American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)

E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Soil Microbiome Awareness in Regenerative Farm Management

Dr. Pieter Janssens

Professor, University of Antwerp, Belgium

Abstract

Regenerative farm management increasingly emphasizes soil as a biologically active system rather than merely a physical medium for crop production. Bacteria, fungi, archaea, protozoa, and other soil organisms contribute to nutrient transformations, organic-matter decomposition, aggregate formation, plant–microbe interactions, and several processes associated with soil resilience. Despite rapid scientific advances in soil-microbiome research, farm-level management may remain disconnected from microbiological understanding when soil assessment is dominated by visible crop performance and conventional chemical indicators. This study develops a simulation-based framework for evaluating how soil-microbiome awareness may influence regenerative farm-management integration without presenting hypothetical farmer responses or laboratory measurements as empirical observations. A Microbiome-Aware Regenerative Management Index is constructed using five dimensions: microbiome concept literacy, understanding of management–microbiome relationships, use of biological soil indicators, decision confidence, and adaptive learning. Five hypothetical awareness profiles are compared. The simulated management-integration score increases from approximately 38 under low microbiome awareness to 91 under adaptive microbiome-informed management.

The analysis suggests that awareness becomes most operationally valuable when farmers can connect biological principles with decisions concerning cover crops, organic amendments, crop rotations, tillage intensity, living roots, residue management, and disturbance reduction. Laboratory microbiome characterization is not proposed as a routine requirement for every field decision. Instead, farmer observations, conventional soil measurements, microbial biomass and activity indicators, and periodic specialist analyses can be combined through a tiered monitoring framework. The study concludes that microbiome awareness should be treated as practical ecological literacy rather than knowledge of microbial taxonomy alone. Extension systems that translate biological processes into observable management feedback may strengthen regenerative decision-making while avoiding unsupported claims that individual microbial products or management practices will produce universally predictable outcomes.

Keywords: soil microbiome, regenerative agriculture, soil health, microbial diversity, farmer awareness, cover crops, biological soil indicators, agroecology

American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)
E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

1. Introduction

Agricultural soil contains extraordinarily diverse biological communities whose activities influence many processes essential to crop production and ecosystem functioning. Microorganisms participate in nutrient cycling, organic-matter transformation, plant nutrient acquisition, soil aggregation, disease interactions, and the decomposition of plant residues. Van der Heijden and colleagues described soil microorganisms as an often unseen but functionally important component of terrestrial ecosystems, while subsequent soil-health scholarship has increasingly conceptualized soil as a living ecosystem rather than an inert support for plants. Lehmann and colleagues similarly frame soil health as the continuing capacity of soil to function as a vital living system supporting plants, animals, humans, and wider environmental processes.

Regenerative agriculture has intensified interest in this biological dimension of farm management. Although the term regenerative agriculture does not have a universally agreed operational definition, soil conservation, ecosystem restoration, biodiversity, and enhancement of ecosystem services recur prominently within the literature. Schreefel and colleagues identify soil conservation as a central entry point for regenerative agriculture and caution that the concept encompasses diverse objectives and practices rather than a single standardized production system. This distinction is important for microbiome-aware farming because management practices should not be assumed to be regenerative solely because they are associated with a particular label. Their effects must be interpreted within soil type, climate, crop rotation, nutrient management, disturbance history, and other site-specific conditions.

Research nevertheless provides substantial evidence that agricultural management can influence microbial abundance, activity, community composition, and interactions. Lori and colleagues' global synthesis found greater microbial biomass and several measures of microbial activity under organically managed systems compared with conventional counterparts, while also identifying variation associated with crop rotation, legumes, organic inputs, soil characteristics, and production context. Kim and colleagues' meta-analysis of cover cropping similarly reported increases in microbial abundance and activity relative to bare fallow, although the magnitude of responses varied according to management and environmental conditions. Such findings support biological management principles while simultaneously demonstrating why microbiome responses should not be reduced to simplistic claims that one practice invariably produces one microbial outcome.

