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Towards a unified framework for integrating plant biologicals into soil health management

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Abstract Plant biologicals are a widely used yet loosely defined term that generally refers to products intended to enhance plant growth, productivity, and protection against pests and diseases. Many, such as microbial inoculants, biostimulants, and plant-derived compounds, also influence microbial communities and processes. The functionality has been recognised for decades, but consistent field-level benefits remain difficult to demonstrate. Advances in formulation and monitoring now offer renewed opportunities to apply biologicals more effectively as tools for managing soil biological processes. They are increasingly recognised for their capacity to influence microbial diversity, stimulate enzymatic activity, and promote nutrient cycling—processes central to soil health. Broader adoption, however, is constrained by unclear definitions of soil health-related effects, lack of harmonised indicators, inconsistent field-testing, and regulatory frameworks misaligned with the characteristics of biological inputs. Drawing on insights from the 2025 Plant Biologicals Network (PBN) workshop on soil health, the opinion paper reviews the current evidence base and key research gaps, highlighting that efficacy remains highly context-dependent and long-term legacy effects are poorly understood. We emphasise the need for emerging technologies and digital tools, including molecular diagnostics, biosensors, and machine learning approaches, that can provide scalable, high-resolution insights into microbial dynamics and soil processes. Finally, we outline a coordinated research and innovation agenda that prioritises harmonised indicators, long-term comparative field measurements, and incentive-aligned frameworks. By integrating scientific, technological, and institutional advances, plant biologicals can evolve from crop-enhancing inputs into credible and scalable instruments for managing soil processes within sustainable soil health strategies.

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Introduction

Plant biologicals, including biostimulants, microbial inoculants, and plant-derived compounds, are increasingly recognised not only for their role in enhancing crop productivity but also for their emerging potential to influence soil biological processes and contribute to soil health. Beyond acting as alternative natural inputs, these products may actively enhance plant and soil biological functionality and ecosystem resilience (du Jardin 2015; Rouphael and Colla 2020). Yet their integration into soil management strategies remains constrained by conceptual and methodological ambiguities (Seifu & Elias 2018) as well as institutional and policy barriers (Murphy & Scherr 2024).

The opinion paper draws on structured input from the 2025 Plant Biologicals Network (PBN) workshop on soil health, held on March 5, 2025, at the University of Copenhagen, convening researchers, industry stakeholders, policy advisors, and practitioners to identify current barriers and opportunities for integrating plant biologicals into soil health management, including the urgent need for systematic effect studies to document promised outcomes. Based on the workshop discussions and subsequent synthesis by the organising committee (see Methodological Note), we offer a forward-looking perspective on how plant biologicals can be systematically embedded in sustainable agriculture.

It is structured around five guiding questions central to advancing mechanistic understanding, technological integration, and applied relevance:

- How can plant biologicals be rigorously defined and measured as modulators of soil biological functioning, with demonstrable impacts on key ecosystem processes and system resilience?
- What does the current evidence base reveal about the effectiveness of plant biologicals in improving soil biological health, and where are the most critical research gaps in terms of mechanisms, consistency, and context-dependency?
- What are the most promising technological innovations, such as molecular diagnostics, biosensors, and predictive modelling, that can enable scalable monitoring of soil biological processes, and how can they be integrated into research and farm-level decision-making?
- Which legal, institutional, economic, and advisory constraints hinder broader adoption of plant biologicals for soil health management, and how can economic and environmental incentive structures be redesigned to support the transition?
- What components are essential for a coherent, transdisciplinary research and innovation agenda that can guide the systematic evaluation, contextual adaptation, and scalable deployment of plant biologicals as tools for enhancing soil health across agroecological systems?

The paper focuses on how plant biologicals can act as modulators of key soil health processes, such as microbial activity, enzymatic function, and carbon and nutrient cycling, beyond their conventional role as growth promoters or input substitutes.

