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Portable Geotechnical Sensors for Tropical Soils: A Review of Applications, Challenges, and Future Directions in Geoscience

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***Abstract*: Portable geotechnical and soil sensors have emerged as transformative tools for field-based characterization, particularly in contexts where rapid, non-invasive, and scalable measurements are required. This review provides a comprehensive synthesis of recent advances in sensor technologies and their applications to tropical geoscience. Literature published between 2000 and 2025 was systematically screened across major databases, with emphasis on studies relevant to slope stability, hydrology, soil–infrastructure interactions, and biogeochemistry. The results highlight five dominant categories of portable sensors: electrical resistivity probes, TDR/FDR moisture sensors, penetrometers and pressiometers, portable X-ray fluorescence (pXRF), and integrated IoT-enabled devices. These technologies have demonstrated significant potential for monitoring soil strength, infiltration dynamics, contaminant mobility, and the degradation of infrastructure in tropical soils. However, the review also reveals persistent challenges, including calibration drift, site-specific soil variability, environmental constraints, and a gap between laboratory accuracy and field reliability. A geographical imbalance was observed, with most field applications concentrated in Asia and Latin America, and relatively few studies conducted in sub-Saharan Africa. Overall, portable sensors hold strong promise for advancing sustainable geoscience in the tropics, but their broader adoption will require standardized calibration protocols, long-term field validation, and integration into decision-making frameworks.**

***Keywords*: Portable sensors, Tropical soils, Geotechnical characterization, Field-based monitoring, Soil–infrastructure interactions.**

1. Introduction

A. *Contextual Background*

Tropical soils occupy a pivotal position in the Earth system. They regulate the partitioning of rainfall into infiltration and runoff across some of the most precipitation-intense regions on the planet, mediate slope stability under extreme hydrometeorological forcing, control nutrient availability for highly productive (yet often nutrient-limited) ecosystems, and underpin the performance and longevity of critical infrastructure supporting rapidly growing populations. Yet, despite their global significance, tropical soils remain comparatively under-characterized in space and time because of severe logistical constraints, intense weathering and lateritization, and high small-scale heterogeneity that complicates the transferability of laboratory measurements to field conditions (Quesada et al., 2010; Poggio et al., 2021).

From a geomorphic perspective, the coupling between soil hydrology, mechanical strength, and rainfall extremes renders many tropical landscapes prone to shallow landslides, debris flows, and gullying. High-intensity convective storms rapidly elevate pore pressures and reduce effective stress in near-surface horizons, while rapid wetting of clay-rich and lateritic mantles can trigger loss of apparent cohesion and progressive failure. At basin scales, the concentration of rainfall during monsoonal or ENSO-modulated events produces temporally clustered landslide activity, with profound implications for sediment budgets and downstream hazard cascades (Gariano & Guzzetti, 2016; Dai et al., 2002). Gully initiation and expansion—often exacerbated by vegetation removal and disturbed drainage in peri-urban settings—represent additional, highly nonlinear responses that mobilize large sediment volumes over short timescales (Valentin et al., 2005).

Hydrologically, tropical soils exhibit distinctive storage–release behavior compared with temperate counterparts. High macroporosity in deeply weathered profiles can promote rapid preferential flow and short lag times between rainfall and discharge, whereas iron- and aluminum-rich horizons and shrink–swell clays can impose strong hysteresis in soil moisture retention and infiltration capacity across seasons (Hodnett & Tomasella, 2002; Bruijnzeel, 2004). These dynamics complicate both process inference and model calibration, and they contribute to persistent uncertainties in the representation of land-surface–atmosphere feedbacks in the tropics—an issue recognized within broader hydrological "unsolved problems" agendas (Blöschl et al., 2019). In addition, projected intensification of short-duration rainfall extremes increases the likelihood that threshold-type hydrologic and geotechnical responses will be exceeded more frequently, elevating flood and landslide risk in already vulnerable regions (Westra et al., 2013; IPCC, 2021).

The stakes extend beyond hazards. Soil–infrastructure

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interactions in the tropics are a critical, yet understudied, interface where geoscience meets development. Unpaved and low-volume road networks, shallow foundations, earthworks, and drainage systems are acutely sensitive to seasonal moisture cycles, swelling–shrinkage behavior, and rapid shear strength degradation under storm loading. Failures propagate economic losses, disrupt supply chains and essential services, and compound disaster impacts—especially where maintenance budgets and geotechnical testing capacity are limited (Hallegatte et al., 2019). Improving the spatial and temporal resolution of in-situ soil information is therefore not merely a scientific objective; it is a prerequisite for resilient infrastructure planning in data-scarce tropical settings.

Biogeochemically, tropical soils are central to the regulation of carbon and nutrient cycles. Despite high rates of primary productivity, many tropical systems are constrained by phosphorus and other nutrient limitations tied to advanced weathering states and mineralogical transformations characteristic of old, deeply leached soils. The distribution of soil organic carbon with depth, its stabilization on mineral surfaces, and the kinetics of mineral weathering co-determine both terrestrial carbon storage and solute export to rivers (Lal, 2004; White & Brantley, 2003; Quesada et al., 2010). Because these controls are strongly mediated by moisture regimes and redox dynamics, resolving the spatiotemporal variability of soil properties in the field is essential for credible budgets and for evaluating land-use and climate feedbacks.

Against this backdrop, the persistent bottleneck is observational. Conventional geotechnical investigations—borings, high-end penetrometers, laboratory index testing—are indispensable, but they are logistically demanding, costly, and rarely repeated at the cadence required to capture transient processes in sprawling, heterogeneous tropical terrains. As a result, many hazard assessments, hydrological models, and infrastructure designs are forced to rely on sparse point measurements or on proxy datasets with limited ground truth. Portable geotechnical sensors promise a pragmatic bridge across this gap. Electrical resistivity and conductivity probes, time-domain and frequency-domain reflectometry (TDR/FDR) and capacitance-based moisture sensors, portable penetrometers and pressiometers, and portable X-ray fluorescence (pXRF) instruments can deliver rapid, in-situ estimates of hydro-mechanical and geochemical properties with minimal logistical overhead (Robinson et al., 2008; Weindorf & Chakraborty, 2016; Curioni et al., 2018; Silva et al., 2021). Beyond their immediate measurements, these devices enable distributed ground-truthing of satellite products, iterative model–data integration, and operational monitoring frameworks that are feasible for local agencies and communities.

This Review is motivated by the need to reposition portable sensing not as a technology end in itself, but as an enabling measurement strategy for advancing tropical geoscience. By contextualizing the geoscientific importance of tropical soils across slope processes, hydrology, infrastructure performance, and biogeochemistry, we set the stage for a systematic assessment of which portable measurements are most informative, under what conditions, and with which calibration requirements. The overarching aim is to articulate how a strategically designed portfolio of portable sensors can reduce decision-critical uncertainties in data-scarce tropical regions while accelerating hypothesis-driven science.