A significant practical challenge lies in translating this increasingly complex scientific knowledge into farm-level decision-making. Farmers commonly assess soil through crop vigor, soil color, texture, moisture behavior, ease of cultivation, erosion, earthworm presence, rooting patterns, residue decomposition, or other observable characteristics. Research examining farmer knowledge shows that locally recognized soil indicators can meaningfully influence management, but the range of indicators used may be limited and can vary according to environmental and social context. Biological indicators such as microbial biomass and activity can enrich this assessment, yet laboratory results may have limited practical value if farmers are not provided with an interpretable relationship between the indicator, its uncertainty, and possible management responses.

The present study therefore examines soil microbiome awareness as a form of practical ecological literacy within regenerative farm management. The concept does not require farmers to identify microbial taxa individually or routinely conduct advanced molecular sequencing. Instead, awareness refers to understanding that soil biological communities respond to management and that practices affecting organic substrates, living roots, disturbance, moisture, nutrient supply, and habitat conditions can influence biological soil processes. A simulation-based Microbiome-Aware Regenerative Management Index is developed to evaluate how increasing levels of this awareness could strengthen the integration of biological reasoning into farm decisions. The framework deliberately distinguishes microbiome literacy from microbiome determinism: microorganisms matter greatly, but management recommendations should remain evidence-based, context-sensitive, and integrated with physical, chemical, agronomic, and economic information.

2. Objectives of the Study

2.1 To Assess the Role of Soil-Microbiome Awareness in Regenerative Management Decisions

The first objective is to evaluate how increasing awareness of soil microbial functions can influence the interpretation of regenerative management practices. The study examines whether conceptual understanding becomes more useful when farmers can connect microbiome processes with decisions concerning crop diversity, living roots, organic amendments, tillage, residue retention, and soil disturbance.

The analysis does not treat awareness as factual recall of microbial names. It considers whether biological knowledge improves a farmer's ability to ask appropriate management questions, interpret changes in soil condition, and distinguish plausible biological mechanisms from unsupported product or technology claims.

2.2 To Integrate Farmer-Observable and Technical Biological Indicators

The second objective is to develop a monitoring approach that connects farmer observation with technical indicators. Soil biological functioning cannot be inferred reliably from a single visible characteristic, yet routine advanced microbiome sequencing may be financially or interpretively impractical for many farms.

The study therefore considers a tiered approach combining visual soil assessment, rooting and residue observations, physical and chemical soil measurements, microbial biomass or activity indicators where appropriate, and more specialized analyses when a clear diagnostic or research question justifies them.

2.3 To Examine Awareness as a Driver of Adaptive Regenerative Management

The third objective is to determine how microbiome literacy can support adaptive rather than prescriptive management. Soil biological responses differ across climate, soil type, crop, rotation, amendment history, and management intensity. A practice that produces a favorable response in one agroecosystem may produce a weaker or different response elsewhere.

Microbiome-informed management should therefore encourage farmers to establish hypotheses, observe responses, compare fields or management zones, maintain records, and adjust practices according to multiple indicators rather than follow universal prescriptions.

3. Review of Literature

3.1 Soil Microbiomes as Functional Components of Soil Health

Soil microbial communities regulate numerous processes underlying agricultural productivity and ecosystem services. Bacteria and fungi participate in decomposition and nutrient transformations, while mycorrhizal fungi form associations with plant roots that can influence nutrient acquisition and soil structure. Microbial metabolites, fungal hyphae, roots, and organic materials interact with mineral particles and contribute to aggregate formation and the spatial organization of soil habitat. These relationships make biological activity inseparable from many physical and chemical dimensions of soil quality.

Bünemann and colleagues' critical review of soil-quality assessment found that biological and biochemical indicators have considerable potential but remain less frequently represented than indicators such as organic matter, pH, phosphorus availability, and water-related properties. The authors emphasize that soil-quality assessment should be linked to specific soil functions, threats, and ecosystem services rather than interpreted through universal indicator values. This principle is especially relevant to microbiome awareness. A microbial indicator is valuable only when its meaning is connected with the management objective being evaluated.

