Systematic Multi-Criteria Assessment of Soil Analysis Technologies for an Agricultural Living Laboratory: Technology Readiness Levels and Field Applicability for Citrus and Sugarcane Production

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Abstract.

The selection of soil analysis technologies for agricultural research platforms requires systematic evaluation considering technical accuracy, practical feasibility, cost, and maturity level. A multi-criteria assessment of soil analysis technologies was conducted for the SB100 Agricultural Living Laboratory at Fatec Pompeia Shunji Nishimura. Physical, chemical, biological, and mineralogical soil attributes were evaluated based on Technology Readiness Level (TRL), analytical time, cost, repeatability, and interlaboratorial reproducibility. A total of 45 soil parameters were mapped. Physical and chemical analysis technologies proved to be well consolidated (TRL 7–9), while biological monitoring methods, particularly metagenomic approaches, remained at intermediate maturity (TRL 3–5). Mineralogical methods were predominantly restricted to research settings. The framework proposed supports decision-making for technology integration within the Living Lab, with strategic implications for citrus and sugarcane management.

Keywords.
soil analysis; technology readiness level; precision agriculture; Living Lab; sugarcane; citrus

Introduction

Soil analysis constitutes a fundamental tool for sustainable agricultural management, enabling the diagnosis of physical, chemical, and biological soil properties that directly influence crop productivity and environmental quality (Tavares 2025). The increasing demand for spatially and temporally explicit data has broadened the scope of available analytical approaches, ranging from conventional laboratory methods to real-time sensor-based systems integrated into precision agriculture platforms (Bassoi n.d.; Embrapa 2025).

The SB100 Platform, based at Fatec Pompeia Shunji Nishimura, operates as an Agricultural Living Laboratory focused on production systems of citrus and sugarcane, two of the most economically relevant crops in the state of São Paulo, Brazil. Within this context, a structured assessment of available soil analysis technologies is essential to determine which methods best meet the technical, economic, and operational requirements of the Living Lab. This work aimed to map, classify, and evaluate soil analysis technologies according to their TRL and practical applicability for the SB100 Living Lab field conditions.

Materials and Methods

A systematic literature review was conducted covering publications from Embrapa, the Agronomic Institute of Campinas (IAC), the University of São Paulo (ESALQ/USP), and international peer-reviewed databases. Technologies were classified by soil attribute group (physical, chemical, biological, or mineralogical) and evaluated using five criteria: (i) TRL on a 1–9 scale; (ii) analytical time, in hours per sample; (iii) estimated cost per analysis; (iv) repeatability, expressed as coefficient of variation (CV%); and (v) interlaboratorial reproducibility (CV%).

Field visits to rural properties and participation in the Agrishow 2026 agricultural technology fair, held in Ribeirão Preto, São Paulo, were also conducted to validate practical applicability assessments alongside producers, agronomists, and technology companies.

Results and Discussion

A total of 45 soil parameters were assessed across the four attribute categories. Table 1 presents selected representative technologies organized by attribute group, together with their TRL and key performance indicators.

Table 1. Summary of soil analysis technologies assessed for the SB100 Living Lab, organized by attribute group.

Attribute	Key Parameter	Reference Method	TRL	Time (h)	Reprod. CV%	Field Adoption
PHYSICAL ATTRIBUTES						
Physical	Soil texture	Hydrometer (Bouyoucos) / NIR spectroscopy	8–9	24–48	8–15%	High
Physical	Soil moisture	Gravimetric (oven) / TDR / FDR sensors	7–9	0.01–48	5–18%	High
Physical	Compaction / penetration	Impact penetrometer (Stolf) / electronic	8–9	<0.1/pt	8–25%	High
Physical	Bulk density	Volumetric ring (Kopecky)	8–9	48–72	3–10%	Medium
CHEMICAL ATTRIBUTES						
Chemical	pH	Potentiometry – glass electrode	9	0.1–0.3	2–4%	Very High
Chemical	Organic matter	Walkley-Black oxidation / NIR / LIBS	7–9	0.5–1	5–14%	High
Chemical	Macronutrients (N,P,K,Ca,Mg,S)	Kjeldahl (N); colorimetry (P); ICP-OES (Ca,Mg)	8–9	1–3	5–15%	Very High
Chemical	Micronutrients (Fe,Mn,Zn,Cu,B)	EAA / ICP-OES + DTPA-TEA extraction	8–9	0.5–1	8–15%	High
Chemical	CEC	Ammonium acetate pH 7 / KCl 1 mol L^{-1}	8–9	2–4	5–12%	Very High
BIOLOGICAL ATTRIBUTES						

Biological	Microbial biomass C	Chloroform fumigation-extraction (CFE)	5–6	24–48	15–25%	Very low
Biological	Basal respiration	Incubation + NaOH capture / IRGA	5–6	24–168	10–20%	Very low
Biological	Microbial diversity	16S rRNA amplicon metagenomics (NGS)	3–4	168–500+	Var.	Absent
Biological	Soil enzymes	Colorimetric assays (urease, phosphatase)	5–6	2–6	12–25%	Very low
MINERALOGICAL ATTRIBUTES						
Mineral.	Clay mineralogy (identification)	X-ray diffraction (XRD) + DTA/TG	3–4	24–72	10–20%	Absent
Mineral.	Clay fraction quantification	XRD + Rietveld method	2–3	48–120	10–25%	Absent

Source: compiled by the authors based on Embrapa (2017, 2025); Tavares (2025); Stolf (1991); Bassoi (s.d.); Lorenz (s.d.); Trivellas (s.d.).

Physical attribute methods showed the highest consolidation, with most technologies reaching TRL 7–9. Gravimetric methods for soil moisture, volumetric rings for bulk density, and impact penetrometers for compaction diagnosis are commercially available and routinely adopted (Stolf 1991; Embrapa 2017). Near-infrared (NIR) spectroscopy represents an emerging alternative for texture assessment, offering potential for rapid non-destructive in-field analysis (Tavares 2025).

Chemical attribute technologies also demonstrated high maturity, particularly pH determination via potentiometry (TRL 9), organic matter by Walkley-Black oxidation (TRL 7–9), and macronutrient analysis via ICP-OES (Embrapa 2017). These methods form the foundation of commercial fertility analysis packages widely adopted in sugarcane and citrus production systems.

Biological attribute methods exhibited the greatest variability in maturity. Microbial biomass carbon by fumigation-extraction and basal respiration are established research tools (TRL 5–6), while 16S rRNA amplicon-based metagenomics remained at TRL 3–4, given high analytical costs, complex bioinformatic pipelines, and limited interlaboratorial standardization (Trivellas n.d.; Embrapa 2025). This gap represents the most critical challenge for biological monitoring in the SB100 Living Lab context.

Mineralogical methods, including X-ray diffraction and differential thermal analysis, were restricted to research settings (TRL 2–4) and are not yet commercially accessible to producers (Lorenz n.d.). Nevertheless, mineralogical characterization of the clay fraction remains strategically relevant for the SB100 Living Lab, providing essential pedological information for long-term soil management decisions in highly weathered tropical soils.

Conclusions

The systematic multi-criteria assessment of 45 soil parameters across physical, chemical, biological, and mineralogical categories revealed a heterogeneous landscape in terms of technological maturity and field applicability. Physical and chemical methods are well established and commercially accessible (TRL 7–9), while biological and mineralogical technologies present significant gaps in standardization, cost-effectiveness, and commercial availability. These results provide a technical foundation for developing a technology integration framework for the SB100 Agricultural Living Laboratory, with priority focus on closing the biological monitoring gap through partnerships with Embrapa, IAC, and ESALQ/USP.

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