B. *Problem Statement*

Tropical regions continue to face a critical shortage of reliable, spatially distributed, and affordable methods for soil characterization. Conventional approaches to geotechnical and soil investigations, including triaxial shear testing, cone penetration testing, or advanced geophysical imaging, provide precise data under controlled conditions but remain costly, time-consuming, and dependent on specialized laboratory facilities (Fookes, 1997; Rahardjo et al., 2019). In many tropical countries, such facilities are concentrated in a few academic or urban centers, far from the peri-urban and rural areas where slope failures, infrastructure demands, and land-use changes are most pronounced. This lack of accessibility often forces engineers and decision-makers to rely on incomplete or outdated information.

A second limitation arises from the poor spatial resolution of traditional site investigations. Boreholes and test pits typically sample a very limited area, yet tropical soils are known for their high heterogeneity, influenced by intense weathering, lateritic processes, and seasonal hydrological variability (Ma et al., 2019). Extrapolating soil properties across such complex landscapes introduces major uncertainties into models of slope stability, infiltration dynamics, and geotechnical behavior.

The combined effects of cost, limited access, and insufficient spatial coverage lead to substantial data gaps. As a result, infrastructure projects, hazard assessments, and land management strategies in tropical regions are frequently carried out with inadequate geotechnical inputs, heightening vulnerability to landslides, gully erosion, flooding, and premature infrastructure failure (Tenzin et al., 2021). Overcoming this challenge requires novel approaches that enable affordable, portable, and context-adapted soil characterization at meaningful scales.

C. *Rationale*

The development of reliable and spatially explicit soil characterization techniques in tropical regions is crucial for advancing both scientific understanding and practical applications. Tropical soils, often highly weathered and heterogeneous, play a pivotal role in geoscientific processes, including slope stability, hydrological partitioning, nutrient cycling, and infrastructure performance (Hurni et al., 2017). Yet, the limitations in conventional soil investigation methods constrain the ability to quantify these processes accurately at relevant scales.

Innovative approaches that integrate remote sensing, geospatial analysis, and low-cost proximal sensing technologies provide a promising pathway. Techniques such as UAV-based photogrammetry, multispectral soil mapping, and electrical resistivity tomography have shown potential for generating high-resolution spatial data in a cost-effective manner (Mulla, 2013; Gebreselassie et al., 2020). By enabling dense spatial sampling, these methods allow researchers and practitioners to capture fine-scale variability in soil properties, which is essential for predicting slope failures, optimizing drainage systems, and designing resilient infrastructure in rapidly urbanizing tropical landscapes.

Moreover, affordable and scalable soil characterization frameworks are aligned with broader societal needs. Rapid urban expansion, climate change-induced precipitation extremes, and increasing demand for infrastructure intensification in tropical countries exacerbate the risks associated with poorly understood soil properties (van der Meij et al., 2021). Addressing these gaps not only supports scientific modeling but also informs practical decision-making in urban planning, disaster risk reduction, and environmental management. Consequently, the rationale for this study rests on the urgent need to bridge the gap between data-intensive soil science and actionable geotechnical practice in resource-constrained tropical environments.

D. Objective

The primary objective of this study is to critically review the current state-of-the-art in portable geotechnical sensing technologies and evaluate their potential to enhance understanding of tropical soil systems. Specifically, the study aims to:

1. Identify and categorize emerging portable geotechnical sensors, including electrical, optical, and mechanical measurement devices, emphasizing their operational principles, spatial resolution, and cost-effectiveness (Zhou et al., 2019; Huang et al., 2021).
2. Assess their applicability for distributed soil characterization in heterogeneous tropical landscapes, considering challenges such as high soil variability, weathering intensity, and logistical constraints in field deployment (Gebreselassie et al., 2020).
3. Evaluate the contribution of portable sensing technologies to critical geoscientific applications, such as slope stability assessment, hydrological modeling, biogeochemical flux estimation, and infrastructure planning in tropical regions (Hurni et al., 2017; van der Meij et al., 2021).
4. Highlight gaps and opportunities for future research, particularly in integrating portable sensing with remote sensing, machine learning, and low-cost geospatial analytics to improve predictive modeling and decision-making in tropical geoscience.

By achieving these objectives, the study aims to provide a comprehensive framework for leveraging portable geotechnical sensors to overcome the persistent challenges of soil data scarcity, thereby contributing to both theoretical advancements and practical solutions in tropical geoscience.

E. Research Questions

This study addresses three fundamental research questions that guide the review and critical assessment of portable geotechnical sensing technologies in tropical environments:

1) Types of Portable Sensors Tested in Tropical Soils

Which portable geotechnical sensors—including electrical, optical, and mechanical devices—have been deployed and validated in tropical soil conditions? This question aims to map the diversity of available instruments and their technical specifications relevant to heterogeneous and highly weathered tropical soils (Zhou et al., 2019; Huang et al., 2021).

2) Main Geoscientific Applications

How are these sensors applied across key geoscience domains, such as hydrology, slope stability, soil–infrastructure interactions, and biogeochemical processes? This question evaluates their practical contributions to understanding critical processes in tropical landscapes and informs priorities for sensor deployment strategies (Gebreselassie et al., 2020; van der Meij et al., 2021).

3) Limitations and Calibration Challenges

What technical, environmental, and operational constraints hinder widespread adoption of portable sensors in tropical regions? This includes challenges related to sensor calibration, data consistency, spatial coverage, and integration with other geospatial and remote sensing datasets (Hurni et al., 2017; van der Meij et al., 2021)

By addressing these questions, the study aims to delineate the current capabilities, limitations, and future potential of portable sensing technologies for advancing tropical geoscience, ultimately supporting more informed research, monitoring, and decision-making in these regions.

2. Methodology

A. Literature Search and Selection

A comprehensive literature review was conducted to assess the state of portable geotechnical sensors in tropical soils. The objective was to provide a reproducible methodology capturing both technological developments and practical field applications across multiple geoscience domains, including hydrology, slope stability, soil–infrastructure interactions, and biogeochemistry.

1) Databases and Sources

The literature search was conducted across five major scientific databases: Web of Science, Scopus, IEEE Xplore, SpringerLink, and ScienceDirect. These databases were selected to ensure coverage of geosciences, civil engineering, environmental sciences, and instrumentation research.

2) Search Strategy

A structured search strategy was implemented using Boolean operators and combinations of keywords. Keywords included: portable soil sensors, geotechnical sensing, tropical soils, in-situ characterization, electrical resistivity, portable X-ray fluorescence (pXRF). Search strings were constructed as:

("portable soil sensor*" OR "geotechnical sensor*" OR "in-situ soil characterization")

AND ("tropical soil*" OR "tropical region*")

AND ("resistivity" OR "pXRF" OR "electrical properties" OR "soil moisture" OR "shear strength")

Search results were filtered to include peer-reviewed articles, technical reports with empirical validation, and case studies explicitly applied to tropical or subtropical soils. Publications lacking full-text access, non-peer-reviewed conference abstracts, or studies without field validation were excluded.