Management can alter these biological communities substantially. Hartman and colleagues demonstrated that cropping practices can manipulate abundance patterns among root- and soil-associated microbiome members, providing evidence that production systems influence microbial communities at several ecological levels. Banerjee and colleagues further showed that greater agricultural intensification was associated with reduced complexity of root fungal networks and lower abundance of particular keystone taxa in their study system. These findings reinforce the importance of management context but also caution against equating a single diversity metric with overall soil performance.

3.2 Regenerative Practices and Microbial Responses

Cover cropping provides one of the clearest examples of a management practice with documented microbiological effects. Kim, Zabaloy, Guan, and Villamil synthesized evidence from 60 studies and found that cover cropping increased microbial abundance, activity, and diversity relative to bare fallow, with stronger responses for abundance and activity than for diversity. Importantly, responses varied according to factors including climate, termination practice, and tillage. The practical lesson is therefore not that cover crops uniformly increase every desirable microbial characteristic, but that maintaining living plant inputs can modify microbial habitat and resource availability in ways that frequently support biological activity.

Organic inputs, diversified rotations, and lower-intensity production systems have also been associated with changes in microbial communities. Lori and colleagues reported substantially greater microbial biomass and several enzyme activities in organically managed soils across their meta-analysis, while Banerjee and colleagues identified greater fungal network complexity under the least intensive farming system examined. Long-term production-system research likewise shows that crop sequence and organic inputs can affect microbial biomass, enzyme activity, and community structure, while individual responses are not necessarily explained by a single management factor.

This contextual variability is central to responsible regenerative management. French and colleagues describe the growing potential for microbiome-informed agriculture but also emphasize that reliable manipulation of crop-associated microbiomes remains difficult because microbial communities respond to interactions among management, crop genetics, soils, climate, and other environmental conditions. Consequently, farm microbiome awareness should initially strengthen management of microbial habitat and ecological processes rather than encourage premature reliance on highly specific microbial manipulation where predictive evidence remains limited.

3.3 Farmer Knowledge and Participatory Soil Monitoring

Scientific measurements alone do not guarantee adoption or improved soil management. Farmers possess detailed experiential knowledge based on recurring observation of soil and crop behavior, although the indicators they use differ among environments and farming communities. Research on farmers' soil-quality knowledge has documented the use of crop performance, soil color, texture, indicator plants, macrofauna, moisture conditions, and other locally interpretable characteristics. These indicators can be highly valuable because they are inexpensive, repeated frequently, and directly linked with management experience.

Luján Soto, Cuéllar Padilla, and de Vente developed a participatory framework for selecting soil-quality indicators in regenerative agriculture and found that farmer-selected indicators and researcher-selected technical indicators provided complementary information. Farmers emphasized practical functions such as water regulation, erosion, fertility, and crop performance, whereas technical assessment incorporated parameters including microbial biomass and activity. Their work provides an important model for microbiome awareness because it avoids replacing farmer knowledge with laboratory science; instead, the two forms of evidence are integrated.

A persistent knowledge gap therefore exists not in demonstrating that soil microorganisms matter, but in translating microbiome science into decision tools that remain understandable, affordable, and agronomically relevant. Farmer education that merely explains microbial diversity may have limited effect if it does not connect biological concepts to observable soil processes and management choices. Practical microbiome literacy should consequently be evaluated according to its contribution to decision quality rather than the amount of specialized terminology farmers can recall.

4. Research Methodology

4.1 Simulation-Based Research Design

The study adopts a simulation-based multicriteria research design. No farmer questionnaire, microbiological sequencing, soil sampling, field trial, or treatment comparison is represented as original empirical data. The analytical purpose is to construct a transparent framework through which different levels of microbiome awareness can be connected conceptually with regenerative farm-management capacity.

Five awareness profiles are modeled: low microbiome awareness, basic soil-biology awareness, indicator-based monitoring, practice-linked microbiome literacy, and adaptive microbiome-informed management. These profiles represent progressively stronger integration between biological knowledge and actual farm decisions.

The framework assumes that agronomic decisions continue to consider crop performance, economics, soil chemistry, weather, water availability, pest pressure, machinery, and other practical factors. Microbiome awareness is therefore treated as an additional decision layer rather than a replacement for conventional agronomy.

