UV–Visible spectroscopy-based prototype platform, including relative error values

Sample	Location	Reference (pH meter)	Prototype platform	Relative error (%)
S1	6°17'20.00"N, 80°46'18.04"E	7.18	6.98	2.79
S2	7°18'14.31"N, 80°9'41.90" E	7.98	7.87	1.38
S3	6°10'7.36"N, 80°10'44.98" E	7.58	7.42	2.11
S4	8°10'14.57"N, 80°18'35.27" E	8.06	7.98	0.99
S5	7°22'45.12"N, 80°21'22.53" E	7.58	7.51	0.92
S6	6°20'50.03"N, 80°53'17.24" E	7.90	7.83	0.89
S7	7°29'52.71"N, 80°37'18.42" E	7.10	7.01	1.27
S8	6°56'44.33"N, 81°7'58.11" E	7.26	7.19	0.96
S9	6°50'16.23"N, 80°0'32.52" E	6.51	6.42	1.38
S10	7°55'44.09"N, 81°2'50.99" E	6.72	6.69	0.45

The developed microfluidic system offers a promising solution for rapid, on-site soil pH monitoring, making it especially well-suited for applications such as greenhouses or hydroponic systems where on-site and continuous pH tracking is critical. In such controlled-environment agriculture settings, maintaining optimal pH is essential for nutrient availability and plant health, and existing automation studies underscore this need. For

example, automated pH monitoring and control systems in hydroponics have demonstrated improved crop yields and reduced human intervention (Rico, 2020).By deploying our compact device in the field (or in greenhouse/hydroponic contexts), real-time pH adjustments become feasible, enabling more responsive management of plant growth conditions, reducing delays associated with laboratory analyses, and supporting precision agriculture workflows that demand high spatial and temporal resolution.

4. CONCLUSION

This study demonstrates the successful development of a spectroscopy-based microfluidic device capable of providing rapid, onsite, and continuous soil pH monitoring. By incorporating an optimized mixture of indicators, the system achieves a linear response across a broad pH range (pH 2–10), overcoming the limitations of single-indicator approaches and enabling reliable detection under diverse soil chemical conditions. The compact design and low reagent consumption further support its suitability for field deployment. Overall, the proposed prototype microfluidic platform offers a practical pathway toward real-time soil chemical sensing, particularly in applications such as precision agriculture, greenhouses, and hydroponic systems where continuous pH monitoring is essential for maintaining optimal plant growth environments. Furthermore, in future this device will be developed to be assessed using a digital platform like a smart phone and pH testing will be integrated with measuring other key soil nutrient parameters like N, P and K.

Acknowledgement: This study was funded by the National Science Foundation, Sri Lanka (NSF Grant No: RG/2023/AG/01).

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H.M.C. S. Wijerathne
Faculty of Graduate Studies, University of Sri Jayewardenepura, Nugegoda 10250, Sri Lanka
Department of Materials and Mechanical Technology, Faculty of Technology, University of Sri Jayewardenepura, Pitipana, Homagama 10200, Sri Lanka
Department of Limnology and Water Technology, Faculty of Fisheries and Marine Sciences & Technology, University of Ruhuna, Matara 81100, Sri Lanka
cwijerathne@fish.ruh.ac.lk
ORCID 0000-0002-8907-2494

R.N. Wijesena
Division of Textile and Clothing Technology, Institute of Technology, University of Moratuwa, Diyagama, Homagama 10200, Sri Lanka
ruchiraw@itum.mrt.ac.lk
ORCID 0009-0003-4893-3483

N.D. Tissera
Division of Textile and Clothing Technology, Institute of Technology, University of Moratuwa, Diyagama, Homagama 10200, Sri Lanka
nadeekat@itum.mrt.ac.lk
ORCID 0009-0001-1134-3063

G. Priyadarshana
Department of Materials and Mechanical Technology, Faculty of Technology, University of Sri Jayewardenepura, Pitipana, Homagama 10200, Sri Lanka
gayanp@sjp.ac.lk
ORCID 0000-0001-7130-3963