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IoT-Enabled Intelligent Lab-on-Chip for Agricultural Nutrient Detection: Soil and Plant Sap as Complementary Approach

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Abstract: Rapid and precise nutrient detection are critical for precision agriculture. Traditional laboratory soil tests are accurate but slow and resource intensive. Plant sap analysis gives a near real time picture of plant nutrient status but can miss soil context. This study presents soil and plant sap testing integrated with an intelligent microfluidic Lab-on-Chip (LoC) platform. This study evaluates the effectiveness of intelligent microfluidic LOC device for nutrient detection in soil samples and plant sap within precision agriculture. The 3D printed microfluidics LOC platform integrates electronics, computing, sensor with Internet of things (IoT) and cloud-based data analytics enabling on-site, point-of-care rapid testing. Plant sap analysis reflects the crop's immediate physiological nutrient status, revealing active uptake and transient deficiencies, while soil testing quantifies the nutrient reservoir available to plants, offering a baseline for fertilization planning. Both sap and soil nutrient assays provide quantitative results within minutes for key macronutrients such as Nitrogen (N), Phosphorous (P), and Potassium (K). The integration of intelligence interface facilitates data collection and decision support, enhancing usability and adoption. Overall, the combined use of sap and soil based nutrient testing via intelligent LOC devices offers a holistic, scalable, and cost-effective approach to nutrient management in precision farming. The platform offers potential for advanced digital agriculture, facilitating rapid sensing through data-driven farming techniques.

Keywords: *Microfluidics, Lab-on-Chip, Point- of-care, Nutrient sensors, IoT*

1. Introduction:

Traditional farming methods are manual and experience based [1]. The growing global population, coupled with resource constraints and climate change, necessitates innovative approaches to agriculture sector like Precision Agriculture [2]. Precision Agriculture which is also called smart farming leverages advanced technologies like sensing, computing, and automation to deliver the right input, in the right amount, at the right place, and at the right time for right decision [3]. Data driven approach reduces overuse of fertilizers, pesticides, and water. Smart farming supports both profitability and sustainability[4]. The integration of intelligence in farming especially sensing, automation, computing, IoT, Block chain, and Artificial Intelligence (AI) further enhances real-time decision making, creating a pathway toward smart farming ecosystems [5] .

Plants require 17 essential nutrients, classified as Macronutrients which are needed in large amounts. In this Primary nutrient are Nitrogen (N), Phosphorus (P), Potassium (K) and Secondary nutrients are Calcium (Ca), Magnesium (Mg), Sulphur (S). Micronutrients which are needed in small amounts are Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu), Boron (B), Molybdenum (Mo), Chlorine (Cl), Nickel (Ni). Nutrient management is a crucial factor influencing crop yield and environmental sustainability. Conventional laboratory-based soil and plant analysis are accurate but time-consuming, requiring sample transport, expensive instrumentation, and skilled personnel [6]. Sap analysis involves measuring the liquids actively flowing in the vascular tissues (xylem and phloem). A soil and plant sap analysis are complementary tools for diagnosing plant nutrition. Soil tests show available nutrients in the soil, while sap analysis indicates the nutrients the plant has actually absorbed and is currently using, revealing uptake inefficiencies or deficiencies missed by soil tests as illustrated in table 1. Analyzing both, gain a comprehensive understanding of nutrient dynamics from supply to uptake, enabling optimized nutrient management and earlier problem detection [7] [8].

Tabel 1: Soil and plant nutrient levels and symptoms

Nutrient	Soil Deficiency (ppm)	Soil Sufficiency (ppm)	Soil Toxicity (ppm)	Sap Deficiency (ppm)	Sap Sufficiency (ppm)	Sap Toxicity (ppm)	Symptoms
Nitrogen (N)	0–20	20–50	>150	0–600	600–1200	>2000	**Deficiency:** yellowing (chlorosis) of older leaves, stunted growth. **Toxicity:** excessive vegetative growth, lodging, delayed maturity.
Phosphorous (P)	0–15	15–30	>100	0–30	30–80	>150	**Deficiency:** purpling/reddening of older leaves, poor root growth. **Toxicity:** rare, can cause micronutrient (Zn, Fe) deficiencies.
Potassium (K)	0–100	100–200	>400	0–2000	2000–4000	>6000	**Deficiency:** leaf margin scorching/burning, weak stems, lodging. **Toxicity:** high K can induce Mg, Ca deficiencies.

Microfluidic lab-on-chip (LOC) technology has revolutionized field-based diagnostics by integrating sample preparation, chemical reactions, and detection on a miniaturized platform [9] [10] [11] Microfluidics LoC integrated with IoT and AI modules, offer rapid, decentralized testing with automated data processing and wireless communication to cloud platforms to become intelligent [11], [12]. In agricultural applications, intelligent LOC can provide farmers with rapid soil and plant nutrient analysis, bridging the gap between laboratory precision and field practicality [13] [14].