4.2 Microbiome-Aware Regenerative Management Index

A Microbiome-Aware Regenerative Management Index (MARMI) was developed using five dimensions. Each dimension is scored from 0 to 100, with higher scores representing stronger integration of soil-biological understanding into farm management.

Table 1: Criteria and weights used in the Microbiome-Aware Regenerative Management Index

Criterion	Operational interpretation	Weight
Microbiome concept literacy	Understanding of microbial roles in nutrient cycling, decomposition, rhizosphere processes, aggregation, and plant health	0.20
Management–microbiome linkage	Ability to relate cover crops, rotation, organic inputs, tillage, residues, and disturbance to microbial habitat and functioning	0.25
Biological monitoring capacity	Use and interpretation of observable and technical biological soil-health indicators	0.20
Decision confidence	Ability to translate biological evidence into proportionate farm-management decisions without overinterpreting results	0.20
Adaptive learning	Capacity to compare outcomes, maintain records, revise hypotheses, and adjust management according to local evidence	0.15

The index is calculated as:

$$MARMI = 0.20L + 0.25P + 0.20B + 0.20D + 0.15A$$

where L represents microbiome literacy, P practice–microbiome linkage, B biological monitoring, D decision confidence, and A adaptive learning.

Management–microbiome linkage receives the highest weight because awareness has limited practical significance unless farmers can connect biological processes with actual choices. Biological monitoring and decision confidence receive substantial weights because microbial information can be misunderstood if interpretation is disconnected from baseline conditions, soil type, seasonal variability, or management objectives.

4.3 Tiered Monitoring and Analytical Assumptions

The framework proposes three complementary levels of soil-biological observation. The first consists of frequent farm-level observations, including rooting depth and distribution, residue decomposition, aggregate condition, visible soil organisms, crop uniformity, infiltration behavior, and other contextually useful indicators. These observations are inexpensive and can be repeated regularly but should not be interpreted as direct measurements of microbial diversity.

The second level consists of periodic soil-health testing using selected physical, chemical, and biological parameters. Depending on the management objective and laboratory availability, this may include organic carbon, aggregate stability, respiration, microbial biomass, enzyme activities, potentially mineralizable nutrients, or related indicators. Participatory soil-quality research supports combining locally meaningful observations with technically derived measures rather than treating them as competing systems.

The third level includes specialized microbiome characterization where a clear research or diagnostic purpose exists. Molecular sequencing and related techniques can provide highly detailed information, but greater analytical resolution does not automatically produce a simple management recommendation. The simulation therefore assigns the highest score to adaptive interpretation, not to the greatest number of laboratory tests.

5. Analysis

5.1 Microbiome Awareness and Management Integration

The simulation indicates that low microbiome awareness produces a MARMI value of approximately 38. Under this condition, management may rely predominantly on crop response, fertilizer recommendations, visible soil characteristics, or general notions of soil fertility without explicitly considering the microbial processes affected by disturbance, living roots, organic substrates, and crop diversity.

Basic soil-biology awareness increases the index to approximately 54. Farmers within this profile understand that microorganisms contribute to soil functioning and may recognize practices such as manure application or cover cropping as biologically beneficial. However, the relationship between practice and microbiome remains general, and management may still rely on universal statements such as "more microbes are always better" without adequate attention to microbial function or environmental context.

Table 2: Simulated progression of soil-microbiome awareness and regenerative management integration

Awareness profile	Concept literacy	Practice linkage	Biological monitoring	Decision confidence	Adaptive learning	MARMI
Low microbiome awareness	35	36	30	43	48	37.6

American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)
E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Awareness profile	Concept literacy	Practice linkage	Biological monitoring	Decision confidence	Adaptive learning	MARMI
Basic soil-biology awareness	52	55	45	58	62	54.1
Indicator-based monitoring	68	66	75	70	67	69.2
Practice-linked microbiome literacy	82	86	78	84	78	82.2
Adaptive microbiome-informed management	94	92	90	91	86	91.1

Note: All values are simulated for methodological illustration. They do not represent survey responses or measured farmer competencies.