Methodological note

The workshop brought together approximately 60 national and international participants, including researchers, industry representatives, policy advisors, and agricultural practitioners. The goal was to identify knowledge gaps, practical challenges, and innovation needs for integrating plant biologicals into soil health management.

The one-day event featured two keynote presentations followed by moderated roundtable discussions and thematic ideation sessions. Three main discussion themes were addressed:

1. Evidence and measurement of plant biologicals' impact on soil health.
2. Technological and digital solutions for monitoring and decision support.
3. Practical and economic pathways for adoption at the farm level.

Ideation sessions explored cross-cutting topics such as soil health indicators development, digital infrastructure, capacity building, and incentive structures.

Insights were collected via posters, participant notes, and oral summaries provided by moderators.

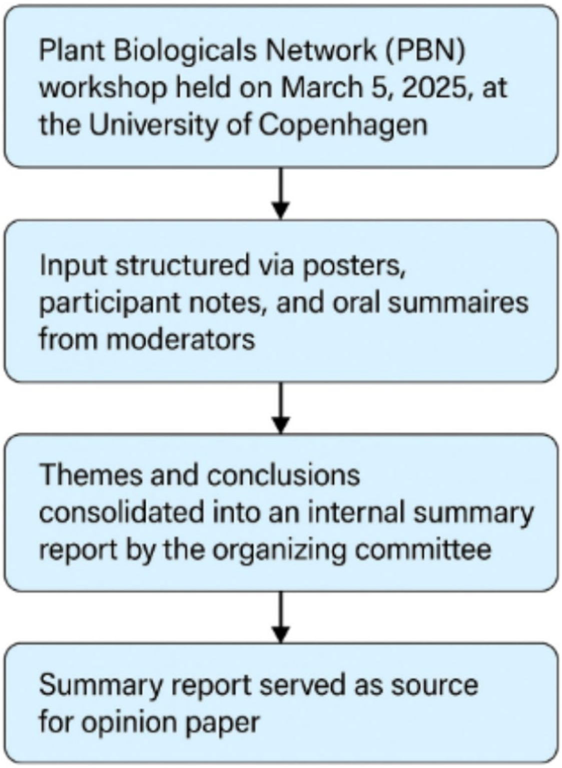

Fig. 1 Methodological workflow

The workshop's organising committee consolidated themes and conclusions into an internal summary report, which served as the basis for framing the five guiding questions and the synthesis presented here. The overall workflow of the workshop-based synthesis process is illustrated in Fig. 1.

While rich in practitioner and cross-sectoral perspectives, the workshop format does not constitute a controlled empirical study. Conclusions drawn from workshop data are therefore interpretative and intended to inform a research and innovation agenda rather than provide definitive evidence.

The need for a common soil health framework

Soil health is widely defined as the capacity of soil to function as a living system that sustains biological productivity, maintains or improves water and air quality, supports plant and animal health, and contributes to the degradation of organic pollutants and broader ecosystem detoxification (Rinot et al. 2019; Lehmann et al. 2020; Maharjan et al. 2020). It is determined by a range of physical, chemical and biological properties, each contributing to key soil processes such as soil structure development, water holding capacity, nutrient cycling, carbon sequestration and biological productivity (Hartmann and Six 2022; Bünemann et al. 2018). The multifunctional perspective highlights the soil's ecological and agronomic relevance.

Bonfante et al. (2020) highlighted that there is still no universally accepted method for defining and measuring soil health, even though several indicator sets have been developed in the USA by Cornell University, the Soil Health Institute, and USDA. The lack of harmonisation creates challenges for effective evaluation of soil health management, although important progress has been made by Nunes et al. (2024), who provided benchmarks for multiple soil health indicators.

The March 2025 PBN workshop strongly underscored the challenge. A key takeaway from researchers, industry representatives, and practitioners alike was that without a robust yet operationally simple definition, it is nearly impossible to evaluate the impact of plant biologicals on soil health in a consistent and meaningful way. The definitional gap not only limits scientific progress but also inhibits policy development and on-farm adoption.

