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Soil health and management assessment kit (SOHMA KIT®): Development and validation for on-farm applications

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ABSTRACT

Soil health is a foundation for long-term soil multifunctionality, sustaining crop yields and enhancing crop resilience to climate change. Nevertheless, soil health assessments are often complex, costly and time-consuming, which acts as a barrier to farmers adopting them. Thus, we hypothesized that a simplified, on-farm approach to evaluate soil health, composed by key indicators, could effectively detect changes in soil health across different land management systems. This study aimed to (i) validate the Soil Health and Management Assessment Kit (SOHMA KIT®) as a reliable tool for on-farm soil health assessment, (ii) compare its performance with standard laboratory methods, and (iii) assess its sensitivity for detecting soil health improvements induced by cover crops. The validation study was conducted in two long-term field experiments in the Brazilian savanna (Cerrado biome), where different cover crop systems were evaluated. After extensive work involving literature review, selection and development of methods, the SOHMA KIT® was created. The SOHMA KIT® integrates seven soil health indicators from physical (infiltration, aggregate stability, Visual Evaluation of Soil Structure - VESS), chemical (pH), and biological (catalase enzyme, macrofauna, biogenic aggregates) components into a Soil Health Index (SHI). In the validation tests, results showed that the SHI increased around 35 % in diversified cropping systems. Strong correlations between SOHMA KIT® and standard methods were observed for key indicators (e.g., infiltration: $r = 0.71$, aggregate stability: $r = 0.40$, pH: $r = 0.88$). Despite its portability and cost-effectiveness, the toolkit has some limitations, such as it is recommended that users have a basic training for assessing visual indicators, and the assessment is focused only on topsoil layers. However, the SOHMA KIT® is user-friendly and scalable, being a valuable tool for on-farm decision-making, regenerative agriculture, and large-scale soil health monitoring.

1. Introduction

Globally, the concept of soil health is associated with the continuous capacity of the soil, as a living ecosystem, to perform its functions in maintaining environmental quality (air and water), promoting human health, and supporting crop productivity (Chang et al., 2022; Haney et al., 2018; Karlen et al., 2019; Lehmann et al., 2020). In addition, healthy soils are crucial in reducing crop vulnerability to biotic and abiotic stresses (Cherubin and Schiebelbein, 2022), sustaining higher crop yields, and providing yield stability despite climate change (Qiao et al., 2022; Souza et al., 2025). Therefore, the health of agricultural soils is directly associated with success in addressing significant global challenges, such as food security and climate change mitigation and adaptation (Whalen and Gul, 2025).

Due to its broad and intricate nature, there is no direct method to measure soil health. Instead, its evaluation relies on integrating chemical, physical, and biological indicators, along with their interactions (Cherubin et al., 2021). These indicators provide insights into the overall soil health, helping monitor changes over time and distinguish different management practices (Guo et al., 2020; Lenka et al., 2022; Rakshit et al., 2020). The selection of suitable and sensitive soil indicators requires a comprehensive understanding of dynamic soil properties, which can vary by region, landscape position or land use (Rakshit et al., 2020; Cherubin et al., 2016a; Rinot et al., 2019). Most methodologies for assessing soil health indicators are conducted in laboratories; however, this approach may be limited by the cost and complexity of the required laboratory analyses, which often involve sophisticated equipment and hazardous reagents (Chaudhry et al., 2024). Additionally, the time

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necessary to obtain the results could delay decision-making in the field, limiting the utility of the results (Lehmann et al., 2020).

Simpler, cheaper, faster, and environmentally friendly techniques such as on-farm methods play a crucial role in decision-making for management programs (Cardoso et al., 2013; McKenzie, 2001) and can assist farmers, consultants, and researchers in conducting soil health assessments with immediate and meaningful results (FAO, 2019). However, there are currently only a few initiatives that offer the possibility of carrying out quantitative on-farm testing for soil health assessment directly in the field, such as Visual Evaluation of Soil Structure – VESS (Ball et al., 2007; Guimarães et al., 2011), Practical Guide for Participatory Evaluation of Soil Quality – PGPE (Comin et al., 2016), Soil Quality Test Guide (USDA, 2001), Soil Health Cards (Purakayastha et al., 2019), Biofunctool® (Thoumazeau et al., 2019), and Solvita Kit (Woods, 2021). Biofunctool® detected soil health gains related to the age of rubber plantations in Thailand. Similarly, the USDA Soil Quality Test Guide showed strong correlations with standard laboratory analyses when evaluating cover crops and tillage systems in southern Brazil (Amado et al., 2007). Frameworks such as the PGPE have also proved valuable for teaching, research, and use by farmers in different tillage systems (Valani et al., 2020). These examples of empirical, qualitative, and quantitative approaches require little (or no) laboratory equipment and focus on immediate in-field assessment. These initiatives can facilitate communication between farmers and scientists (Valani et al., 2020; Bünemann et al., 2018; Franco et al., 2019).

A robust soil health protocol should be built based on a careful selection of a minimum dataset of indicators that capture key soil health trends (Hughes et al., 2023; Smith et al., 2024). Farmers and land managers must be involved in the design and application of these protocols, employing their expertise to monitor and improve soil health through practical and observable indicators (Morrow et al., 2016). Such collaborative efforts lay the foundation for globally relevant soil health frameworks that support regenerative agricultural practices and complement national programs (Karlen et al., 2019).

In this context, this study presents a new framework, the Soil Health and Management Assessment Kit (SOHMA KIT®), for assessing soil health based on a set of functional indicators that can be measured directly in the field. Therefore, we tested the hypothesis that the SOHMA KIT®, a simplified, on-farm approach to evaluate soil health assessment, composed by key indicators, would be able to capture changes in soil health due to land use and management. The SOHMA KIT® was developed and initially tested under tropical conditions, primarily focusing on agricultural systems with different cover crops. Large-scale cover crops provided a relevant study model, as they allowed the assessment of improvements in soil health, including enhanced organic matter, nutrient cycling, and soil structure, across different pedoclimatic contexts. Here, we present the principles of soil health assessment using the SOHMA KIT® and provide a detailed step-by-step guide to the experimental procedure. In addition, we apply the SOHMA KIT® Soil Health Index to a case study for validation, assessing its applicability, validation, and correlation with standard methods at two long-term experimental sites with cover crop treatments.

2. Material and methods

The SOHMA KIT® is an on-farm method to evaluate soil health developed by the Soil Health & Management Research Group (SOHMA) of "Luiz de Queiroz" College of Agriculture - University of São Paulo (ESALQ/USP), located in Piracicaba-SP, Brazil. The innovation process was also supported by the Center for Carbon Research in Tropical Agriculture (CCARBON/USP). The evaluation protocol to use the SOHMA KIT® was documented in the Patent Application No. BR 10 2024 015629-3.

2.1. Selection of SOHMA KIT® indicators

This approach was developed in three stages (Fig. 1). A global non-systematic literature review was conducted to identify potential on-farm methods to be included in the SOHMA KIT®. It followed two main criteria: i) methods with direct and full on-farm applications and ii) methods that are cost-effective, fast, reliable, reproducible, and sensitive to detect soil health changes induced by land use and management. The literature review was conducted using databases such as Scopus, Web of Science, and Google Scholar, selecting articles published from 1990 to 2021. The keywords used were: 'soil health,' 'soil quality,' 'land quality,' 'soil fertility,' 'soil biology,' and 'soil capability,' combined with terms like 'on-farm,' 'field test,' or 'visual evaluation.' Both national and international field methods for soil health assessment were considered to select the most promising approaches for the *in situ* evaluation of chemical, physical, and biological indicators (Table S1).