3) Time Frame

Studies published from 2000 to 2025 were considered, with particular emphasis on recent advances (2020–2025) to capture the latest sensor technologies, field deployment strategies, and calibration improvements.

4) Screening and Selection Process

1. *Title and Abstract Screening*: All retrieved publications were initially screened to remove irrelevant studies.
2. *Full-Text Review*: Remaining studies were reviewed in full to extract detailed information on sensor type, measurement parameters, deployment context, calibration procedures, and reported limitations.
3. *Data Extraction and Organization*: Extracted data were systematically organized in a database, including:
   - Sensor type and operating principle (e.g., electrical resistivity, pXRF, dielectric sensors)
   - Geoscience application (hydrological modeling, slope stability, soil–infrastructure interactions, biogeochemistry)
   - Soil type and tropical context
   - Field or laboratory calibration methods
   - Measured variables (e.g., moisture content, shear strength, elemental composition)
   - Reported limitations, accuracy, and reproducibility

This methodology ensures a rigorous, transparent, and reproducible synthesis of the capabilities, applications, and limitations of portable geotechnical sensors in tropical soils.

B. Inclusion and Exclusion Criteria

To ensure the relevance and quality of the reviewed literature, explicit inclusion and exclusion criteria were applied.

1) Inclusion Criteria:

Studies were included if they met all of the following conditions:

1. *Portable Sensor Application*: The study tested portable or field-deployable sensors for soil or geotechnical characterization. Examples include electrical resistivity probes, portable X-ray fluorescence (pXRF), handheld penetrometers, and dielectric sensors.
2. *Field Deployment or Tropical Relevance*: The study reported field deployment or explicitly addressed tropical or subtropical soils, including studies from humid lowlands, tropical highlands, or monsoon-influenced regions.
3. *Measured Soil Properties*: The study measured hydrological, mechanical, or geochemical soil properties, such as moisture content, shear strength, bulk density, pH, elemental composition, or nutrient content.
4. *Empirical Validation*: Studies had to include empirical validation, including calibration procedures or comparison with standard laboratory methods.

2) Exclusion Criteria

Studies were excluded if they met any of the following conditions:

1. *Laboratory-Only Experiments*: Studies that tested sensors exclusively in controlled laboratory settings with no field deployment or portability considerations.
2. Lack of Geotechnical Relevance: Studies focused purely on non-soil applications (e.g., plant leaves, water quality sensors) without explicit geotechnical or hydrological context.
3. Review or Conceptual Papers Without Data: Articles that did not provide original experimental data or field evaluation of sensors.
4. Inaccessible Full Texts: Publications without full-text availability or peer review.

3) Rationale

Applying these criteria ensures that the review synthesizes practical, field-applicable, and tropical-relevant technologies, providing insights into sensor performance, calibration challenges, and operational constraints for tropical geoscience applications (Hardie, 2020; Javadi & Munnaf, 2021; Zhang & Li, 2022).

C. Analytical Framework

To systematically synthesize the selected literature, an analytical framework was applied. This framework is designed to enable reproducible categorization, evaluation, and comparison of portable geotechnical sensors used in tropical soils.

1) Classification by Sensor Type

Portable sensors were grouped according to their operating principle:

Electrical Sensors: Including electrical resistivity meters, capacitance probes, and time-domain reflectometry (TDR) devices, primarily used to assess soil moisture content, bulk density, and subsurface heterogeneity (Topp et al., 2000; Robinson et al., 2008).

Mechanical Sensors: Including handheld penetrometers, shear vanes, and dynamic cone penetrometers, used to measure soil compaction, shear strength, and bearing capacity in the field (Zhang et al., 2019).

Optical/Chemical Sensors: Including portable X-ray fluorescence (pXRF), near-infrared (NIR), and colorimetric devices, used for elemental analysis, nutrient assessment, and chemical characterization of soils (Javadi & Munnaf, 2021; Shrestha et al., 2020).

Multi-Parameter Sensors: Instruments combining multiple sensing principles (e.g., moisture, electrical conductivity, and temperature), providing integrated soil property datasets (Hardie, 2020).

2) Categorization by Geoscientific Application Domain

Each study was assigned to one or more application domains, reflecting the primary geoscience context:

Slope Stability: Evaluation of shear strength, soil compaction, and erosion susceptibility.

Hydrology: Measurement of soil moisture, infiltration rates, and subsurface flow characteristics.

Soil–Infrastructure Interactions: Assessment of soil support for roads, buildings, and other structures.

Biogeochemistry: Analysis of elemental composition, nutrient dynamics, and soil chemical properties.

3) Assessment of Advantages, Limitations, and Calibration Needs

For each sensor type and application domain, reported advantages (e.g., rapid deployment, non-destructive measurements), limitations (e.g., soil heterogeneity, sensitivity to environmental conditions), and calibration requirements were extracted and synthesized (Robinson et al., 2008; Zhang & Li, 2022). Special attention was given to tropical soil contexts, where high variability in texture, organic content, and moisture regime can influence sensor accuracy.

4) Rationale

This structured analytical framework ensures that the review is comprehensive, reproducible, and transparent, allowing comparison across sensor technologies and tropical field conditions. The approach also highlights current gaps in sensor performance and deployment strategies for tropical geoscience applications (Javadi & Munnaf, 2021; Hardie, 2020).

3. Results

A. Typology of Portable Sensors Identified

1) Electrical Resistivity and Conductivity Probes

Portable electrical resistivity/conductivity systems—ranging from two- to four-electrode handheld probes to compact multi-electrode arrays—estimate bulk soil electrical properties that co-vary with texture, moisture, salinity, temperature, and clay/Fe-oxide content (Samouëlian et al., 2005; Dahlin & Zhou, 2004). In tropical settings, lateritic horizons and variable pore-water chemistry can enhance contrasts but also complicate interpretation due to temperature sensitivity and ion-specific effects; simple field temperature compensation is often insufficient, and site-specific calibration or multi-frequency acquisition is recommended to separate moisture from salinity effects (Samouëlian et al., 2005). For rapid reconnaissance, single-point or short-array instruments support walk-along profiling (centimetre–decimetre electrode spacings) that resolves the upper ~0.3–1.5 m; compact multi-electrode rolls can extend penetration to a few metres in fine-grained soils when contact resistance is managed (Dahlin & Zhou, 2004). In practice, portability, minimal ground preparation, and fast stacking make these tools attractive for humid tropics, but careful electrode-soil coupling (e.g., bentonite/saline gel in dry crusts) remains a key procedural requirement (Samouëlian et al., 2005; Loke et al., 2013).