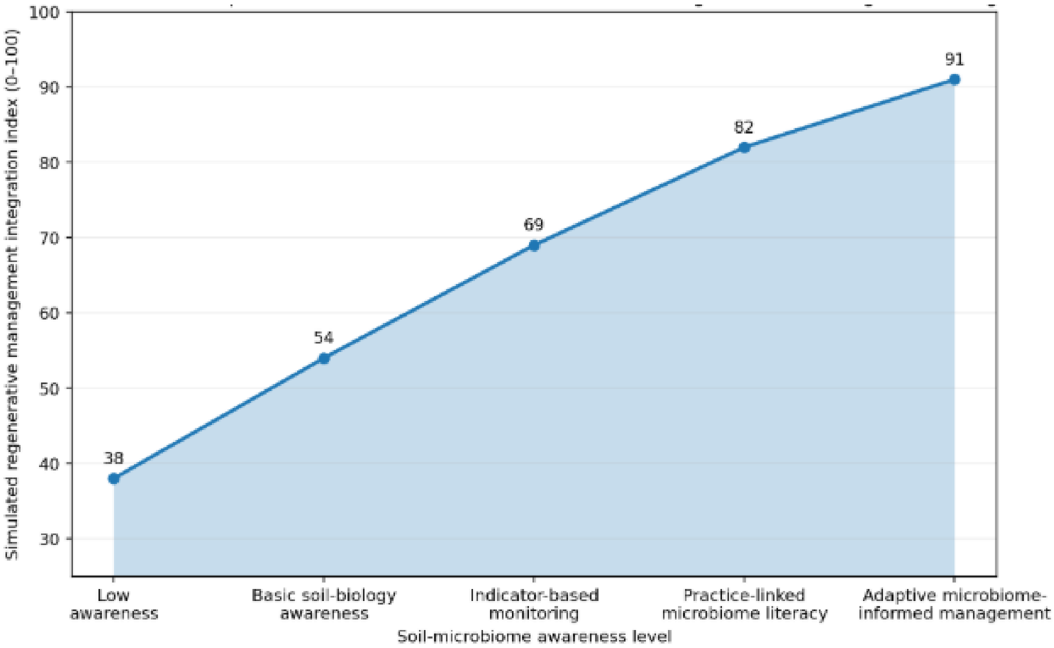
Indicator-based monitoring produces a simulated MARMI of approximately 69 because farmers begin to combine biological observations with other soil-health information. Practice-linked literacy increases the score further to approximately 82 because biological information directly influences decisions regarding disturbance, cover, rotations, amendments, and management timing.

Adaptive microbiome-informed management achieves the highest simulated score of approximately 91. This profile does not assume perfect knowledge of soil microbial communities. Its principal distinction is that farmers understand both the usefulness and the limitations of microbiome information and use repeated observations to refine management.

5.2 Relationship Between Awareness and Regenerative Management Capacity

The simulated progression suggests a positive relationship between microbiome awareness and regenerative-management integration, although the relationship should not be interpreted as proof that awareness alone causes improved soil outcomes. Financial constraints, weather, equipment, land tenure, market requirements, labor, and risk tolerance can prevent implementation even when biological understanding is strong.

Graph 1: Simulated Relationship Between Soil-Microbiome Awareness and Regenerative Management Integration



The graph illustrates a transition from awareness as general knowledge toward awareness as an adaptive management capability. The most important increase occurs when farmers begin connecting biological information with observable management responses rather than simply learning that soil microorganisms exist.

Research supports this emphasis on practice linkage. Cover-crop evidence shows that microbial responses vary according to management and environmental covariates, while participatory regenerative-agriculture research demonstrates the value of combining technical indicators with indicators farmers can interpret directly. Awareness is therefore most useful when it improves the quality of questions farmers ask about their own fields.