In the second step, methods were selected and adapted to Brazilian conditions. The majority of indicators identified by the non-systematic review were physical and biological (Table S1), which required adaptations from the standard methods according to two key principles of on-farm methods: practicality and effectiveness. The SOHMA KIT® consisted of seven indicators: three physical, one chemical, and three biological. The physical indicators included tests for water infiltration, VESS, and aggregate stability. Water infiltration was based on the proposal from the USDA (USDA, 2001), which meets the evaluation criteria. The visual evaluation method selected was the VESS (Guimarães et al., 2011), because of its successful use in numerous studies in Brazil and worldwide (Franco et al., 2019), as well as its rapid and cost-effective nature. For aggregate stability, we developed a methodology based on the qualitative slaking test from the USDA (USDA, 2001), that effectively captures the impact of management practices on soil structure. This development was necessary because it is a critical indicator of soil health, and there was no established methodology for field evaluation of aggregate stability at the time (Almajmaie et al., 2017; Herrick et al., 2001). Chemical indicators present a challenge for direct field assessment (Chaudhry et al., 2024). To address this, we included pH as the indicator by adapting the standard pH in water method using a portable sensor to enable field application. For biological indicators, the SOHMA KIT® includes tests for catalase enzyme, macrofauna evaluation, and biogenic aggregate. The catalase enzyme test was adapted from the method proposed by Nicholls et al. (2004) and macrofauna evaluation from Anderson & Ingram (Anderson and Ingram, 1989). Biogenic aggregate test was based on a modification of the standard laboratory method for visual separation of aggregates by proposing visual and aggregated patterns in the User Guide and using a pocket magnifier (5× magnification) to observe these visual patterns to make it feasible for field use. All these methodology adaptations and developments aimed to increase the performance of the methods under field conditions to ensure that they provide practical, efficient, and effective tools for assessing soil health, while taking into account soil multifunctionality (Fig. S1–A).

Finally, in the third step, the selected methods from step 1 and newly developed methods from step 2 were applied and compared with standard methods under contrasting soil textures and agricultural conservation management systems inside the USP *campus* (Piracicaba - São Paulo, Brazil), to validate the SOHMA KIT® and monitor soil health in these cultivation areas.

2.2. Protocol and experimental procedure

2.2.1. Soil health assessment by SOHMA KIT®

Detailed protocols for field measurements of the seven indicators (i. e., infiltration test, aggregate stability, VESS, pH, catalase enzyme, macrofauna evaluation, and biogenic aggregates) contained in the SOHMA KIT® are described in Schiebelbein & Cherubin (Schiebelbein and Cherubin, 2024) and also provided in the Supplemental Material.

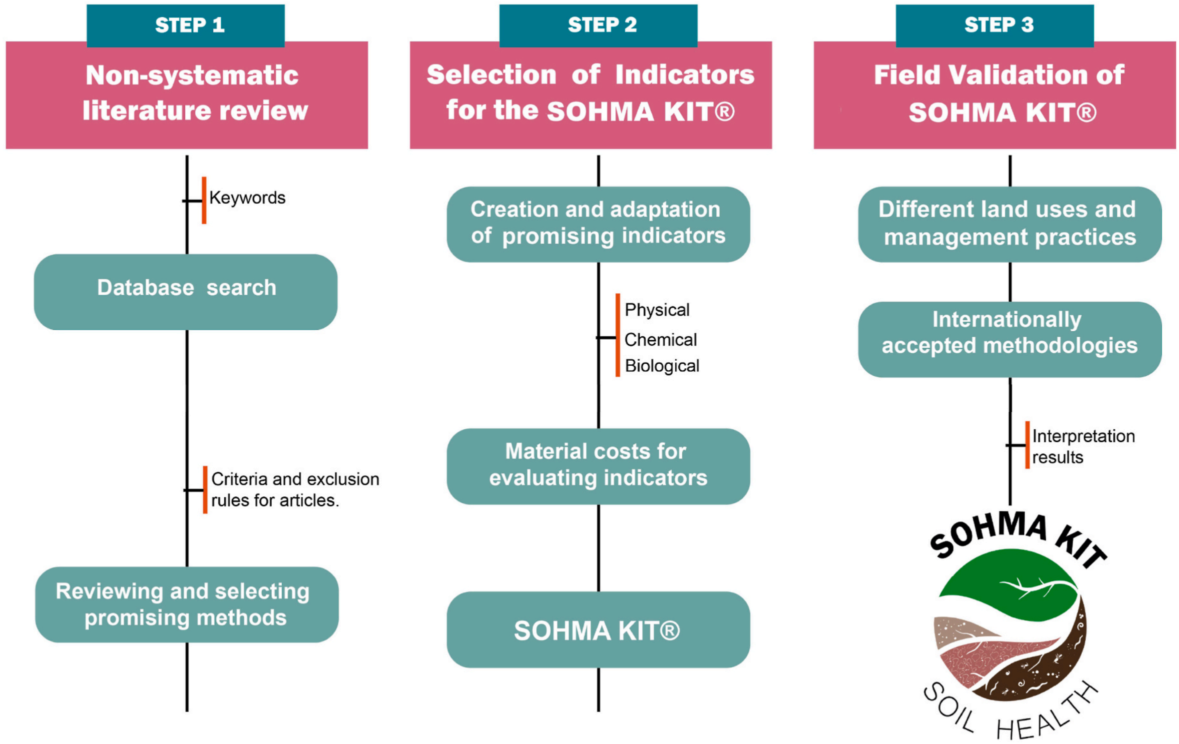

Fig. 1. Workflow of three steps to develop the Soil Health and Management Assessment Kit (SOHMA KIT®).

All seven indicators were measured directly in the field at a 0–10 cm soil depth, except for the VESS, which was assessed over the first 25 cm, according to the original protocol (Guimarães et al., 2011).

In the field, it takes two people approximately 120 min per sampling point to assess the seven indicators. The assessments should be carried out during the rainy season when soil is in the field capacity to improve the visual assessments (Guimarães et al., 2011). To optimize the time during the field measurements, the following order is recommended: Infiltration test; pH; Catalase enzyme; Aggregate stability; Biogenic aggregates; VESS and Macrofauna evaluation (Fig. S2). As the analyses are completed, observations should be recorded directly and manually in the paper copies of tables provided in the User Guide (Fig. 2). Once all the analyses have been completed, the Soil Health Index (SHI) can be generated by integrating the results of each indicator into an on-farm SHI. The measured values, originally expressed in different units, are converted into scores ranging from 0 to 1 using interpretation tables at the end of the step-by-step instructions for each indicator, considering the soil texture class, thresholds described in the literature, and expert opinion (Supplementary Material). The SHI can then be calculated by integrating all seven soil indicators using a weighted additive approach – Eq. (1).

$$SHI = \sum SiWi \tag{1}$$

Where SHI is the soil health index, Si is the indicator score, and Wi is the weighted value of the indicators. The indicators are weighted based on chemical (pH), physical (infiltration test, aggregate stability, and VESS) and biological (catalase enzyme, macrofauna evaluation, and biogenic aggregates) components, so regardless of the number of indicators, each group has equal weight (33.33 %) in the final index (Cherubin et al., 2016b).

These tables allow the readings to be classified into the categories: very low, low, moderate, high, or very high. This classification helps to identify which indicators are limiting soil health and should be prioritized for improvement in the short to medium term. In summary, a score is assigned based on the interpretation tables, allowing all indicators to be integrated into a SHI. Additionally, each indicator and the SHI can be interpreted using a five-color system, similar to the Cornell Assessment of Soil Health (Moebius-Clune et al., 2016): red, orange, yellow, light green, and dark green for very low, low, medium, high, and very high, respectively. This scale is useful to identify which indicators are limiting key soil processes and helps propose targeted management strategies for improving soil health indicators. In practical terms, the red and orange on the system indicate conditions where soil functions are significantly impaired and necessitate urgent intervention. Yellow indicates intermediate conditions in which processes are functioning but could benefit from improvement. Finally, light and dark green indicate favorable to optimal conditions, where soil functions support sustainable productivity and resilience.

Alternatively, users can input their observed data into an online form – https://forms.gle/Qeg4J8hT46H7ZNev8 – to receive a soil health report (Fig. 2), including the interpreted values for each indicator and the overall SHI, calculated and sent by email. This step is particularly important for users to create an online backup of the data, as well as to contribute to a dataset of on-farm soil health that can be useful for future updates of the SOHMA KIT®.