This research proposes a comparative study of soil and plant sap analysis using an intelligent microfluidic Lab-on-Chip (LoC) platform designed for rapid, low-cost, and on-site nutrient detection. The microfluidics LoC integrates microfluidic channels, mixer, detection chamber, colorimetric detection or optical sensors, Internet of Things (IoT), Cloud to measure micronutrients Nitrogen (N), Phosphorus (P), Potassium (K), and pH. Comparative analysis shows that soil testing is superior for long-term nutrient availability assessment, while sap testing provides immediate nutrient uptake status.

The intelligent microfluidics LoC system combines both approaches, reducing fertilizer misapplication and enabling real-time decision making in smart farming [15], [16], [17]

This research aims to comparatively evaluate soil and plant sap nutrient testing using a smart LOC platform to explain their roles and benefits in precision agriculture and explore integrated application possibilities.

2. Materials and Methodology:

2.1 Sample Collection

- **Soil samples:** Soil samples are typically collected from the 0–15 cm layer (root zone) using a soil auger or core sampler. After collecting sample, it is prepared by air drying to remove moisture. Also stones and roots are removed from it. Then it is filtered usually through a 2 mm filter paper. Extract prepared using distilled water for pH and nutrient testing [18].

- **Plant sap samples:** Young leaves or petioles are selected; press device or sap extractor used for fresh sap (juice) collection. After squeezing it is filtered [19].

Both sample types are introduced to the one inlet of Y- channel microfluidics LoC via a syringe pump and reagent to another inlet as shown in figure 1.

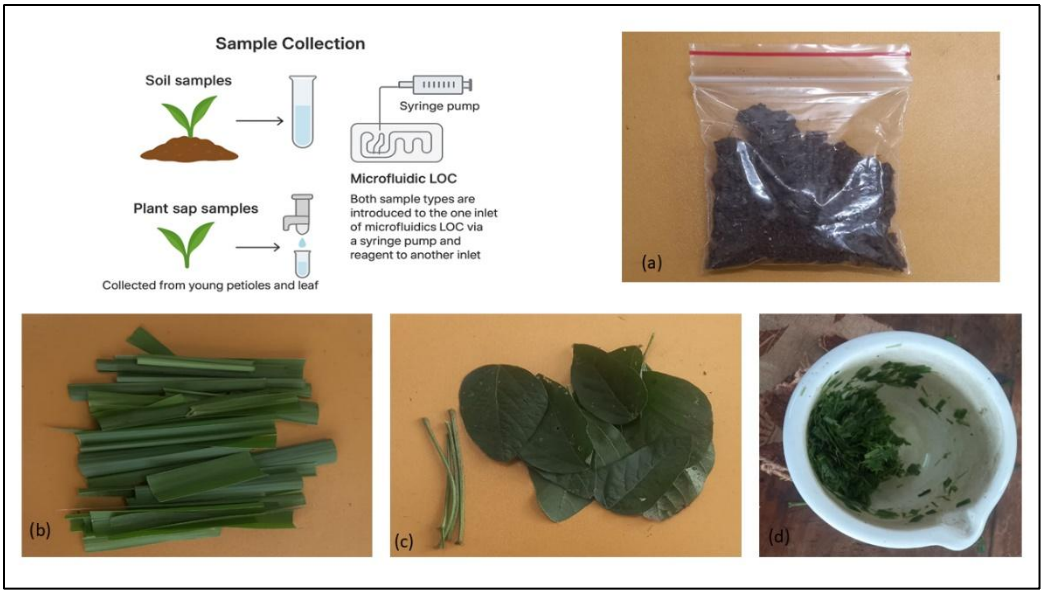


Figure 1. Soil and plant Sample Collection (a) Soil (b) Sugar cane (c) Soyabean (d) sap extraction

2.2 Microfluidic Lab-on-Chip (LOC) Design:

The design and development of microfluidics chip have done in AutoCAD and SolidWorks software. Microchannel architectures, including Y-channel and serpentine mixers, utilizing CAD and simulated in COMSOL[20]. 3D printer was used for chip fabrication [21] [22]. Design flow of system is as shown in figure 2. Figure 3 shows microfluidics chip design with dimensions and fabricated prototype.

- Microfluidics Chip Design: Fabricated via 3D printing
- Microchannels: Designed to transport microliter volumes of soil extract or sap to reaction chambers.
- Detection: Integrated optical sensor array for colorimetric absorbance measurement.
- Electronics and IoT: ESP-32 Arduino microcontroller with wireless connectivity for real-time data transfer to a cloud server.
- AI integration: On-chip regression model calibrated against laboratory standards for concentration prediction.