Participants emphasised that current measurement frameworks often lack the sensitivity or standardisation needed to capture changes induced by biological products, especially over shorter timescales. While there is growing consensus on the relevance of biological indicators, such as earthworm abundance, arthropod diversity and microbial community structure and activity, enzymatic processes, and soil physical properties like aggregation or aggregate stability, these indicators can only serve as reliable proxies if linked to clearly defined soil health targets.

Maharjan et al.'s (2020) Soil Health Gap framework offers a constructive way forward by conceptualising soil health benchmarks as the difference between undisturbed native soils and managed croplands, thereby highlighting the extent of soil degradation and the maximum attainable soil health goals through improved management. Amsili et al. (2023) emphasise that benchmarks based solely on native reference systems may not always provide realistic or achievable targets for farmers. Their Production Environment Soil Health (PESH) framework develops benchmarks that incorporate inherent soil properties, climate, and cropping systems, offering more context-specific and management-relevant targets. Together, these approaches illustrate the complementary value of both gap-based and empirically derived benchmarks for advancing soil health assessment and guiding the evaluation of biologicals in agricultural systems.

By comparing actual soil conditions to functionally relevant benchmarks, such a framework can enable more consistent evaluation of soil health responses to management practices, including the use of plant biologicals. The approach may help direct research, guide advisory services, and support regulatory recognition of biological impacts.

To move from conceptual alignment to actionable insight, it is imperative to couple definitional clarity with functionally relevant, scalable measurement approaches that reflect soil biological responses to plant biological inputs. Such indicators are critical for assessing soil processes and soil health status, including nutrient cycling, microbial activity, and soil organic matter turnover, independent of any direct effects on crop performance. For instance, linking extracellular enzymatic activity to nitrogen mineralisation rates or microbially driven soil respiration patterns can provide mechanistic insight into soil biological processes beyond what taxonomic diversity alone can offer.

Additionally, measurement protocols must be designed to capture temporal and spatial variability, enabling detection of both short-term biological responses and long-term legacy effects. Importantly, protocols should also be aligned with the type of product being tested and its intended outcome. For example, short-term indicators may be most relevant for products aimed at improving plant establishment through soil-mediated effects, whereas microbial inoculants may require longer-term monitoring to capture persistence and influence on soil biological processes beyond the initial application. Such guidance does not imply a uniform process; rather, evaluation frameworks need flexibility to accommodate product-specific mechanisms while ensuring comparability across studies**.**

Integrating both temporal and product-aligned indicators within the Soil Health Gap framework or the Production Environment Soil Health framework could provide a dynamic reference model to evaluate the extent and direction of change induced by biological inputs. Such an approach would allow researchers and practitioners to differentiate between transient fluctuations in soil biology and system-level improvements in resilience and productivity, an essential distinction for ensuring scientific robustness, transparent communication, and farmer trust and decision-making.

The challenge is particularly pronounced for plant biologicals, whose effects on soil health are often indirect, context-dependent, and expressed through shifts in microbial activity, community composition, and soil function. In the absence of sensitive and functionally relevant indicators, it remains difficult to separate genuine soil biological responses from background variability and short-term fluctuations. Consequently, the lack of mechanistic understanding following soil interventions not only constrains scientific understanding but also undermines efforts to validate, regulate, and adopt biological inputs in practice.

Ultimately, a shared definition of soil health, rooted in function, grounded in measurable indicators, and usable across sectors, is not a theoretical exercise. It is a practical necessity for accelerating the integration of plant biologicals into sustainable farming systems.

Current evidence base and key research gaps

Evidence increasingly shows that biologicals influence soil microbial diversity, enzymatic activity, and soil aggregation and hence soil health (Schütz et al. 2018; Ulrich et al. 2019). However, existing studies are often limited to short-term trials, lack replication across soil types, and do not integrate soil health indicators. Key gaps include:

(1) Mechanistic understanding of how plant biologicals impact soil development
(2) Legacy effects and context-specific interactions with indigenous microbiomes
(3) Knowledge of dose–response relationships and temporal dynamics
(4) Field trials that evaluate interactions between biologicals, management practices, environmental conditions, and their effects on both soil processes and overall soil health. Addressing these

gaps is essential for developing predictive frameworks and robust efficacy claims.