2.3. *Case studies: validation of SOHMA KIT® under conservation agriculture in the Brazilian savanna*

Two experimental areas located in the savanna (Cerrado biome), a region with highly intensified and technological agriculture, with long-term experiments were selected to evaluate soil health by comparing SOHMA KIT® and standard methods. The area has *Latossolo Vermelho,* in the Brazilian Soil Classification System (Santos et al., 2018), corresponding to a Rhodic Hapludox in the Soil Taxonomy (Soil Survey Staff, 2022). The indicators evaluated (Table 1) included chemical (pH), physical (infiltration, macroaggregation, and VESS [SOHMA KIT® only]), and biological parameters. Biological indicators included soil macrofauna index and catalase enzyme (SOHMA KIT® only), biogenic aggregates (both methods), and macrofauna with Shannon index (standard method only). The standard methods used in this study are the most commonly accepted and referenced in the scientific literature

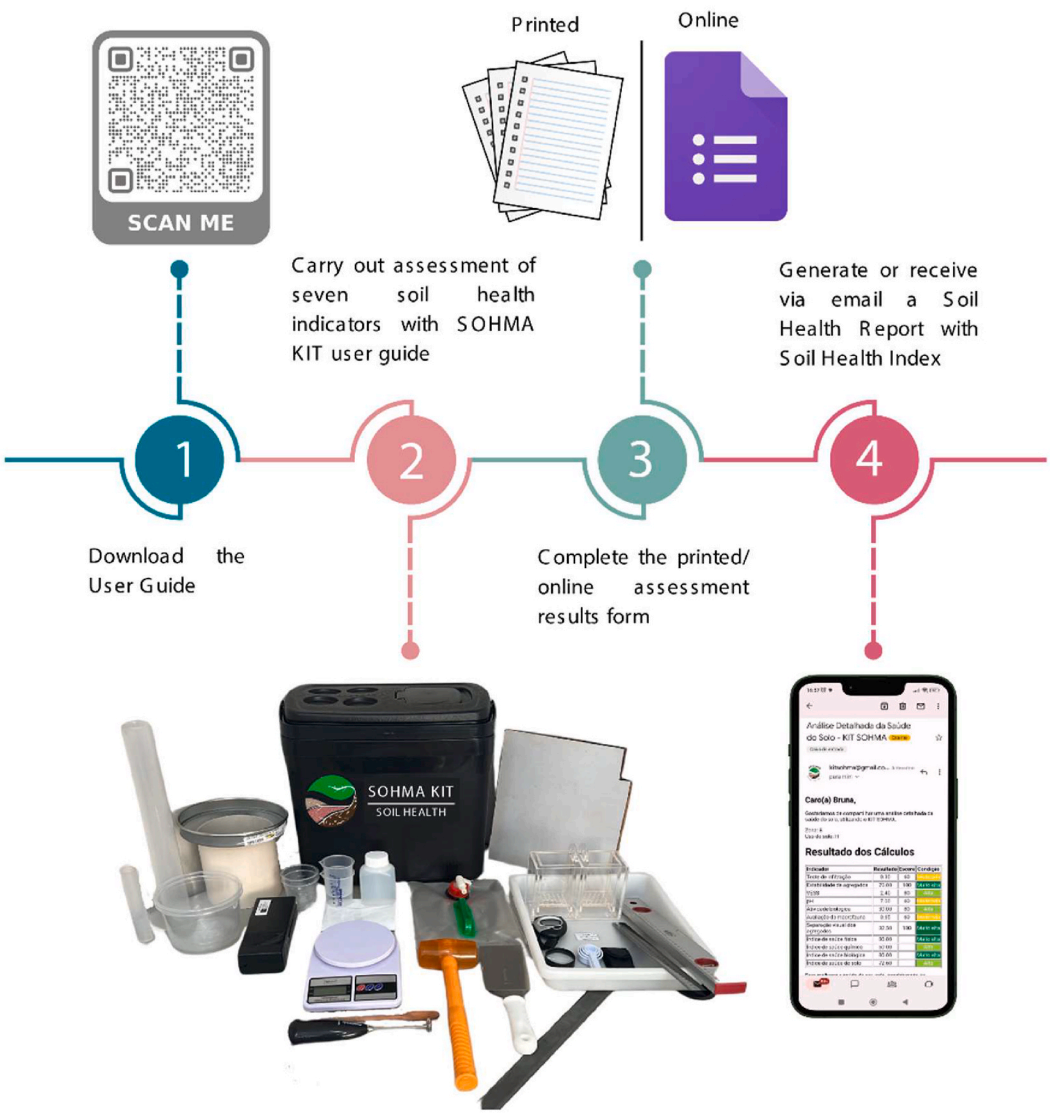

Fig. 2. Step-by-Step process for On-Farm Soil Health assessment using the Soil Health and Management Assessment Kit (SOHMA KIT®).

(Table 1). These methods serve as reliable benchmarks for comparison with the SOHMA KIT® approach.

The experimental trials have been conducted for five years in Rio Verde, Goiás (17° 47′ 53″ S and 50° 55′ 41″ W, altitude 715 m), and for nine years in Rondonópolis, Mato Grosso (16°27′41.75"S and 54°34′52.55"W, altitude 292 m). Soil texture in Rio Verde is composed of 33 % clay, 13 % silt, and 54 % sand, while in Rondonópolis, it is 48 % clay, 19 % silt, and 33 % sand. The climate of this region is classified as tropical savanna with dry winters and rainy summers (Aw), with an average annual precipitation higher than 1600 mm, and 80–90 % of which fall between October and April (Alvares et al., 2013).

In Rio Verde, the field trial was designed using a randomized strip design measuring 12 m × 80 m, covering an area of 960 m^2 with three replications for each treatment. Each treatment consisted of an experimental area measuring 10 m long and 12 m wide, while the measurements were taken in the area corresponding to the two central rows of soybean. The field trial consisted of five different winter crop treatments: 1) Fallow (no crop); 2) Maize; 3) maize_ruzigrass (*Urochloa ruziziensis*); 4) Ruzigrass; and 5) Mix of cover crops (Millet *(Pennisetum glaucum)*, showy rattlebox (*Crotalaria spectabilis*), and ruzigrass).

In Rondonópolis, a randomized block design was carried out with four different winter crop treatments and three replicates. The treatments were: 1) fallow (no weed control); 2) showy rattlebox; 3) palisade grass (*Urochloa brizantha*); and 4) mix of cover crops, in which: maize_ruzigrass was grown (during one year), followed by eight years of pigeon pea (*Cajanus cajan*), three years of sunflower/ruzigrass, and five years of mix (showy rattlebox, millet, ruzigrass, and pigeon.

Soybean was the cash crop grown in all production systems during the cropping season (November to March). These treatments represent the most important alternative for the second season in the region, with: i) maize – the main cash crop for the second season in that region, characterizing the typical soybean-maize succession system; ii) maize intercropped with ruzigrass intercropping is a well-established alternative, reconciling grain production (maize) and abundant biomass production and deep root system of the ruzigrass (Souza et al., 2025); iii) ruzigrass (alone) – the most cultivated grass of the region to produce high above- and belowground biomass, and it has been used for both covering soil and cattle grazing; iv) showy rattlebox used due its capacity fixing N_2 and to input fresh organic matter into the system, improving soil biota and nematode control; and v) cover crop mix composed of ruzigrass, millet, and showy rattlebox in Rio Verde and composed of showy rattlebox, millet, ruzigrass, and pigeon pea in Rondonópolis. Both alternatives include crops well adapted to the region. The cover crop mix added multiple complementary traits to the system and benefits described below. More details about the experimental sites can be accessed in Souza et al. (2025).

Table 1
Corresponding methodologies in the SOHMA KIT® and standard methods for each soil health indicator applied in the cropping systems in the Brazilian savanna.

Category	Indicator	Method	
		SOHMA KIT®	Standard
Physical	Infiltration	One PVC ring – Adapted from USDA (USDA, 2001)	Beerkan infiltration test – Bagarello et al. (Bagarello et al., 2017)
	Aggregate stability	Wet sieving with fast wetting – Adapted from USDA (USDA, 2001) Ball et al. (Ball et al., 2007), Guimarães et al. (Guimarães et al., 2011)	Wet sieving – Elliott et al. (Elliott, 1986)
	VESS	Ball et al. (Ball et al., 2007), Guimarães et al. (Guimarães et al., 2011)	–
Chemical	pH	In bottled water – Adapted from USDA (USDA, 2001), Teixeira et al. (Teixeira et al., 2017)	In distilled water – Teixeira et al. (Teixeira et al., 2017)
Biological	Catalase enzyme	Catalase enzyme test with hydrogen peroxide – Adapted from Nicholls et al. (Nicholls et al., 2004)	Activity of arylsulfatase enzyme – Tabatabai (Tabatabai, 1994)
	Macrofauna	Classification and Soil Macrofauna Index (diversity index) – Adapted from Vanolli et al. (Vanolli, 2024)	Classification from Anderson & Ingram (Anderson and Ingram, 1989) and Shannon index (diversity index)
	Biogenic aggregates	Aggregates from 8 to 10 cm to identification – Adapted from Pereira et al. (Pereira et al., 2021)	Pereira et al. (Pereira et al., 2021)
Soil Health Index	Minimal data set	Infiltration, aggregate stability, VESS, pH, catalase enzyme, macrofauna, biogenic aggregates	Aggregate stability, bulk density, pH, phosphorus, potassium, β-glucosidase enzyme, soil organic carbon
	Interpretation	Thresholds suggested by expert opinion and interpretation table found in literature	Soil Management Assessment Framework – scoring curves (Andrews et al., 2004)
	Integration	Weighted additive approach – Cherubin et al. (Cherubin et al., 2016b)	Weighted additive approach – Cherubin et al. (Cherubin et al., 2016b)

In each treatment, disturbed and undisturbed soil samples were collected (standard methods) and evaluated directly in the field (SOHMA KIT®) in February 2024 (wet season), from the 0–10 of depth, except for VESS and macrofauna in which evaluations occurred from 0 to 30 cm.