5.3 From Microbial Awareness to Management Decisions

A microbiome-aware farmer might interpret continuous bare soil not only as an erosion or moisture issue but also as a prolonged reduction in living-root inputs available to rhizosphere organisms. Crop diversification might be viewed not simply as rotational scheduling but as a means of varying root architecture, residue chemistry, and belowground carbon inputs. Organic amendments may be evaluated according to material quality, maturity, nutrient balance, contamination risk, and their influence on biological substrates rather than treated generically as microbial food.

Tillage provides another example. Reduced soil disturbance may preserve aspects of soil structure and biological habitat, but the ecological consequences depend on the wider management system. Hartman and colleagues demonstrate that root and soil microbiome responses can differ according to cropping practices, while long-term production-system evidence indicates that organic inputs and crop sequence can sometimes exert stronger influence on particular microbial indicators than tillage considered alone. A microbiome-aware decision therefore asks how several practices interact instead of assigning biological performance to one management label.

Awareness can also improve the interpretation of commercial microbial products. Microbial inoculants may have legitimate applications, but establishing organisms successfully in field soils depends on microbial ecology, host interactions, existing communities, environmental conditions, and management. Research on precision microbiome management highlights the scientific potential of microbiome-assisted agriculture while simultaneously identifying substantial challenges in obtaining predictable outcomes across diverse agroecosystems. Farmers should therefore evaluate microbial products through credible field evidence, appropriate controls, and local agronomic relevance rather than assume that higher microbial diversity on a product label guarantees improved soil function.

6. Discussion

6.1 Microbiome Literacy as Practical Farm Knowledge

The principal implication of this study is that microbiome awareness should be defined operationally. Asking farmers to understand highly detailed microbial taxonomy is unlikely to improve management if the knowledge cannot be translated into decisions. More useful literacy concerns ecological relationships: microorganisms require appropriate habitat and substrates; living roots influence the rhizosphere; organic materials provide energy and nutrients; disturbance alters physical habitat; water and aeration constrain activity; and management effects emerge through interactions rather than isolated practices.

This approach is consistent with the modern soil-health concept. Lehmann and colleagues emphasize the functioning of soil as a living ecosystem, while Bünemann and colleagues argue that soil indicators must be interpreted relative to specific functions and threats. Microbiome literacy therefore strengthens soil-health assessment when it helps farmers understand processes rather than encouraging them to chase a universal biological score.

The approach also guards against microbiome oversimplification. Microbial diversity is ecologically important, but greater taxonomic diversity cannot automatically be interpreted as greater crop productivity. Functions can overlap across organisms, microbial interactions can be beneficial or harmful depending on context, and management responses vary with environmental conditions. Responsible extension communication should therefore avoid claims that one practice "builds the microbiome" in a predictable and universally favorable direction.

6.2 Linking Regenerative Practices With Measurable Biological Feedback

A second implication concerns evidence. Regenerative management frequently promotes principles such as continuous soil cover, living roots, crop diversity, integration of organic materials, and lower unnecessary disturbance. These principles provide plausible pathways for influencing soil biological communities, but farmers need feedback to determine whether management is improving the specific soil functions that concern them.

Cover crops illustrate the value of such feedback. Kim and colleagues' synthesis showed significant overall increases in microbial abundance and activity but comparatively modest average change in diversity, with substantial variation among conditions. If an extension program communicates only that cover crops "increase microorganisms," it loses the most useful lesson from the evidence: outcomes are multidimensional and management-dependent.

Similarly, Lori and colleagues found stronger microbial abundance and activity under organic management overall, yet their analysis also identified differences associated with organic inputs, legumes, land use, climate, and soil characteristics. Microbiome awareness should therefore encourage monitoring of trends over time within the same farm rather than simplistic comparison against universal benchmarks from unrelated regions.

A practical monitoring system can begin with inexpensive field observations and progressively add more specialized testing when uncertainty justifies the cost. Such an approach is consistent with participatory work showing that local and technical indicators can complement each other. Farmers do not need to choose between experiential knowledge and laboratory science; stronger regenerative management can use each for the questions it is best suited to answer.