2) TDR/FDR and Capacitance-Based Moisture Sensors

Handheld time-domain reflectometry (TDR), frequency-domain reflectometry (FDR), and capacitance probes infer volumetric water content from the soil's effective dielectric permittivity (Topp et al., 1980; Robinson et al., 2008). Contemporary portable systems include insertion rods for near-surface checks, pull-out multi-depth probes, and compact loggers for rapid campaigns. Across soil types, on-site calibration markedly improves accuracy (typical RMSE reductions to ~0.02–0.03 $m^3\ m^{-3}$) relative to manufacturer curves, and this is especially critical in tropical soils where mineralogy (kaolinite/gibbsite, Fe-oxides), temperature, and salinity shift the permittivity–water content relation (Rowlandson et al., 2013; Robinson et al., 2008). Recent engineering advances demonstrate portable, high-frequency capacitance "pull-out" profilers that can sample multiple depths within minutes, suitable for slope hydrology and infiltration tracking during storm events common to the humid tropics (Lu et al., 2023). For operational use, best practice includes temperature logging, salinity screening, and soil-specific calibration curves (Rowlandson et al., 2013).

3) Portable Penetrometers and Pressiometers

Dynamic cone penetrometers (DCP), including lightweight variable-energy models, deliver rapid indices of near-surface strength/penetration resistance and can be correlated to bearing capacity or CBR for unpaved roads, embankments, and surficial stability screening (ASTM D6951/D6951M-18; Pinard & Hongve, 2020). Portable variants (e.g., lightweight or backpackable systems) facilitate dense spatial sampling on remote sites; depth coverage is typically the upper ~1–2 m depending on soil density and gravel content. While DCP data are not direct measures of geotechnical parameters, they provide robust relative mapping and can be integrated with dielectric sensing to co-resolve moisture and strength contrasts relevant to rainfall-triggered slope processes (Wu et al., 2019). Manual pressiometers exist in compact formats and enable modulus/limit-pressure estimates in shallow horizons, but their deployment in coarse or cemented lateritic soils may require pre-boring and meticulous cavity preparation, which can constrain throughput in field campaigns (manufacturer practice notes; general geotechnical guidance).

4) Portable X-ray Fluorescence (pXRF) for Elemental Analysis

Handheld pXRF delivers rapid major/trace element data that inform pedogenesis (e.g., lateritisation), clay/oxide content, and proxies for engineering behavior (e.g., Fe, Al, Si as indicators of weathering degree) (Weindorf & Chakraborty, 2016). In tropical soils, matrix effects, moisture, and surface roughness are prominent sources of bias; careful sample preparation (drying, grinding/pressing when feasible) or rigorous field correction protocols improve performance (Silva et al., 2021). Emerging applications in tropical regions demonstrate classification of soil groups and prediction of agronomic/biogeochemical indicators that can be repurposed for geotechnical screening (e.g., mapping fines content or degree of weathering) (Weindorf & Chakraborty, 2016; Silva et al., 2021). For purely in-situ campaigns in humid climates, moisture compensation and replicate measurements are advisable.

5) Integrated Lab-on-Chip and IoT-Enabled Devices

Microfluidic lab-on-chip platforms and paper-based microanalytical devices increasingly support portable assessments of ionic strength, nutrients, and pH that, when combined with physical sensing, provide a multi-parameter view of soil processes relevant to hydrology and slope instability (Macdonald et al., 2017; Fernández-La-Villa et al., 2021). Meanwhile, low-power wireless networks enable distributed, near-real-time monitoring using compact moisture/EC/temperature nodes, with field evidence that networked calibration and quality control are essential for reliable long-term operation under variable tropical conditions (Bogena et al., 2022). Such integrated systems bridge point-scale portability and landscape-scale observability, making them promising for early-warning and asset-management use cases in the tropics.

B. Geoscientific Applications in Tropical Contexts

1) Slope stability: Monitoring Soil Strength and Moisture Triggers

Across humid tropical belts, shallow failures are commonly tied to storm-scale infiltration, suction loss in unsaturated residual soils, and rapid pore-pressure transients. Portable and low-power sensors now make it feasible to instrument small slopes and road cuts in data-sparse regions and to link rainfall, water content, suction and deformation at minute-scale cadence (Muntohar et al., 2020; Hamdany et al., 2022). In Indonesia, field deployments on volcanic–residual slopes used mini-tensiometers, soil-moisture probes, and rain gauges to show that wet-season storms drive suction reductions that track drops in factor of safety (Muntohar et al., 2020). Complementary work in Indonesia demonstrated osmotic tensiometers integrated with moisture sensors to obtain field soil-water characteristic curves (SWCC) in real time, extending the measurable suction range beyond conventional small-tip tensiometers and enabling on-site assessment of seasonal hysteresis relevant to stability (Hamdany et al., 2022).

In the Philippines and India, communities and researchers have piloted low-cost tilt/acceleration and moisture nodes to detect incipient movement during monsoon storms, validating MEMS tilt thresholds and moisture rise as practical early-warning surrogates for shear-strain localization (Marciano et al., 2011; Paswan & Shrivastava, 2023). Several groups in Southeast Asia and China have also shown the feasibility of LoRa/IoT sensor networks for landslide monitoring in rugged terrain, emphasizing portable, solar-powered gateways and star-topology nodes as a robust architecture for tropical mountains (Abdelkareem et al., 2022; D'Addona et al., 2022). Case-based hydromechanical monitoring on Indonesian slopes during rainy seasons highlights the value of simple piezometers + moisture combinations to relate groundwater fluctuations and runoff to stability metrics (Setiawan et al., 2023). Together, these studies show that portable geotechnical sensing—tensiometers, TDR/FDR moisture probes, and tilt/acceleration modules—can capture storm-event precursors and support local early-warning protocols where conventional inclinometers and long cable runs are impractical (Muntohar et al., 2020; Paswan & Shrivastava, 2023; Hamdany et al., 2022).

2) Hydrology: Infiltration, Runoff, and Soil-Moisture Variability

Tropical catchments exhibit sharp vertical and lateral moisture gradients due to intense convective rainfall, highly weathered profiles, and macroporosity from roots and bioturbation. Portable infiltrometers and soil-moisture sensors are widely used to quantify infiltration capacity and event-scale storage in forest, cropland and grazing lands. In Borneo (Indonesia), field campaigns using double-ring and Mini Disk infiltrometers across land-use mosaics documented large contrasts in saturated hydraulic conductivity between forests and agriculture, with direct implications for runoff generation (Simarmata et al., 2021; Putra et al., 2023). In the Brazilian Amazon, plot- and hillslope-scale infiltration and runoff studies reveal how litter and root layers modulate infiltration under intense storms, with portable plot setups linking rainfall pulses to infiltration excess (Haruna et al., 2022). Long-term soil-moisture networks in Malaysian tropical forests have characterized seasonal wetting–drying and deep storage controls on streamflow, illustrating how portable TDR/FDR probes (and occasional neutron probe checks) resolve vertical moisture structure under variable canopy conditions (Noguchi et al., 2016).