2.4. Data analysis

The data set was subjected to analysis of variance (ANOVA) using a completely randomized design. Normality of the residuals was assessed using the Shapiro-Wilk test ($p > 0.05$) to ensure the adequacy of parametric testing. When significant differences were detected (F-test, $p < 0.05$), Tukey's HSD test was applied to compare treatment means. We used $\alpha = 0.10$ to interpret significance as weak evidence, respectively, following the approach suggested by Muff et al. (2022), using the *agricolae* package (Mendiburu, 2020). All statistical analyses were performed with RStudio version 4.0.4 (Team RC, 2023). Box plots were generated to evaluate the sensitivity, data variability, and similarity of results obtained from the SOHMA KIT® indicators compared to the corresponding standard methods for discriminating between cover crop treatments. In addition, random forest models were implemented with the *randomForest* package (Liaw and Wiener, 2002) to determine which indicators were most important in determining the overall SHI obtained by each method. Pearson's linear correlation analysis was performed to assess the relationships between the results obtained by the SOHMA KIT® and the standard methods.

3. Results

3.1. Response of soil health indicators assessed by the SOHMA KIT® and corresponding standard methods

In Rio Verde, all physical indicators assessed by both the SOHMA KIT® and the standard method detected significant treatment-induced changes. Infiltration rates increased by 164 % under maize, 178 % under ruzigrass, 246 % under maize_ruzigrass, and 165 % under the cover crop mix, compared to the fallow treatment (Fig. 3-A), as measured by the SOHMA KIT®. Similarly, the standard method showed that infiltration rates were up to 30 % higher when crops were integrated into the system than fallow (Fig. 3-A). However, for soil macroaggregation, the SOHMA KIT® indicated that the ruzigrass treatment had the highest aggregate stability (up to 95 %) compared to maize. In contrast, the standard method showed that the maize_ruzigrass treatment had the lowest aggregate stability (about 65 %) (Fig. 3-B). In general, when analyzing the VESS, greater plant diversity resulted in lower scores, indicating improved soil structure. On average, the cover crop mix treatment had a structure score 1.6 times less than the other treatments, reflecting better soil conditions (Fig. 3-C). No differences in pH were observed between treatments using the SOHMA KIT® approach ($p > 0.10$), while changes in maize intercropped with ruzigrass exhibited a 7 % reduction in pH compared to fallow in the standard method (Fig. 3-D). Among the biological indicators, biogenic aggregates were able to distinguish strong differences between cover crop treatments using both approaches ($p < 0.01$). Adoption of crop diversification using maize intercropped with ruzigrass and a mix of cover crops resulted in up to 43 % of biogenic aggregates (Fig. 3-G).

In Rondonópolis (Fig. 4), only pH ($p = 0.05$) and biogenic aggregation ($p < 0.01$) assessed by the standard method showed weak and strong evidence, respectively, of management-related changes. In contrast, infiltration was the only indicator in the SOHMA KIT® assessment to show weak treatment effects ($p = 0.09$), indicating a management response, with a 4.6-fold increase in infiltration rates in the cover crop mix treatments. Both indicators followed similar patterns to those observed in Rio Verde, with cover crops decreasing pH (Fig. 4-D) and increasing biogenic aggregate formation up to 50 % in mix treatment (Fig. 4-G).

Overall, soil health indicators assessed using the SOHMA KIT® had greater variability at both study sites than those measured using the standard method (Figs. 3 and 4). Despite these differences in variability and sensitivity, both approaches displayed consistent tendencies. The cover crop treatments consistently resulted in higher infiltration rates (Fig. 3-A and 3–4), increased soil macroaggregation (Fig. 3-B,C and 4-B, C), lower soil pH (Fig. 3-D and 4-D), and greater catalase enzyme (Fig. 3-E and 4-E), including increased biogenic aggregate formation (Fig. 3-G and 4-G).

3.2. Comparison of soil health index between SOHMA KIT® and standard approach

Soil health improved with crop diversification, especially in the mix treatment ($p = 0.08$), suggesting weak evidence of treatment effects. In Rio Verde (Fig. 5-A), the soil health index (SHI) derived by SOHMA KIT® measurements increased from 52 % (fallow) to 70 % (cover crop mix). The improvement in SHI was mainly attributed to higher scores in