The role of microbial inoculants in modulating soil biological processes has been studied for decades and remains a focal point of research, with renewed momentum in the context of sustainable agriculture and environmental restoration. These biological agents can influence microbial structure and activity, enzymatic activity, and nutrient cycling for improved soil health—thereby supporting agricultural productivity and ecological balance (Schütz et al. 2018). While some studies indicate that microbial inoculants improve root development and nutrient uptake (Li et al. 2022), these responses are often context-dependent and may not consistently translate into improved soil health. Ulrich et al. (2019) further highlight that plant–microbe interactions can stimulate microbial activity and nutrient turnover, reinforcing the notion that microbial inoculants can affect soil function beyond changes in microbial abundance alone. Greater transparency, for instance, labelling that efficacy may vary across soils, seasons, and years, would align expectations with science results and build trust in microbial inoculants. Several of the benefits are context-dependent, reflecting the fundamental roles of microbial communities in soil–plant interactions and their influence on soil biological processes. The effectiveness of microbial inoculants varies according to their origin and composition, as different strains influence rhizosphere dynamics, nutrient cycling, and other soil biological processes that collectively underpin soil health (Gu et al. 2020). Such variability underlines a central research challenge: mechanistic understanding of how inoculants interact with native microbial communities under specific environmental conditions, but also how long they persist in soil and whether they alter soil structure, as well as the composition, diversity, or functionality of existing microbiomes, a challenge made more urgent by increasing biotic and abiotic stress under climate change. Jiang et al. (2023) emphasise the need for long-term, context-aware trials to capture both the legacy effects of microbial amendments and their variability across systems.

In addition, the mechanistic basis of microbial inoculant function remains only partially understood. For example, inoculants may influence soil moisture retention by stimulating microbial activity and root exudation, which in turn can enhance soil aggregation and improve soil structure, key factors in soil physical health (Ulrich et al. 2019; Singh et al. 2020). These structural changes may also shape microbial community composition. Co-inoculation strategies using multiple microbial species have shown synergistic effects in controlled environments (Wang et al. 2018), but such outcomes, particularly concerning drought-related responses, require cautious interpretation, as they are often inconsistent under field conditions. These findings underline the importance of investigating dose–response relationships and time-dependent dynamics in soil systems, especially through field-based studies.

Moreover, the full potential of microbial inoculants is unlikely to be realised without field trials that reflect actual farming conditions. Increasing evidence shows that pedoclimatic factors, including soil type, texture, nutrient status, native soil microbiome composition, and field management practices such as cropping systems, fertilisation regimes, and climate, strongly influence inoculant efficacy and microbial colonisation (Luo et al. 2024; Lutz et al. 2023; Yim et al., 2025). Compatibility studies are therefore essential to define the environmental and management conditions under which microbial strains perform optimally to enhance soil biological functioning and support long-term soil health improvement (Hernández-Montiel et al. 2017). Such a need calls for co-designed research that integrates biological inputs into broader management strategies, ensuring that findings are relevant and scalable for soil health outcomes.

In our view, microbial inoculants hold substantial untapped potential as a cornerstone of soil health management in sustainable agriculture. They do more than enhance plant growth; they modulate biological functioning in ways that could improve system resilience, reduce reliance on synthetic inputs, and improve soil health. However, the potential can only be fulfilled through research that moves beyond generic applications toward tailored, context-specific strategies grounded in a deeper mechanistic understanding of plant–microbe–soil interactions. Future work should prioritise field-validated, systems-based approaches that integrate inoculants with edaphic conditions, cropping systems, and agronomic practices. Only through such targeted innovation can microbial biologicals successfully transition from promising tools to reliable components of resilient agroecological farming systems.