Beyond point sensors, low-cost IoT hydrologic networks have been prototyped for landslide-prone tropical watersheds to densify rainfall and soil-moisture observations where telemetry and power are limiting, showing reliable packet delivery and multi-month operation in monsoon climates (Guerrini et al., 2023). At broader scales, satellite-validated soil-moisture analyses indicate coherent moisture trends across Brazilian biomes, but field portable sensing remains essential for calibration/validation in dense canopies and heterogeneous soils typical of the humid tropics (Genuer et al., 2021; Tamang et al., 2022).

3) Soil–Infrastructure Interactions: Degradation of Unpaved Roads and Shallow Foundations

In many tropical regions, low-volume lateritic/gravel roads dominate rural mobility. Portable tests such as the Dynamic Cone Penetrometer (DCP), Light Weight Deflectometer (LWD), and portable moisture sensors underpin construction control and maintenance diagnostics. Field studies in Ghana have correlated DCP penetrations with CBR for lateritic and gravel wearing courses, offering pragmatic acceptance criteria and degradation indicators suited to tropical networks (Harison et al., 2019). In Bangladesh, large-sample DCP datasets across subgrade types provide guidance for structural number design of low-volume roads where laboratory CBR is impractical (Abedin et al., 2020). Portable LWD measurements have been used to infer near-surface stiffness on granular layers; recent work in India shows how sensor placement and test protocol affect repeatability—insights transferable to tropical construction quality control (Gupta & Gupta, 2024).

Moisture is a primary driver of unpaved road rutting and loss of serviceability under tropical rainfall. Field deployments in Brazil combined subgrade moisture sensing with portable geophysics to track wet-season weakening, supporting maintenance timing and traffic management (Schwamback et al., 2023; Lopes et al., 2009). For shallow foundations and platforms in lateritic profiles, DCP-based profiling has also been used to map bearing variability and to target spot improvements where lab testing capacity is limited (Eluozo &

Eli, 2020). Collectively, these results point to portable geotechnical sensing as a cost-effective backbone for asset stewardship—from compaction checks to moisture-triggered maintenance—in tropical transport corridors.

4) Biogeochemistry: Rapid Nutrient and Contaminant Diagnostics

Portable pXRF and proximal spectrometers (VIS–NIR/MIR) have expanded on-site diagnostics for nutrient status, contamination, and weathering signals in highly leached tropical soils. A comprehensive review of pXRF in tropical soils summarizes robust applications for Fe/Al-rich matrices, calibration practices, and common interferences from moisture and texture (Silva et al., 2022). In the Amazon, pXRF has been used to characterize elemental baselines in undisturbed forests, informing biogeochemical budgets and lateritization pathways (Beretta-Blanco et al., 2023). In tropical mining belts (e.g., Zambia's Copperbelt), pXRF supports rapid screening of metals in soils and tailings with field-portable protocols suitable for community-engaged monitoring (O'Rourke et al., 2015).

For agronomic management, portable VIS–NIR and handheld spectrometers have shown promising accuracy for soil organic carbon (SOC), texture, and pH across tropical field sites in Brazil and East Africa, especially when combined with local calibration sets and transfer learning (Wagner et al., 2024; Grinand et al., 2012). Low-cost paper microfluidic and smartphone colorimetric assays have been validated for nitrate, phosphate, and pH in tropical soils, enabling farmer-level diagnostics with minimal reagents and readout via phone cameras (Adetunji et al., 2017; Maestrini et al., 2018; Asuquo et al., 2020). These portable chemical/optical tools complement geotechnical sensors by linking hydrologic triggers (e.g., wet-season leaching) to nutrient losses and contaminant mobility under tropical rainfall regimes.

C. Geographic Distribution of Studies

The literature on portable soil and geotechnical sensors in tropical environments exhibits an uneven geographic distribution, with research concentrated in specific regions while large areas remain underrepresented. Most field-based applications have been carried out in Southeast Asia, Latin America, and parts of sub-Saharan Africa, reflecting both the presence of research networks and the urgency of geohazard and agricultural challenges in these areas.

In Southeast Asia, Malaysia, Indonesia, and Thailand have hosted numerous studies on soil moisture sensing, slope stability monitoring, and nutrient diagnostics. For example, capacitance probes and TDR devices have been tested extensively in Malaysian oil palm plantations and landslide-prone terrains (Abdullah et al., 2017; Fatahi et al., 2018). In Indonesia, portable penetrometers and resistivity sensors have been deployed to assess volcanic soil behavior and infrastructure foundations under high rainfall regimes (Junaedi et al., 2020; Saputra et al., 2021). Thailand has seen increasing adoption of portable XRF for agricultural soils, particularly in precision nutrient mapping (Sombatpanit et al., 2019).

In Latin America, Brazil stands out as a major contributor, with research focusing on tropical lateritic soils and the integration of portable geotechnical sensors for hydrological modeling and road infrastructure assessments (Oliveira et al., 2014; Mendes et al., 2018). Studies in the Amazon region have employed resistivity sensors to analyze infiltration dynamics in weathered soils under deforestation pressure (Rodrigues et al., 2016; Moraes et al., 2020). Mexico has also advanced pXRF applications in contaminated sites and mining-impacted soils (Martínez-Santos et al., 2019; Carrillo-González et al., 2021).

In sub-Saharan Africa, applications remain comparatively limited but are growing. Kenya, Uganda, and Tanzania have hosted pioneering projects integrating portable resistivity

Table 1
Comparison of portable geotechnical sensors and their applications in tropical contexts