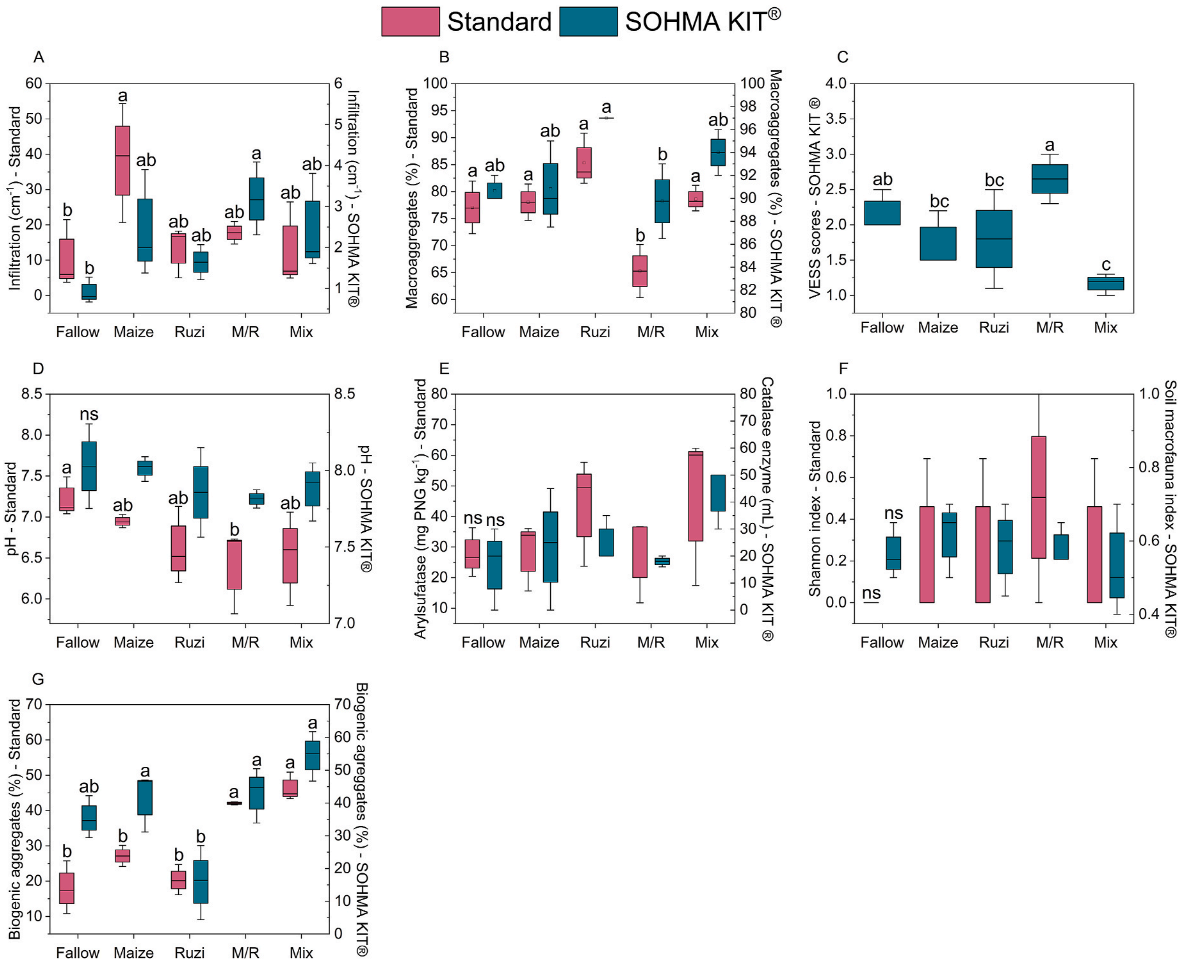

Fig. 3. Physical, Chemical, and Biological Indicators Measured by the SOHMA KIT® (blue) and Standard Methods (red) at 0–10 cm Depth in Rio Verde, Goiás, Brazil. A) Infiltration test, B) Aggregate stability, C) Visual Evaluation of Soil Structure VESS, D) pH, E) Catalase enzyme, F) Macrofauna evaluation, G) Biogenic aggregate. Cover crops: Ruzigrass (*Urochloa ruziziensis*), M/R (maize and ruzigrass), Mix (millet, showy rattlebox, and ruzigrass). Conventional systems (Fallow and Maize). Means followed by the same letter do not differ according to Tukey's HSD test ($p < 0.1$). ns = non-significant. *VESS was evaluated from 0 to 25 cm.

the physical (from 28 % to 33 %) and chemical (from 7 % to 13 %) components, with significant contributions from higher infiltration rates and pH values (Fig. 6-A). No significant differences were observed in the biological component ($p > 0.10$), although biogenic aggregates proved to be an important indicator in explaining variations in the overall SHI (Fig. 6-A). For the standard method, a similar pattern was observed; however, only the biological component captured the increase from 0.22 to 0.24 between the fallow and mix treatments (Fig. 5-A). The soil organic carbon and β-glucosidase activity, combined with bulk density and pH (Table S4), were the main indicators explaining the variability in the overall SHI (Fig. 6-B).

In Rondonópolis, although both methods showed similar results (Fig. 5-B), the SOHMA KIT® result was slightly higher. No changes in the SHI were observed regardless of the method applied. The physical components assessed by the SOHMA KIT® had moderate differences ($p = 0.02$) between the fallow and cover crop treatments. A decrease in physical conditions was observed when maize was intercropped with ruzigrass compared to the fallow treatment (from 32 % to 27 %). For the standard evaluation, weak differences ($p < 0.10$) were detected only in the chemical component, with a decrease observed when showy rattlebox was adopted in the second season compared to maize intercropped with ruzigrass (from 0.32 to 0.30), with pH being one of the main indicators explaining the variations in the overall SHI (Fig. 6-B, Table S5).

3.3. *Relationship between SOHMA KIT® and standard methods for soil health assessment*

Pearson correlations between the SOHMA KIT® and the standard methods for each soil health indicator (except VESS), as well as the soil health indexes (physical, chemical, biological, and overall SHI) are in Table 2. All physical indicators evaluated by the SOHMA KIT® correlated ($p < 0.05$) with their corresponding standard methods. The infiltration test and aggregate stability displayed strong and moderate positive associations ($r = 0.71$ and $r = 0.40$, respectively) with their standard counterparts. The same trend was observed for pH, with a strong positive correlation between the results obtained by the two methods ($r = 0.87$). Among the biological indicators, only catalase enzyme and biogenic aggregate showed strong associations with their corresponding standard methods, with correlation coefficients of 0.61 and 0.59, respectively ($p < 0.05$). Despite the differences in the indicators used to construct the overall SHI by the SOHMA KIT® and the standard method, both approaches obtained a moderate positive association ($r = 0.44$, $p < 0.05$).

4. Discussion

4.1. *SOHMA KIT®: A field-based tool for monitoring soil management changes*

We sought to test the effect of two soil health assessment approaches

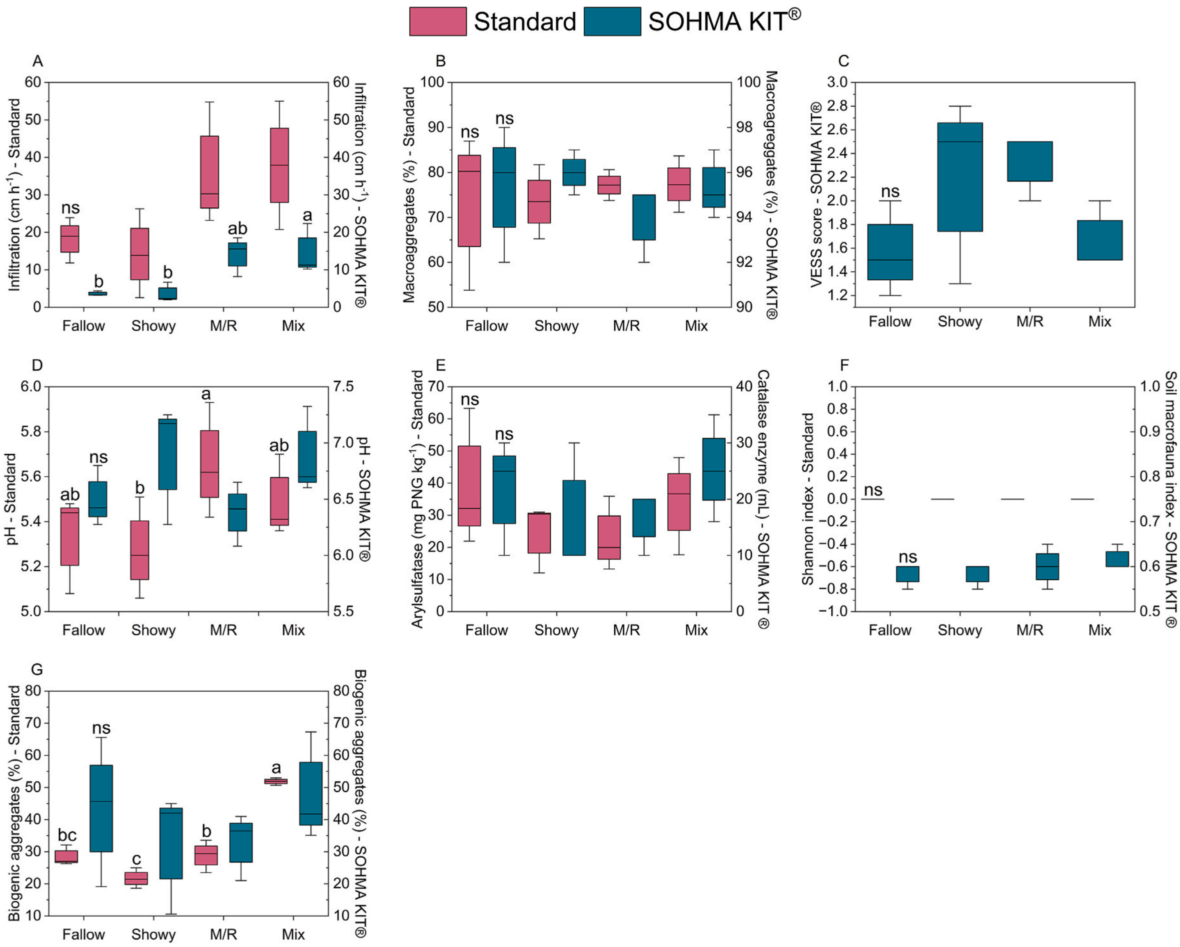

Fig. 4. Physical, Chemical, and Biological Indicators Measured by the SOHMA KIT® and Standard Methods at 0–10 cm Depth in Rondonópolis Mato, Grosso, Brazil. A) Infiltration test, B) Aggregate stability, C) VESS, D) pH, E) Catalase enzyme, F) Macrofauna evaluation, G) Biogenic aggregate. Cover crops: Showy rattlebox (showy rattlebox), M/R (maize and ruzigrass), Mix (showy rattlebox, millet, ruzigrass, and *C. cajan*). Conventional systems: Fallow (no weed control). Means followed by the same letter do not differ according to Tukey's HSD test ($p < 0.1$). ns = non-significant. *VESS was evaluated from 0 to 25 cm.