From an industry standpoint, microbial inoculants with the highest commercial potential demonstrate consistent field efficacy, scalable production processes, robust formulations, and compliance with regulatory standards. To optimise product registration dossiers and marketing claims, it may be necessary to align field trial data with both regulatory and commercial objectives. Achieving this alignment may involve systematically capturing and analysing variability in product performance across diverse pedoclimatic conditions and geographic regions. Such detailed field performance data enables the development of differentiated marketing strategies tailored to specific markets. For example, precision agriculture technologies that leverage detailed, site-specific data on edaphic properties, climatic factors, and management practices can be instrumental in developing targeted product recommendations, thereby enhancing both efficacy and grower confidence. In addition, offering data-driven, location-specific guidance informed by trial variability and local environmental conditions may increase the likelihood of achieving optimal product performance and market success. These integrated, data-driven approaches have the potential to accelerate product approvals, enhance market penetration, and promote broader acceptance of biologically based agricultural solutions.

Emerging technologies and digital tools

Recent advances in molecular diagnostics, biosensor design, and AI-driven analytics offer new avenues for assessing soil biological processes with improved temporal and spatial resolution. These tools enhance our capacity to monitor how plant biologicals modulate microbial dynamics, nutrient cycling, and ecosystem functioning under real-world conditions. Crucially, they can help bridge the gap between mechanistic understanding and practical decision-making by making biological processes in soil more observable and interpretable.

eDNA sequencing technologies are increasingly employed to evaluate microbial diversity and functional potential in soils (Kestel et al. 2022). These methods allow for high-resolution tracking of microbial community responses to environmental and management changes, including biological inputs. Valle et al. (2021) highlight the potential of synthetic biology and molecular sensing platforms to provide new insight into microbial behaviour within heterogeneous soil environments. However, sequencing outputs must be interpreted alongside functional indicators to avoid conflating presence with activity. Recent studies illustrate how metagenomic data combined with machine learning can bridge the gap, enabling the prediction of soil health measures in addition to metrics of abundance and diversity (Wilhelm et al. 2022, 2023).

Biosensors have likewise emerged as powerful tools for real-time assessment of soil conditions, including molecular biosensors that can detect microbial activity through gene-based markers or reporter systems linked to specific functional genes involved in nutrient cycling or stress responses. Designed to detect specific biochemical markers, biosensors can quantify nutrient levels, enzymatic activity, or contaminant presence, thus directly linking biological activity to environmental parameters. For instance, Ma et al. (2019) demonstrated a biosensor method for detecting extractable tetracyclines in soils, while Abena (2023) reviewed biosensor applications across agricultural monitoring domains. As Dzyadevych et al. (2022) argue, biosensors are well-suited for capturing microbial–environment interactions and provide quantitative insights crucial to soil health assessment.

Importantly, these technologies are most relevant when focused on biological indicators of soil health, such as extracellular enzymatic activity, nutrient transformations, or microbial stress responses, that reflect functionally relevant soil processes. Their integration into field research can improve the specificity, scalability, and temporal resolution of biological measurements. However, their application should remain focused on soil processes that are mechanistically linked to soil health, rather than broader agronomic outputs that may not capture underlying biological dynamics. The integration of biosensors with AI and machine learning platforms further strengthens their utility. AI tools can synthesise large, multidimensional datasets generated by sensor networks and sequencing efforts, producing predictive models for soil function and crop response. Gupta et al. (2023) describe the application of machine learning algorithms in precision agriculture, showing how these tools can support site-specific management decisions. Similarly, Townshend et al. (2021) demonstrate automated discovery pipelines for biosensor development, enabling broader coverage of microbial functions and scalable field deployment.

While promising, these technologies are not without limitations. Challenges include high implementation costs, a lack of standardisation, and limited interoperability between platforms. Furthermore, user-oriented decision-support systems remain underdeveloped, hindering the practical application of these innovations at the farm scale.