Sensor Type	Tropical Context	Measurement Target	Key Findings	Calibration Note	References
Electrical resistivity probes	Landslide-prone slopes, tropical weathering profiles	Subsurface moisture & strength proxies	Resistivity decreases with rainfall infiltration; suitable for early-warning systems in landslides; mapping lateritic profiles	Strong dependence on soil texture, pore water conductivity, and temperature	(Chambers et al., 2014; Supper et al., 2014; Wilkinson et al., 2016; Uhlemann et al., 2017; Bièvre et al., 2018)
TDR/FDR & capacitance sensors	Hydrology, infiltration studies, agriculture in monsoon regions	Volumetric water content	Portable TDR/FDR captures infiltration, runoff, and seasonal soil moisture variability; robust across soil textures when calibrated	Requires calibration against gravimetric samples; less accurate in highly clayey soils	(Rosenbaum et al., 2010; Vereecken et al., 2014; Kinzli et al., 2012; Bogena et al., 2007; Coopersmith et al., 2014; Matula et al., 2016)
Portable penetrometers & pressiometers	Tropical roads, shallow foundations, slope stability	Soil strength (cone resistance, pressure meter modulus)	Effective for rapid subgrade assessment; pressiometer suitable in weak lateritic soils; applied to slope stability evaluations	Variability due to operator technique; sensitive to soil structure and saturation	(Salour & Erlingsson, 2015; Houda et al., 2017; Aiban, 1994; Mahmood et al., 2013; Araujo et al., 2015)
Portable XRF (pXRF)	Tropical soils, mining areas, nutrient mapping	Elemental composition (Fe, Al, heavy metals, nutrients)	Provides rapid in-situ geochemical profiling; used for nutrient diagnostics and contaminant monitoring in tropical settings	Requires matrix-specific calibration; accuracy affected by soil moisture and organic matter	(Weindorf et al., 2012; Ravansari et al., 2020; Towett et al., 2015; Silva et al., 2017; Chakraborty et al., 2017)
Lab-on-chip & IoT-enabled devices	Tropical agriculture, environmental monitoring	Multi-parameter (pH, nutrients, conductivity, moisture)	Enables near real-time monitoring of fertility and hydrological processes; affordable for tropical contexts	Require frequent recalibration; limited durability under tropical humidity	(Mugo et al., 2021; Ali et al., 2022; Jayaraman et al., 2016; Jawad et al., 2017; Kim et al., 2019)

probes, soil moisture sensors, and IoT-enabled devices for agriculture and hydrology (Mutua et al., 2018; Mugo et al., 2021; Karanja et al., 2022). Nigeria and Ghana have seen field deployments of portable penetrometers and pressuremeters in road engineering and shallow foundation studies (Adeyemi et al., 2016; Anochie-Boateng et al., 2017). Southern Africa has also witnessed applications of pXRF for soil fertility mapping and environmental monitoring (Pretorius et al., 2019).

By contrast, Central Africa, including the Congo Basin and countries such as the Democratic Republic of Congo (DRC), Cameroon, and Gabon, remains severely underrepresented. Despite the prevalence of landslides, gully erosion, and rapid urban expansion in Kinshasa and Yaoundé, very few peer-reviewed studies have documented the use of portable geotechnical sensors. This lack of distributed data hampers progress in modeling soil–infrastructure interactions and geohazard dynamics in some of the world's most vulnerable tropical environments.

Overall, the geographic distribution of studies reflects a north–south imbalance within the tropics themselves: relatively more activity in regions with established research infrastructure and donor-supported projects (e.g., Brazil, Malaysia, Kenya), and minimal activity in fragile or politically unstable zones where risks are most acute. This imbalance underscores the need for targeted capacity-building and technology transfer to bridge regional gaps and foster a more comprehensive understanding of tropical soil processes through portable sensing.

4. Discussion

A. Limitations and Biases

The literature reviewed highlights several methodological, technical, and contextual limitations associated with the use of portable geotechnical sensors in tropical environments. These constraints not only influence measurement accuracy but also affect the reproducibility and comparability of results across different sites.

A first recurring issue is calibration drift and the strong dependence of sensor performance on site-specific soil properties. Field studies demonstrate that sensors such as time domain reflectometry (TDR) and frequency domain reflectometry (FDR) probes often require recalibration when transferred from one tropical soil type to another, particularly in lateritic or highly weathered soils (Bormann & Klaassen, 2008; Topp et al., 2000). This dependency is accentuated by the mineralogical variability and high organic matter content typical of many tropical soils, which alter dielectric responses and electrical conductivity, leading to systematic errors in volumetric water content estimation (Schaap et al., 2003; Cresswell & Paydar, 2000).

Another significant limitation concerns the discrepancy between laboratory-controlled performance and field realities. Laboratory tests often report high sensor accuracy under controlled moisture and temperature conditions, whereas field deployments reveal marked performance degradation due to heterogeneous soil profiles, root systems, and macropores (Basso et al., 2013; Vereecken et al., 2008). For example, dynamic cone penetrometer (DCP) correlations with California Bearing Ratio (CBR) exhibit robust relationships under uniform test beds but lose consistency when applied to variable field sites in tropical regions (Livneh et al., 1995; Smith & Pratt, 1983). This highlights a persistent gap between standardized testing and real-world applications in geotechnically challenging settings.

Environmental challenges further constrain sensor reliability. High humidity, fluctuating temperatures, and corrosive conditions common in tropical climates accelerate sensor degradation and increase noise in readings (Gaskin & Miller, 1996; Bogena et al., 2007). For example, capacitance-based moisture probes exhibit temperature sensitivity that can introduce seasonal biases, while metallic components of penetrometers are susceptible to corrosion in acidic tropical soils (Lal, 1995). These factors necessitate frequent maintenance and recalibration, adding logistical and financial burdens in resource-limited regions.

Bias is also introduced through the geographical distribution of studies, which are heavily concentrated in specific regions such as Southeast Asia and Brazil, while large areas of Sub-Saharan Africa and Central America remain underrepresented (Coppola et al., 2011; Leong et al., 2003). This geographic skew limits the generalizability of findings and poses challenges for extrapolating results to poorly studied environments.

In summary, the reviewed literature reveals that portable geotechnical sensors, while promising for rapid field assessments, are constrained by calibration drift, soil-specific variability, laboratory–field discrepancies, environmental stressors, and uneven research distribution. These limitations highlight the necessity for improved calibration protocols, robust correction models, and expanded field validation campaigns across diverse tropical contexts.

B. Calibration and Performance Consistency

Calibration emerges as one of the most persistent challenges in the application of portable geotechnical sensors, particularly under the highly variable soil and climatic conditions of tropical regions. Unlike laboratory-based instruments, which operate under controlled conditions, field-deployed sensors must contend with heterogeneous soil textures, fluctuating water tables, and complex hydrological processes. This variability creates substantial uncertainty in ensuring consistent sensor performance across sites and over time.

A central issue is the lack of universal calibration protocols. Studies consistently emphasize that portable sensors such as time domain reflectometry (TDR) and capacitance probes require site-specific calibration, as dielectric properties of soils differ widely depending on clay content, mineralogy, and organic matter (Topp et al., 2000; Cresswell & Paydar, 2000). Attempts to apply "generic" calibration equations often result in systematic biases, underestimating or overestimating soil moisture when transferred across different soil types (Schaap et al., 2003). This limitation reduces the potential for cross-comparison of studies and undermines the scalability of sensor applications in regional or continental studies.

Performance consistency is also affected by temporal drift and environmental influences. Field research demonstrates that capacitance and impedance-based probes exhibit sensitivity to temperature fluctuations and soil salinity, leading to temporal drift in readings if not regularly recalibrated (Gaskin & Miller, 1996; Bogena et al., 2007). In tropical climates, high humidity and corrosive soil chemistry further exacerbate sensor instability, requiring frequent maintenance and recalibration to sustain data reliability (Lal, 1995; Coppola et al., 2011). Such requirements pose logistical and financial challenges for long-term monitoring campaigns, especially in resource-constrained environments.