– the SOHMA KIT® and standard methods – within different cropping systems in the Brazilian savanna. The SOHMA KIT® was able to detect meaningful differences in soil health across cropping systems with contrasting levels of plant diversification. In Rio Verde, the cover crop mix and maize–ruzigrass systems showed higher SHI values compared to the fallow treatment, with an increase of around 35 % in the overall index for the cover crop mix (Fig. 5-A). Improvements were consistently observed across chemical, physical and biological indicators, demonstrating the sensitivity of the SOHMA KIT® to changes in soil health induced by management. These results align with previous studies conducted under comparable conditions that reported the inclusion of ruzigrass enhances nutrient cycling and improves soil structure (Souza et al., 2025; Crusciol et al., 2015; Favilla et al., 2021; Anghinoni et al., 2021). At the Rondonópolis site (Fig. 5-B), the fallow treatment without control of spontaneous weeds unexpectedly exhibited higher SHI values than the cover crop treatments. This may be due to spontaneous vegetation contributing to soil organic matter, root activity and microbial processes, thereby enhancing soil physical and biological properties. These results were confirmed with both the SOHMA KIT® and standard laboratory methods.

The SOHMA KIT® proved to be an effective method, having a significant correlation ($r = 0.44$ $p = 0.02$ - Table 2) of SHI score generated by the SOHMA KIT® and with standard soil health assessments across different treatments at both study sites in the Brazilian savanna (Table 2). It was easy to use, but requires careful observation of the chemical, physical, and biological attributes of the soil through indicators and scoring by layer. We evaluated the effectiveness of the SOHMA KIT® and standard methods in detecting changes in soil health. Both methods were generally consistent in identifying significant changes in key indicators, including infiltration ($r = 0.71$), aggregate stability ($r = 0.40$), pH (0.88), catalase enzyme (0.61), and biogenic aggregates (0.60) (Table 2). Our results aligned with other studies that correlated on-farm and laboratory methods. For example, Amado et al. (2007), reported correlations between the USDA Soil Quality Test Kit and standard laboratory methods, which further supports the reliability of these simplified tools for distinguishing between management systems that have different impacts on soil health in Southern Brazil. However, unfortunately the USDA Soil Quality Test Kit project was discontinued and this tool is no longer available. In a more recent study, also in southern Brazil, Valani et al. (2020) concluded that on-farm PGPE protocol effectively distinguished soil health in Cambisols under conventional farming, no-tillage farming, organic farming, agroforestry systems and native vegetation. They found correlations of up to 0.80 between data generated by PGPE and SMAF in the assessed land uses.

The standard method includes many ways to measure or evaluate soil physical health, including bulk density (McKenzie, 2001), soil water characteristic curves (Reynolds et al., 2009), or penetration resistance (McKenzie, 2001); and various image processing methods applied in two dimensions (Holden, 1993) or three dimensions using X-ray computed tomography (Anderson et al., 1990; Ghosh et al., 2023). However, these methods, while scientifically well-established and accepted, are generally inaccessible for farmers and consultants due to technical and

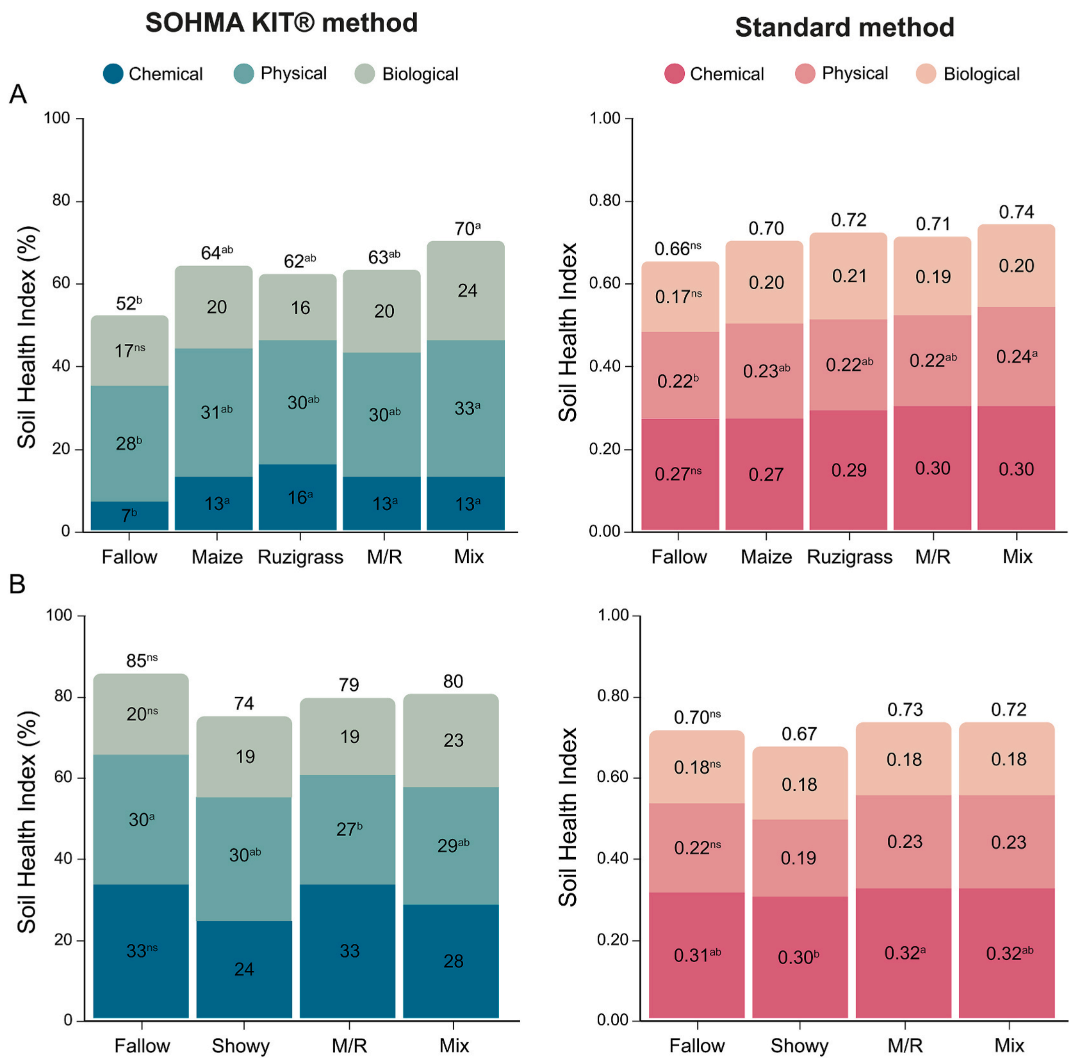

Fig. 5. Soil health index by SOHMA KIT® and standard method applied in Rio Verde (A) and (B) Rondonópolis at 0–10 cm depth by cover crops management systems: Rio Verde - Fallow, Maize, ruzigrass (*U. ruziziensis)*, M/R (maize and ruzigrass), Mix (millet, showy rattlebox, and ruzigrass) for 5 years. Rondonópolis – Fallow (weeds), Showy (showy rattlebox), M/R (maize and ruzigrass), Mix (showy rattlebox, millet, ruzigrass, and *C. cajan*) for 9 years). Means followed by the same letter do not differ according to Tukey's HSD test ($p < 0.1$). ns = non-significant.

financial limitations. Therefore, a rapid, low-cost, and reproducible field method is still needed to assess soil physical health. Our results indicated that the SOHMA KIT® detected soil physical changes, including improved infiltration rates, soil macroaggregation, and soil structure (via VESS scores) induced by adopting cover crops, particularly ruzigrass and a mix of cover crops (ruzigrass, millet, and showy rattlebox), confirmed that SOHMA KIT® can offer reliable and comparable results to standard method, but in a cheap, faster, and on-farm way. The SOHMA KIT® was also the most sensitive in detecting changes in management in Rondonópolis, detecting a decline in soil physical health under the maize_ruzigrass treatment.

In terms of soil chemical indicator (i.e., pH), the SOHMA KIT® was slightly less sensitive than the standard method, but the correlation ($r = 0.88$) between the two methods remained strong (Table 2). The most important differences were observed for biological indicators, where the standard method showed greater sensitivity to changes in enzyme activity, particularly under the mix treatment (0.61). Finally, the contrasting sensitivity of chemical, physical, and biological indicators to management changes underscores the importance of using an integrated soil health assessment. This approach is crucial for understanding the impacts of land management practices on soil multifunctionality, supporting decision-making to promote the sustainability of agricultural systems.