Nevertheless, digital and diagnostic tools could play a critical role in enabling incentive-based frameworks. Biosensor-generated indicators, for example, could provide verifiable, high-frequency data needed for performance-based subsidies or ecosystem service payments. In this sense, the monitoring technologies discussed here not only support research and advisory functions but also underpin emerging environmental policy instruments that reward measurable improvements in soil biological functioning.

In our view, the convergence of molecular diagnostics, biosensing, and AI represents a pivotal development in soil biology and agroecology. These tools can transform how we understand and manage soil health, but only if they are embedded in collaborative research frameworks that prioritise accessibility, field relevance, and functional integration.

Economic and environmental incentives for broader adoption

The widespread adoption of plant biologicals, such as microbial inoculants, biofertilizers, and biostimulants, remains constrained by persistent uncertainties, including limited return on investment (ROI), lack of regionally validated evidence, and weak integration with existing agricultural advisory systems (Jiang et al. 2023). These barriers are particularly pronounced for applications targeting soil health, where biological effects are context-dependent and not yet consistently reflected in standard evaluation frameworks. As a result, the use of plant biologicals to support soil biological function remains underdeveloped, despite increasing scientific interest in their potential contributions to sustainable soil management.

A central challenge is the uncertainty surrounding ROI, which remains a key consideration for farmers when evaluating new agricultural inputs. While products for soil health improvement are still lacking, meta-analyses on plant-growth-promoting rhizobacteria report that economic returns from the use of microbial inoculants, e.g. biofertilizers, vary significantly across different environmental conditions and management practices (Mahanty et al. 2017). For instance, biofertilizers have been shown to increase yields by approximately 20% in arid climates but only 8.5% in continental climates. Moreover, many studies report no significant effects at all, particularly under field conditions or in systems with high baseline fertility (Schütz et al. 2018). However, such variability, ranging from clear benefits to negligible impact, contributes to farmer scepticism, particularly when comparing biologicals with the more predictable outcomes of synthetic pesticides and fertilisers.

Despite these uncertainties, growing evidence indicates that, when applied appropriately, biologicals can reduce input costs, enhance nutrient efficiency, and support long-term carbon sequestration in soils (Cullen et al., 2008; He et al. 2021). Economic viability remains a primary concern for farmers considering the use of biological products for soil health optimisation. Although initial investment costs may be higher, several studies indicate that biological inputs can lead to increased system performance, e.g. higher yield, and improved economic resilience over time, especially when integrated with organic or conservation practices (Naranjo et al. 2015). Biologicals often show lower or more variable efficacy, particularly under temperate high-input conditions, whereas meta-analyses indicate stronger and more consistent yield responses in arid or subtropical regions (Schütz et al. 2018). Such context-dependent performance highlights the importance of adaptive strategies and system-level integration. When successfully implemented, biologicals can not only offer immediate economic benefits but also strengthen the long-term sustainability and market adaptability of farming systems.

Environmental considerations further reinforce the case for biological inputs, particularly in pest management. Biological approaches contribute to improved environmental quality by reducing the need for and use of chemical pesticides, thereby lowering environmental and health risks, conserving natural resources, improving soil health, and supporting broader ecosystem functioning (Brewer et al. 2004). These outcomes align with broader societal goals, providing a compelling rationale for public investment in biological transitions.

Innovative financial mechanisms, such as cost-share programs and input reduction subsidies, may play a catalytic role in promoting the adoption of conservation technologies, including biological inputs. However, their effectiveness depends on whether they account for heterogeneity in land quality and in the costs and benefits experienced among different farmers (Khanna et al. 2017). Importantly, such mechanisms also need to weigh the relative effectiveness of different practices. For example, cover crops and other organic matter–building strategies have a well-documented capacity to enhance soil health and carbon stocks, whereas the benefits of plant biologicals are more variable and context-dependent. Cost-sharing portfolios may need to prioritise proven practices such as cover crops, while still supporting targeted evaluation and adoption of biologicals where they can provide complementary benefits.