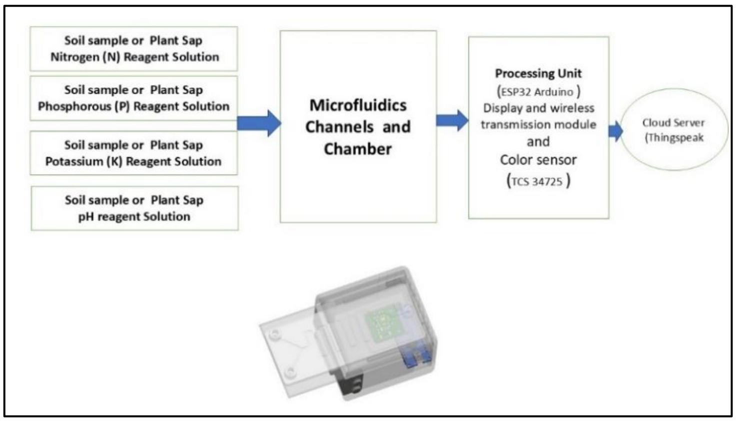


Figure 2. Microfluidic Lab-on-Chip (LOC) Design flow

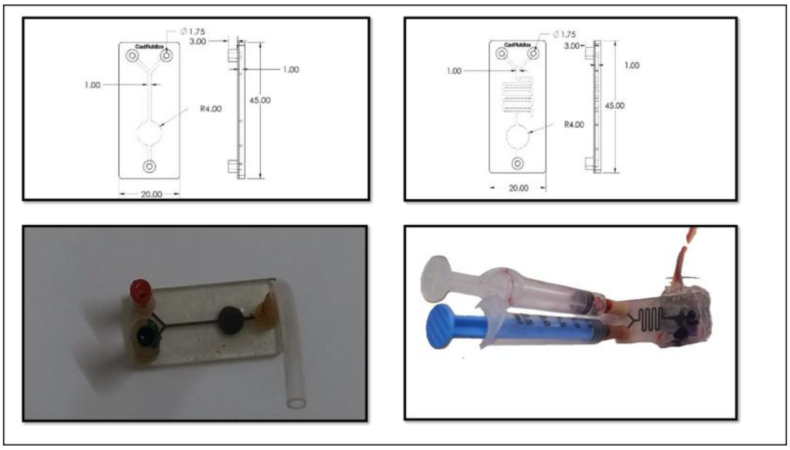


Figure 3. Microfluidics chip design dimension and prototype

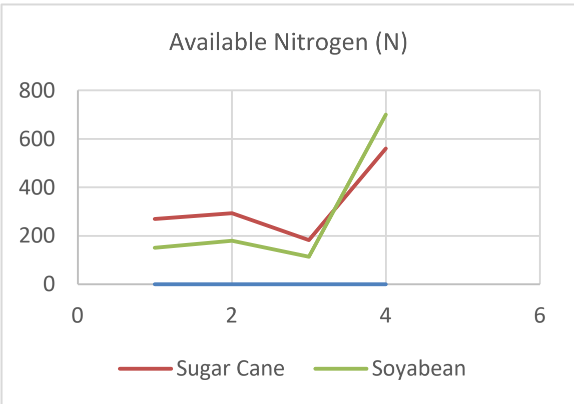
3. Result and Discussion:

A. Soil and Plant Sap Nutrient Detection:

Available Nitrogen (N) and Phosphorous (P) was measured for standard solution by commercially available soil testing kit (STK-50) by manually using color comparator chart and using proposed microfluidics lab-on-chip device. The results of Nitrogen (N), Phosphorous (P) are tabulated in Tabel 2. The results were reported after performing a minimum 3 repeats for each measurement. N and P results against the Soil and plant sap sample solution displayed good results. Comparative between manual method and device results shows less analysis time and 80% reduced reagent volume compared to traditional method as shown in figure 4.

Tabel 2: Microfluidics LOC device for Nitrogen (N) and Potassium (P)

Available Nutrient	Plant Sap Sample	R	G	B	Manual Reading (Kg/Ha)
NITROGEN (N)	Sugar Cane	270	293	182	560
	Soyabean	150	179	113	700
PHOSPHOROUS (P)	Sugar Cane	156	186	118	21
	Soyabean	250	273	177	21