4.2. SOHMA KIT®: advantages and limitations

The SOHMA KIT® is an innovative tool designed for on-farm assessment of soil health in a portable, cost-effective, and sensitive way. Its greatest advantage lies in its ability to be used directly in the field, without the need of costly and/or complex laboratory equipment and analysis. This portability, coupled with its low cost, makes it an accessible solution for farmers and land managers across diverse regions, including remote areas that lack adequate soil laboratory infrastructure. The SOHMA KIT® is sensitive enough to capture critical physical changes in the soil, such as infiltration rates and aggregate stability, allowing users to obtain valuable insights into soil health status with minimal resources and facilitating early implementation of sustainable management strategies (Mora-Motta et al., 2024).

An important advantage of the SOHMA KIT® is its versatility for teaching, exhibitions, extension, and outreach initiatives. As a practical and didactic tool, it serves as an effective means to illustrate soil health concepts and the implications of management decisions to students, farmers, extension workers, and other stakeholders. Similar to other on-farm soil assessment methods such as VESS (Ball et al., 2007; Guimarães

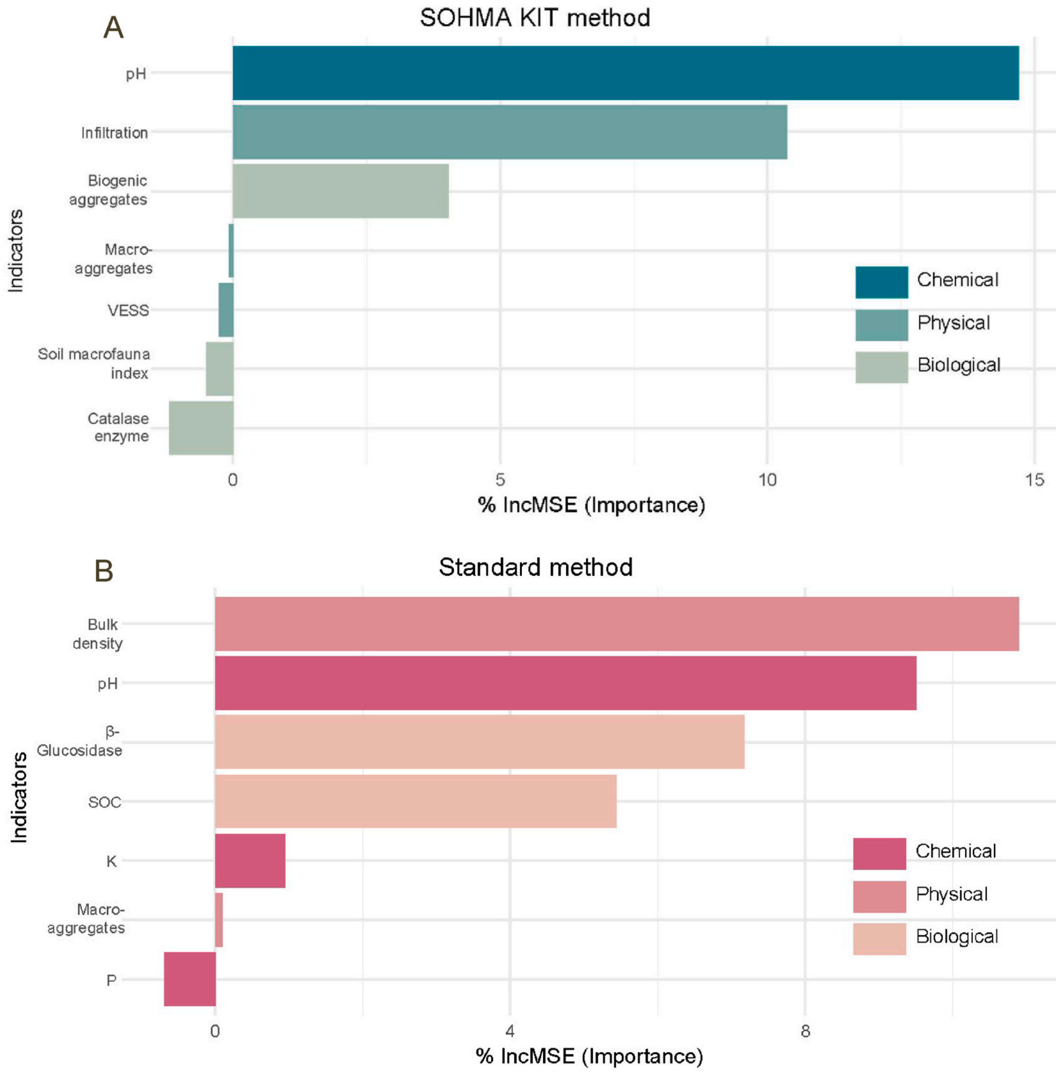

Fig. 6. Contribution of individual soil indicators to explain variations in soil health index by SOHMA KIT® (A) and standard assessment (B). VESS: Visual evaluation of soil structure, %IncMSE: percentage increase in Mean Squared Error.

Table 2
Pearson correlation of soil health indicators and index by SOHMA KIT® *vs* corresponding standard method. n = 27.

	Pearson's correlations	*p-value*
Infiltration	0.712	0.000
Aggregate stability	0.400	0.038
pH	0.876	0.000
Catalase - Arylsulfatase enzymes	0.615	0.001
Macrofauna	0.021	0.917
Biogenic aggregate	0.599	0.001
Soil health index	0.444	0.020

et al., 2011) and PGPE (Comin et al., 2016), the SOHMA KIT® provides an accessible, hands-on approach that allows a wide range of users, including farmers themselves, to engage in soil health assessment. In addition, like the Biofunctool® (Thoumazeau et al., 2019), USDA Soil Quality Kit (USDA, 2001), and PGPE (Comin et al., 2016), the SOHMA KIT® incorporates process-based assessments of soil functions and relies on thresholds and expert-based interpretations rather than crop-specific response curves. The inclusion of a comprehensive user guide further enhances its accessibility, making it a valuable tool for both practical decision-making and educational purposes.

The SOHMA KIT® could also be applied for monitoring the impact of large-scale public or private initiatives/program related to regenerative agriculture and carbon farming, pasture reclamation, and forest restoration, e.g., the Brazilian Agricultural Policy for Climate Adaptation and Low Carbon Emission (ABC+) – MAPA (MAPA, 2021); Public-private carbon farming initiative (Cherubin et al., 2024); Living Soils of America and Africa (Alliance for a Green Revolution in Africa, and Inter-American Institute for Cooperation on Agriculture) (Alliance for a Green Revolution in Africa, n.d.; Inter-American Institute for Cooperation on Agriculture, 1942); FAO- Soil Doctors (FAO, 2019); and Coalition of Action for Soil Health (https://www.coalitionforsoilhealth.org/). These large-scale initiatives are supported by governments, non-governmental organizations and private sectors.

Nevertheless, we acknowledged that the SOHMA KIT® has its own particular difficulties and constraints that must be taken into account. Firstly, basic user training is recommended to reduce subjectivity when interpreting visual indicators, such as VESS and macrofauna assessments. Ball et al. (2007) also identified this limitation for VESS, emphasizing the importance of training to minimize variability in soil structure scores attributed by different evaluators. Secondly, the SOHMA KIT® does not currently facilitate direct measurement of important soil health indicators, such as soil organic matter and plant-available nutrients. To overcome these limitations, we recommend that farmers make use of the data on soil fertility that is routinely collected for liming and fertilization purposes. Additionally, the SOHMA KIT® was specifically designed and validated for topsoil assessment (0–10 cm), except for VESS, which evaluates soil structure at depths of 0–30 cm. While this aligns with many on-farm soil quality assessment methods (Guimarães et al., 2011; Comin et al., 2016; USDA, 2001), it does not account for deeper soil layers, where key processes, including water retention, root penetration, carbon sequestration and long-term nutrient cycling, play a critical role. Alternatively, existing methodologies, such as the Sub-VESS proposed by Ball et al., 2015, 2017, could be incorporated to extend assessments into deeper soil layers, enhancing the tool's applicability to a broader range of agricultural and conservation contexts.