While some economic assessments indicate that biological inputs may yield positive long-term returns, especially when potential improvements in soil health are considered, such outcomes are highly context-dependent and often influenced by site-specific conditions, timeframes, and market dynamics (Schütz et al. 2018; Kannan & Moorthy 2022). More regionally grounded economic evaluations are needed to inform effective incentive design.

Knowledge exchange represents another critical enabler for adoption. Strengthened collaboration among researchers, advisory services, and farmers is essential for building knowledge and trust in plant biologicals. Demonstration trials are particularly effective in showcasing real-world performance and demystifying biological products. Huang et al. (2018) emphasise the importance of visible, successful demonstrations in influencing farmer perceptions and adoption rates. Similarly, Wu et al. (2018) highlight the value of helping farmers understand the cost–benefit dynamics of adopting new practices, which can significantly increase their willingness to engage with novel technologies.

Farm-level case studies can provide valuable context for understanding how biologicals are integrated into complex management systems. For instance, Wortman et al. (2011) documented evidence of significant differences in soil health and crop yields between long-term organic and conventional systems, differences largely driven by inputs such as animal manure, perennial forages, and diversified crop rotations. While not directly linked to plant biologicals, these systems underscore the foundational role of organic matter inputs in building soil health and resilience. Within such biologically active systems, plant biologicals may have a complementary role by enhancing nutrient cycling, but empirical evidence remains limited. Case studies thus offer important context for targeted stakeholder engagement, while also illustrating the challenge of showing robustness and isolating the specific contributions of plant biologicals in complex agroecosystems.

Educational initiatives play a vital role in enabling informed use of biological inputs for soil health management. Programs that address misconceptions and offer comprehensive training can substantially influence the adoption of plant biologicals. Such approaches often build on extension-type systems already familiar in many countries. For example, Zhang et al. (2016) describe an innovative approach in which agricultural scientists engage directly with farming communities to foster participatory innovation and facilitate effective technology transfer. Although conceptually similar to long-established extension systems in the United States, the case highlights how such models can be adapted to strengthen understanding of the economic and agronomic implications of biological inputs in different regional contexts.

In our view, the broader adoption of plant biologicals will only be realised through a coordinated approach that combines economic rationality, environmental stewardship, strong institutional support, and targeted education and knowledge transfer. Policies that recognise and reward contributions to soil health are essential to redirect current agricultural trajectories toward greater sustainability. However, we believe that economic incentives alone are insufficient. Successful implementation must also involve inclusive frameworks that are responsive to regional variability, have high efficacy and are tailored to the practical realities faced by farmers. Without such adaptive and participatory approaches, even well-intentioned policy measures risk falling short of their potential impact.

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Coordinated research and innovation agenda

Integrating plant biologicals into soil health management requires a strategic, transdisciplinary research and innovation agenda that can address the complexity of biological processes, agricultural variability, and institutional barriers. Participants in the PBN workshop emphasised the need for coordinated efforts to span across disciplines, scales, and geographies.

First, the use of harmonised and functionally relevant soil health indicators is essential for evaluating soil responses to plant biologicals across agricultural systems. Existing indicators often focus on compositional metrics, such as microbial diversity, but fail to capture ecosystem functions like nutrient mineralisation or carbon cycling. Further, interpretation of data is key. Functional indicators must be designed to reflect changes induced by biologicals under field conditions. Examples include enzymatic activity assays or RNA-based indicators of microbial gene expression, which can provide more direct evidence of functional responses. To ensure broad applicability, such indicators must be adaptable across different soil types and farming systems.

Recent results from the SOILGUARD project highlight the importance of combining functional and taxonomic indicators to reliably track biodiversity responses and ecosystem functioning (Olivares-Martínez et al. 2023). Specifically, SOILGUARD recommends a core set of four indicators for monitoring soil biodiversity and its potential functional indicators:

(1) Prokaryote richness
(2) Fungal biomass
(3) Microarthropod (mite) richness
(4) Total microbial biomass

While the practicality of microarthropod richness in high-throughput frameworks is limited, it captures key soil faunal contributions that are otherwise overlooked. In routine applications, it may need to be complemented by more scalable proxies, such as DNA-based approaches, but together these indicators provide a useful framework for linking biodiversity and functional outcomes when evaluating the effects of biologicals on soil health.