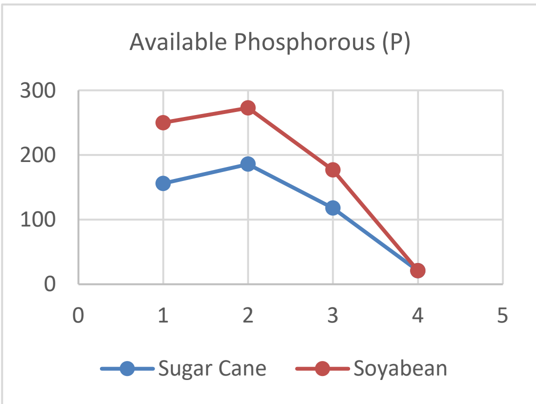
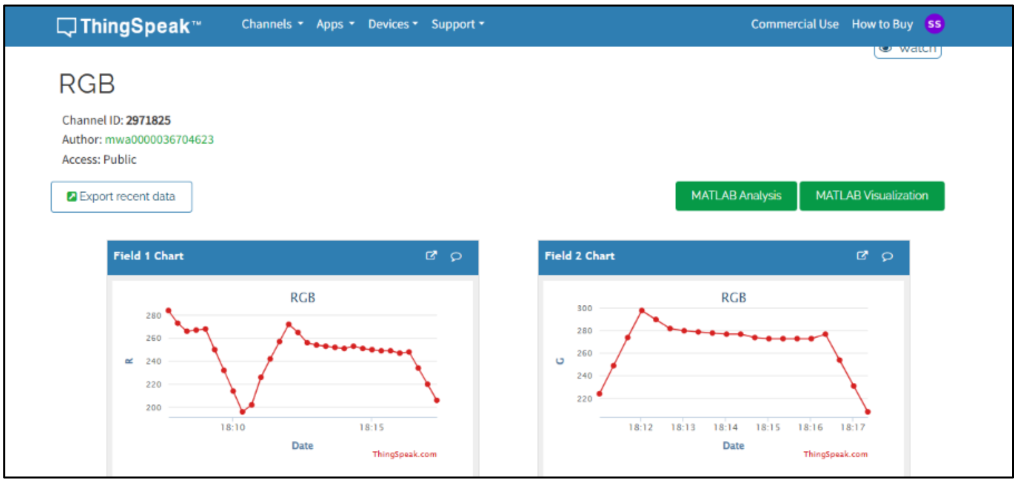


Figure 4. Nutrient response of Sugarcane and Soyabean sap

B. IoT, Data Transmision and Monitoring:



For the online measurment of Nutrient data is transferred to cloud and it also has been studied.A analysis was also made with data transmited by device to server and corresponding R,G, B values obtained directly using LCD display on device.

Figure 5. IoT data collection through Thingspeak servers showing R, G, B wavelength concentration

The preceding plant sap analysis illustrates:

- If soil has nutrients but sap is low → uptake issue (root stress, pH imbalance).
- If soil is low and sap is low → real deficiency.
- If sap is high but soil is low → luxury consumption or mobilization.

C. Salient Features of Microfluidics LoC platform:

i. Immediate Results: Offers a prompt assessment of a plant's present nutritional condition, indicating the nutrients available for growth at that moment.

ii. Proactive Nutrient Deficiency Identification: Facilitates the recognition of nutrient deficiencies before to the manifestation of symptoms, hence enhancing productivity

iii. Speed and Sensitivity: Both sap and soil LOC testing yielded quantitative results within 5–10 minutes, in contrast to the days required for laboratory analysis.

iv. Usability: Minimal sample preparation, drop-and-read functionality, and automated smartphone analysis facilitated swift implementation by field operators with limited training.

v. Data Integration: Both sample modalities may facilitate variable-rate suggestions and time-series monitoring.

D. Limitations and challenges:

i. Sap variability exhibits a significant dependence on sampling techniques, plant water status, and growth stages, necessitating the implementation of strict standard operating procedures and crop-specific guides.

ii. The stability of reagents necessitates meticulous formulation for the long-term storage of colorimetric reagents in field cartridges.

iii. Calibration: Sap readings are subject to transient environmental influences, and soil testing may overlook short-term plant stress. LOCs enable swift assessment. However, they necessitate calibration specific to crop and soil types.

4. Conclusion:

This work presents an IoT-enabled intelligent soil and plant sap nutrient detection system based on a 3D printed microfluidics lab-on-chip device. It also demonstrates the development of portable, low cost and rapid colorimetric detection platform with an integrated microfluidics Lab-on-chip device and IoT platform for sap nutrient detection. A color detection optoelectronics and LOC chip has been used to determine nutrient concentration with good precision. 3D printed microfluidics chip helped in controlled fluid flow and mixing with detection chamber for precise measurement. Such integrated LOC arrangement and IoT enabled data transmission module helped in easy data collection, analysis and visualization. An Intelligent microfluidic LOC system fundamentally improves the practicality and impact of nutrient diagnostics. Employing both soil and plant sap testing at the point of care empowers farmers to make timely, informed decisions, maximizing crop yield while minimizing environmental impact. Further enhancements, including field trials to validate, IoT integration and machine learning-driven decision support, will accelerate the adoption of these next-generation Agro diagnostic tools.

Conflicts of interest

There are no conflicts of interest to declare.

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