An important limitation of the SOHMA KIT® is that it relies exclusively on field-based evaluations. While this is advantageous for practical on-farm use, it limits the inclusion of laboratory-based indicators that could provide greater analytical accuracy. In addition, the accuracy of the results depends on optimal sampling conditions, which may vary depending on the location and timing of the assessments. A similar limitation was reported by Guimarães et al. (2017) in assessments using VESS, highlighting the importance of controlled assessment conditions to minimize the influence of soil moisture variability on visual soil assessments. Similar to the Biofunctool® (Thoumazeau et al., 2019), SOHMA KIT® requires a time investment of 1.5–2 h per assessment, which limits the number of repetitions that can be performed in the field. Due to these limitations, it is highly recommended to carefully select a representative sampling location within the field or farm to ensure reliable and meaningful soil health assessments.

One of the key challenges is that the interpretation of results is based on soil functions rather than specific crop response curves, which may limit its use in providing direct management recommendations. Further improvements, particularly through continuous feedback from field data, will help refine the tool's performance and ensure its usefulness in a variety of agricultural contexts. This will enhance its ability to provide practical and reliable insights for sustainable soil management.

In general, we summarized the performance of key soil health indicators (physical, chemical, and biological) evaluated using the

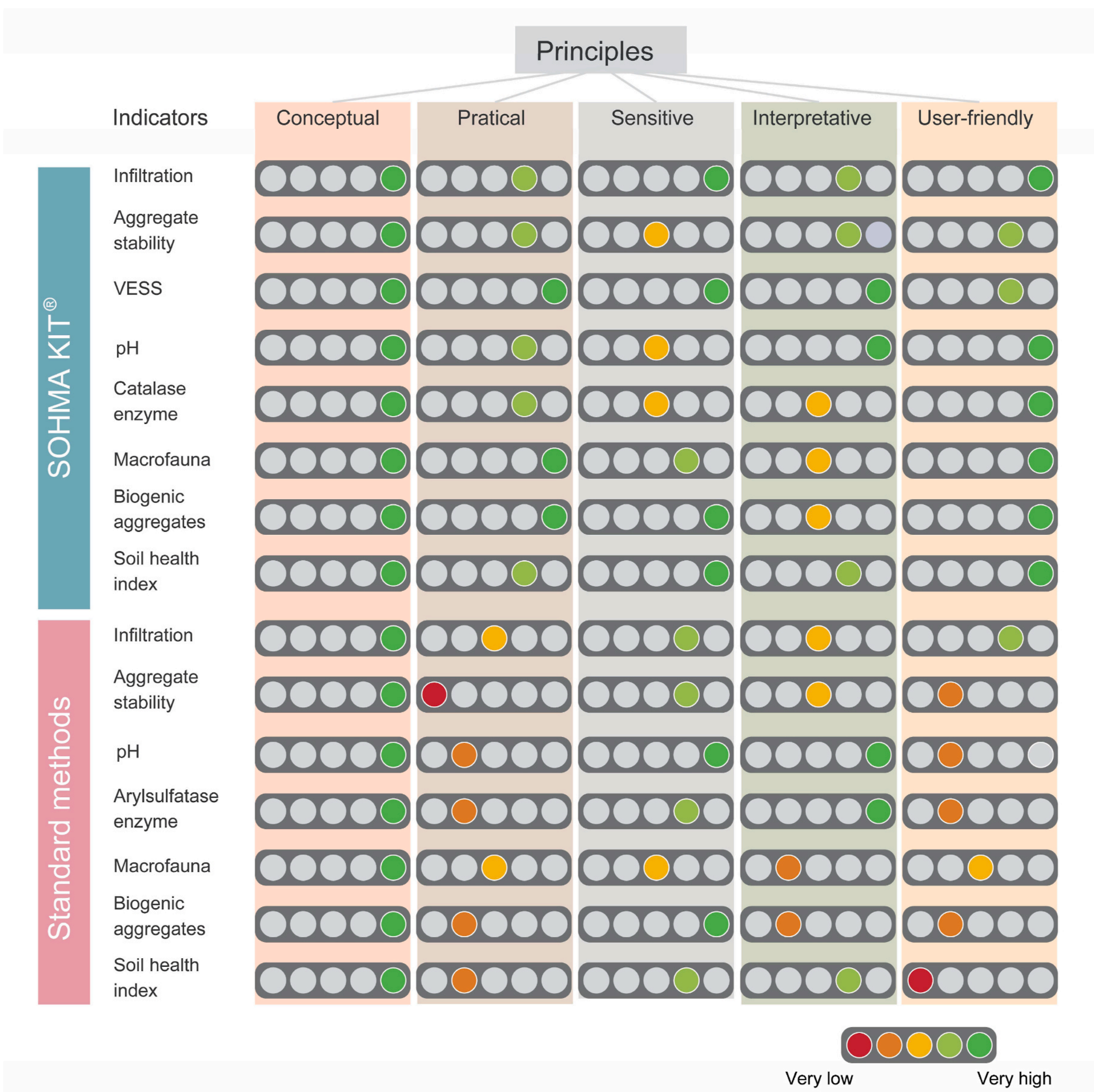

Fig. 7. Comparative Evaluation of Soil Health Indicators: SOHMA KIT® vs. Standard Methods. The chart illustrates the performance of key soil health indicators (physical, chemical, and biological) across different evaluation criteria – conceptual, practical, sensitive, interpretative, and user-friendly. VESS: Visual Evaluation of Soil Structure, The ranking of each indicator into the categories very low, low, medium, high, and very high was based on the team's expertise, expert opinion, literature review, and methodological papers.

SOHMA KIT® and standard methods according to five principles: conceptual, practical, sensitive, interpretative, and user-friendly (Fig. 7), as outlined by Doran and Parkin (1995), Bünemann et al. (2018) and Lehmann et al. (2020). The SOHMA KIT® consistently outperforms standard methods on the practical and user-friendly criteria, offering high to very high levels of practicality by eliminating the need for complex and expensive laboratory setups. Infiltration, VESS, and macrofauna are very practical indicators, while standard methods are hampered by the time and infrastructure required for processes such as aggregate stability analysis (Flynn et al., 2020). The SOHMA KIT® shows moderate sensitivity for certain indicators, including aggregate stability, pH, and catalase enzymes, due to its simplified field-based protocols.

The SOHMA KIT®'s interpretative strength lies in its use of established scoring frameworks and expert-driven interpretation tables, which make the results both actionable and accessible. In addition, its user-friendly design, supported by free protocols and instructional videos, ensures it can be used easily by people with varying levels of expertise. Overall, the SOHMA KIT® provides a scalable and reliable solution for on-farm soil health assessment with practicality and feasibility of use, making it particularly suitable for both smallholders with limited access to laboratory infrastructure and large-scale farmers/initiatives across the country. Thanks to its adaptability and cost-effectiveness, it can be a powerful tool for promoting soil health assessment in agricultural areas of Brazil and elsewhere around the world.

5. Conclusions

Our hypothesis was confirmed: the indicators present in the Soil Health and Management Assessment Kit (SOHMA KIT®) effectively captured changes in soil health resulting from land use and management practices. In this study, we validated the SOHMA KIT® as an accessible and reliable on-farm tool for assessing soil health directly in the field. The SOHMA KIT® demonstrated its applicability across contrasting agricultural cropping systems, providing a cost-effective and practical alternative (or complement) to traditional laboratory-based methods. Our findings showed that the SOHMA KIT® was sensitive to management-induced changes in key physical and biological indicators, including infiltration rates, aggregate stability, and biogenic aggregate formation, which highlights its potential for broader use in sustainable land management practices. Future efforts will be applied to refine the SOHMA KIT® by incorporating user feedback and expanding its applicability across different soil types, climate conditions, and cropping systems (including pastures and restored/native vegetation). The inclusion of new indicators and the updating of indicator interpretation tables are also part of the medium-term plans, while the development of the SOHMA KIT® app is a key long-term goal. These advances will ensure that the tool remains adaptable, flexible, and useful for assessing and monitoring soil health for different purposes not only in Brazil but also with the potential to be extended to other regions of the world.

CRediT authorship contribution statement

Bruna Emanuele Schiebelbein: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Victória Santos Souza:** Writing – review & editing, Writing – original draft, Formal analysis. **Maurício Roberto Cherubin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bruna Emanuele Schiebelbein has patent #BR102024015629-3 pending to University of Sao Paulo - USP. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100802.

Data availability

Data will be made available on request.

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