Second, there is a need for comparative field measurements that go beyond short-term experiments to capture how biologicals perform under real-world farming conditions. Long-term observatories across contrasting agroecological contexts and management practices would enable consistent evaluation of both effectiveness and variability. By integrating biophysical data with socio-economic information, these platforms can support hypothesis-driven experimentation but also inform regulatory assessments and enhance advisory services.

Third, digital infrastructure must support the synthesis and sharing of soil biological data. Investment in interoperable platforms, capable of integrating outputs from molecular diagnostics, sensor networks, and field observations, can accelerate data harmonisation and facilitate the development of predictive models. Open-access tools are particularly important for enabling knowledge exchange across research institutions, private stakeholders, and farmers. From an industry perspective, proprietary microbial databases enhance data mining and candidate screening by linking genomic and functional traits directly to product development pipelines. In addition, remote sensing technologies such as multispectral drone imagery and in-field sensors can provide spatially resolved, real-time data on soil moisture, nutrient status, and crop stress. Integrating these data streams within digital platforms enables field-level validation of product efficacy. When embedded into interoperable systems, these tools also enhance data traceability and standardisation, helping streamline regulatory submissions and compliance. The integration supports real-time dataset validation, increases operational efficiency, and facilitates timely product approvals, ultimately accelerating the commercialisation of biologically based agricultural solutions. Additionally, open-access tools play a crucial role in facilitating knowledge exchange among research institutions, private stakeholders, and farmers, fostering collaboration and accelerating innovation across the sector.

Fourth, aligning economic incentives with soil health outcomes is critical for ensuring adoption beyond research contexts. Policy frameworks should support payment schemes based on measurable ecosystem services, such as soil carbon sequestration or nutrient use efficiency. While plant biologicals may modestly promote SOC gains under favourable conditions (Just et al. 2024), substantial soil carbon accumulation is generally achieved through practices that deliver greater organic matter inputs, such as cover cropping and diverse rotations (Anuo et al. 2023). Within these systems, biologicals may play a complementary role by enhancing the performance and stability of carbon-building practices. To ensure credible outcomes, policy frameworks must be underpinned by clear indicators, rigorous verification protocols, and traceable data, ideally integrated into digital systems. Finally, capacity building is a cross-cutting necessity. Training researchers, advisors, and practitioners in systems-based approaches to soil health and biological inputs will be key to mainstreaming biologicals in agriculture. Such efforts include both formal education and hands-on learning through collaborative field programmes.

In our view, without a coordinated agenda that combines efficiency of the biologicals, scientific rigour, practical relevance, and institutional innovation, the promise of plant biologicals will remain unrealised. A research framework that fosters collaboration across disciplines and sectors is essential for building the infrastructure, evidence base, and stakeholder trust needed to scale biologicals as core components of sustainable soil management.

Conclusion

The integration of plant biologicals into soil health management is both a scientific and institutional frontier. Yet, the potential is tempered by challenges such as inconsistent field performance, variable economic returns, and regulatory systems that are not fully adapted to biological inputs. At the same time, advances in formulation technologies, emerging monitoring tools, and growing demand for sustainable solutions provide new opportunities for progress. A systems-based research and innovation agenda, rooted in functional soil indicators, digital infrastructure, and incentive-aligned frameworks, will be essential to guide implementation across diverse agroecosystems. Real progress depends not only on scientific breakthroughs but on building the structures that connect research, practice, and governance in service of healthier soils and more resilient farming systems.

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Author contributions SC conceptualised the manuscript and led the writing. AW, HH, MW, MN, REJ and VH contributed to the literature review, writing and approved the final manuscript.

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