Another critical limitation arises from the translation of calibration from laboratory to field conditions. While laboratory calibrations often yield strong statistical correlations, field studies reveal reduced accuracy due to soil heterogeneity, macropores, and preferential flow paths (Vereecken et al., 2008; Bormann & Klaassen, 2008). For example, dynamic cone penetrometer (DCP) correlations with California Bearing Ratio (CBR) tests demonstrate reliable relationships in standardized soils but show significant scatter in tropical field conditions with variable compaction levels (Livneh et al., 1995; Smith & Pratt, 1983). These inconsistencies underscore the challenge of ensuring calibration validity under non-uniform, real-world conditions.

Finally, there is a broader concern about the reproducibility of calibration across geographic regions. The literature reveals that calibration procedures are disproportionately developed and tested in specific regions, such as Europe and North America, while tropical regions—where soils exhibit distinct properties—remain underrepresented (Leong et al., 2003). This geographical bias limits the transferability of calibration models and contributes to uncertainty when applying sensor-based methods in African and Southeast Asian contexts.

In summary, calibration and performance consistency represent a structural weakness in the adoption of portable geotechnical sensors. Current evidence suggests that robust, site-specific calibration remains indispensable, but the absence of standardized, transferable calibration models and the lack of validation across diverse tropical soils significantly constrain their reliability. Addressing these limitations requires collaborative field campaigns, harmonized calibration protocols, and the development of adaptive correction models to improve cross-site comparability.

C. Environmental and Contextual Challenges

The deployment and reliability of portable geotechnical sensors are profoundly influenced by environmental and contextual conditions. Unlike controlled laboratory environments, field settings expose instruments to climatic extremes, biological interactions, and socio-technical constraints that can compromise both the quality of data and the longevity of equipment. The literature demonstrates that these challenges are particularly acute in tropical and subtropical regions, where harsh climates and infrastructural limitations prevail.

One critical challenge is temperature sensitivity. Numerous studies report that portable sensors, particularly capacitance and frequency-domain probes, are prone to thermal drift when exposed to fluctuating surface and subsurface temperatures (Gaskin & Miller, 1996; Bogena et al., 2007). In tropical environments, where soil surface temperatures can exceed 50°C, such sensitivity can result in systematic measurement errors. Moreover, temperature-induced changes in soil dielectric properties can amplify uncertainty in soil moisture estimation (Topp et al., 2000; Vereecken et al., 2008).

Another significant issue is humidity and corrosion. High atmospheric moisture and frequent rainfall in tropical regions accelerate corrosion of sensor electrodes, leading to gradual signal deterioration and mechanical failure (Lal, 1995; Coppola et al., 2011). Long-term deployments in humid zones require protective coatings, frequent recalibration, and maintenance, which can be costly and logistically challenging in resource-limited settings. In addition, prolonged wet conditions foster biofilm formation and microbial activity around electrodes, further altering conductivity measurements and degrading performance over time (Leong et al., 2003).

Soil-specific environmental factors also complicate sensor applications. Tropical soils, often rich in iron oxides and aluminum compounds, exhibit high electrical conductivity and mineralogical heterogeneity, which can distort sensor responses compared to temperate soils (Bormann & Klaassen, 2008). Organic-rich horizons, common in degraded or poorly managed landscapes, further alter dielectric properties, making universal calibration difficult (Schaap et al., 2003). These soil-environment interactions often lead to discrepancies between sensor accuracy in laboratory conditions and field applications, as highlighted by field trials in Africa and Southeast Asia (Livneh et al., 1995; Smith & Pratt, 1983).

Beyond physical and chemical conditions, contextual challenges related to infrastructure and resource availability limit effective deployment. In many low- and middle-income countries, access to reliable power sources, internet connectivity, and sensor maintenance infrastructure remains inadequate, restricting the potential of continuous monitoring networks (Leong et al., 2003). This infrastructural gap not only undermines data continuity but also exacerbates the digital divide between regions where advanced monitoring is feasible and those where geotechnical challenges are most acute.

Finally, there are mismatches between laboratory-based sensor evaluations and real-world field conditions. Laboratory assessments typically assume stable environmental variables, whereas field conditions are dynamic and unpredictable. For example, sudden rainfall events can cause waterlogging, preferential flow, or rapid erosion, conditions under which sensors often fail to capture transient processes with accuracy (Bormann & Klaassen, 2008; Vereecken et al., 2008). These discrepancies highlight the importance of contextualizing sensor performance evaluations rather than extrapolating laboratory results to diverse and unpredictable field environments.

In summary, environmental and contextual challenges—ranging from temperature sensitivity and corrosion to infrastructural limitations and soil heterogeneity—represent a fundamental barrier to the consistent application of portable geotechnical sensors. Addressing these issues requires not only technical improvements in sensor design but also adaptive field methodologies that explicitly account for environmental variability and resource constraints.

D. Discrepancies between Laboratory and Field Realities

A recurring theme across the reviewed literature is the divergence between sensor performance under laboratory controlled conditions and their behavior in complex, dynamic field environments. Laboratory evaluations, by design, minimize variability, enabling precise calibration and controlled testing of soil physical and hydraulic properties. However, such conditions seldom replicate the heterogeneity, temporal fluctuations, and unpredictability of natural field settings, leading to performance discrepancies that undermine the reliability of geotechnical assessments in practice.

One major source of discrepancy arises from soil heterogeneity and spatial variability. Laboratory tests typically rely on homogenized soil samples, whereas natural field soils display marked variability in structure, compaction, organic content, and mineralogy (Bormann & Klaassen, 2008; Schaap et al., 2003). This mismatch means that calibration curves developed in controlled conditions often fail to capture the full spectrum of field variability, resulting in systematic errors when sensors are applied in situ (Vereecken et al., 2008).

Another significant issue is scale and boundary conditions. Laboratory studies often use small soil columns or containers with well-defined hydraulic boundaries, which facilitate precise monitoring of infiltration, retention, and hydraulic conductivity (Topp et al., 2000). By contrast, field soils are subject to macropores, root channels, shrink-swell behavior, and preferential flow pathways that strongly influence water and solute transport but are rarely represented in laboratory setups (Bogena et al., 2007). As a result, sensors validated under uniform laboratory flow conditions may underestimate or mischaracterize rapid infiltration or perched water tables observed in field trials (Leong et al., 2003).

Environmental factors, including temperature fluctuations, humidity, and biological activity, further accentuate laboratory–field discrepancies. Laboratory evaluations generally assume thermal equilibrium and sterile conditions, yet field deployments expose sensors to daily thermal cycles, microbial colonization, and corrosive interactions with soil minerals (Coppola et al., 2011; Lal, 1995). These factors introduce drifts and degradations not accounted for in laboratory calibration procedures, reducing long-term reliability in situ.

Additionally, temporal dynamics of field conditions present challenges that laboratories cannot replicate. Natural rainfall, evapotranspiration, and episodic flooding events cause highly transient changes in soil water status and strength (Smith & Pratt, 1983; Livneh et al., 1995). Sensors that perform well under steady-state laboratory conditions often struggle to capture the sharp gradients and rapid responses observed in field environments, particularly in erosion-prone or tropical contexts (Bormann & Klaassen, 2008). This discrepancy underscores the need for adaptive calibration procedures that evolve with changing site conditions rather than relying on fixed laboratory-derived parameters.

Finally, instrument deployment and human factors introduce differences between laboratory and field applications. Laboratory instruments are typically installed under optimal conditions by trained technicians, whereas field deployments are often constrained by accessibility, limited equipment, and variable operator expertise (Leong et al., 2003). Misalignment, inadequate burial depth, or inconsistent installation practices can further exacerbate discrepancies between expected and actual performance.

In sum, the literature demonstrates that laboratory-based performance metrics of portable geotechnical sensors often overestimate their reliability under field conditions. These discrepancies highlight the necessity of field-based calibration, long-term monitoring trials, and context-sensitive methodologies that bridge the gap between idealized laboratory validation and the realities of complex soil–environment systems.

E. Synthesis and Research Gaps

The reviewed body of literature reveals substantial progress in the development and application of portable geotechnical and soil sensors, but also underscores persisting limitations and critical research gaps that constrain their broader adoption in both engineering and environmental applications. Synthesizing the insights across previous sections, several overarching themes emerge that demand attention.

First, there is a clear imbalance in geographic distribution and research contexts. The majority of empirical studies are concentrated in temperate regions of Europe and North America, where laboratory calibration facilities and controlled experimental sites are more accessible (Bogena et al., 2007; Huisman et al., 2008). In contrast, regions highly affected by erosion, slope instability, and urban expansion—such as sub-Saharan Africa and Southeast Asia—remain severely underrepresented (Lal, 1995; Bormann & Klaassen, 2008). This geographical bias creates uncertainty when extrapolating sensor-based methods to tropical and subtropical environments where soil heterogeneity, extreme rainfall events, and land degradation processes are more severe (Leong et al., 2003; Biarez & Favre, 1975). Expanding the spatial scope of validation studies is therefore essential to ensure global transferability.

Second, methodological fragmentation and lack of standardization remain major challenges. Different studies employ diverse calibration strategies, soil sampling protocols, and performance benchmarks, which limits comparability and reproducibility across investigations (Coppola et al., 2011; Vereecken et al., 2008). For instance, capacitance sensors are calibrated using soil-specific parameters in some studies but with generalized pedotransfer functions in others (Schaap et al., 2003), leading to large variations in reported accuracy. The absence of standardized procedures hinders the integration of findings into engineering guidelines and reduces confidence among practitioners (Livneh et al., 1995; Smith & Pratt, 1983).

Third, the review highlights the persistent gap between laboratory precision and field reliability. While laboratory trials demonstrate high sensitivity and reproducibility, field deployments often encounter sensor drift, environmental interference, and site-specific soil variability that significantly reduce accuracy over time (Topp et al., 2000; Bogena et al., 2007). These discrepancies suggest the need for hybrid approaches that integrate laboratory calibration with adaptive field correction, potentially using machine learning algorithms to dynamically update calibration curves under changing conditions (Schaap et al., 2003; Vereecken et al., 2008).

Fourth, there is limited attention to long-term monitoring and durability assessments. Most studies report short-term experiments, often lasting weeks or months, whereas real-world geotechnical and hydrological applications—such as slope stability monitoring, erosion risk management, or infrastructure resilience—require performance validation over multiple years (Leong et al., 2003; Bormann & Klaassen, 2008). Corrosion, thermal stress, and biofouling remain poorly quantified, despite being major determinants of sensor lifespan (Coppola et al., 2011; Lal, 1995). Longitudinal studies that systematically evaluate degradation under different climatic regimes are urgently needed.

Finally, the literature reveals insufficient integration of sensor data into decision-making frameworks. While most studies emphasize sensor accuracy and calibration, fewer investigate how data from portable geotechnical sensors can be operationalized within risk assessment models, resilience planning, or real-time hazard early warning systems (Vereecken et al., 2008). This lack of application-oriented research limits the practical impact of technological advances, particularly in regions where decision-making must account for multihazard interactions (Livneh et al., 1995; Bormann & Klaassen, 2008).

In summary, despite promising technological progress, the literature underscores significant research gaps: (i) geographic underrepresentation of vulnerable regions, (ii) methodological inconsistencies and absence of standards, (iii) laboratory–field discrepancies, (iv) lack of long-term durability studies, and (v) weak integration of sensors into operational frameworks. Addressing these gaps requires multi-site international collaborations, standardized protocols, and interdisciplinary approaches that bridge engineering, soil science, hydrology, and risk management. Such efforts will not only enhance sensor reliability but also expand their relevance in supporting sustainable infrastructure and environmental resilience under diverse global contexts.

5. Conclusion

This study set out to provide a comprehensive assessment of portable geotechnical and soil sensors, examining their performance, calibration requirements, and practical implications for engineering and environmental monitoring. The analysis combined empirical findings with a critical evaluation of existing methodological practices, offering an integrated perspective on both their potential and their limitations.

The results presented in Sections 3A, 3B, and 3C demonstrated that portable sensors have advanced considerably in terms of measurement accuracy, portability, and accessibility. They enable rapid in situ assessments of key soil parameters such as moisture content, strength, and compaction, offering significant advantages over traditional laboratory-based methods. At the same time, the findings revealed important constraints. Sensor performance is strongly influenced by soil type, environmental conditions, and calibration approaches, underscoring the need for context-specific adjustments. Furthermore, the results highlighted the persistent gap between laboratory precision and field applicability, with variability and reliability remaining major challenges in real-world conditions.

The discussion deepened this analysis by synthesizing the broader state of knowledge. It identified clear thematic gaps: a strong geographical imbalance in research efforts, methodological fragmentation and lack of standardized procedures, limited long-term monitoring, and insufficient integration of sensor data into decision-making frameworks. While the technology shows promise, especially in supporting hazard assessment and resilience planning, its widespread adoption is hindered by uncertainties in transferability, durability, and operationalization.

Overall, this study concludes that portable geotechnical and soil sensors represent a critical step toward more efficient, scalable, and field-oriented approaches in geotechnical and environmental engineering. However, their future impact will depend on bridging the current gaps through coordinated international research, the development of standardized calibration protocols, and greater emphasis on long-term field validation. By aligning technological innovation with practical application, these tools can move from experimental devices to essential instruments for sustainable infrastructure development, risk management, and environmental stewardship.

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