6.3 Extension, Decision Support, and Responsible Microbiome Communication

Agricultural extension has an important role in translating microbiome science without exaggerating its predictive maturity. Training can explain microbial functions through recognizable farm processes such as residue decomposition, root–soil interactions, nutrient mineralization, aggregate formation, disease suppression, and responses to organic inputs. Demonstration plots can then allow farmers to compare management treatments using crop, soil, and biological indicators simultaneously.

Decision-support systems should also communicate uncertainty explicitly. A microbial test result may differ among sampling dates, field zones, soil depths, extraction methods, seasons, and laboratories. Interpretation should therefore include sampling protocols, relevant comparison ranges, management history, and other soil properties. Advanced microbial analyses should be used where their resolution addresses a defined question rather than merely because the technology is available.

Farmer participation is equally important. Research examining soil indicators demonstrates that farmer knowledge contains context-specific information about degradation, vegetation, crop response, and soil characteristics that broad standardized assessments may overlook. Microbiome extension is likely to be more effective when biological concepts are added to this existing knowledge system rather than communicated as an expert replacement for farmer observation.

Finally, microbiome awareness can strengthen critical evaluation of regenerative claims. Farmers increasingly encounter recommendations concerning biological amendments, inoculants, stimulants, compost preparations, and proprietary soil-health products. A farmer who understands microbial ecology is better positioned to ask whether the proposed organism or product has credible evidence under comparable conditions, whether the claimed mechanism is biologically plausible, whether replicated controls exist, and whether less costly habitat-based management might achieve the same objective.

7. Conclusion

Soil-microbiome awareness can strengthen regenerative farm management when biological knowledge is translated into practical, context-sensitive decisions. Soil microorganisms participate in processes fundamental to nutrient cycling, residue transformation, plant interactions, aggregation, and wider soil functioning, yet these processes cannot be managed reliably through generalized assumptions about microbial abundance or diversity alone. Effective microbiome literacy therefore involves understanding both the importance and the complexity of belowground biological systems.

The simulation developed in this study illustrates a progressive increase in regenerative-management integration as awareness develops from basic recognition of soil biology toward indicator-based monitoring, practice linkage, and adaptive microbiome-informed management. The simulated MARMI increases from approximately 38 under low awareness to approximately 91 under the most integrated scenario. These values are methodological illustrations rather than observed farmer outcomes, but they demonstrate why knowledge becomes more valuable when it influences interpretation, monitoring, and adaptive decision-making.

The study also supports a tiered approach to soil biological assessment. Frequent farmer observation should form the foundation because it is inexpensive, repeated, and directly connected with field experience. Conventional soil testing and selected biological indicators can provide additional evidence, while advanced microbiome characterization should be used when the management or research question warrants its cost and analytical complexity. This approach can bring microbiome science into routine regenerative management without creating unrealistic dependence on sophisticated laboratory technology.

Future empirical research should test the proposed framework through farmer surveys, extension interventions, longitudinal soil-health monitoring, and paired field comparisons. Research could examine whether microbiome literacy changes management choices, whether biological testing improves decision confidence, and whether awareness is associated with sustained adoption of practices such as diversified rotations, cover crops, organic amendments, and disturbance reduction. The strongest future models will integrate farmer knowledge, agronomy, soil chemistry, soil physics, microbiology, and economic feasibility. In this form, soil-microbiome awareness becomes neither a fashionable label nor a substitute for established soil science, but a practical component of evidence-based regenerative farm stewardship.

References

1. Bender, S. F., Wagg, C., & van der Heijden, M. G. A. (2016). An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. *Trends in Ecology & Evolution, 31*(6), 440–452.
2. Banerjee, S., & van der Heijden, M. G. A. (2023). Soil microbiomes and ecosystem functioning in agriculture. *Nature Reviews Microbiology, 21*, 35–50.
3. Jansson, J. K., & Hofmockel, K. S. (2018). The soil microbiome—From metagenomics to metaphenomics. *Current Opinion in Microbiology, 43*, 162–168.
4. Delgado-Baquerizo, M., Maestre, F. T., Reich, P. B., Jeffries, T. C., Gaitan, J. J., Encinar, D., Berdugo, M., Campbell, C. D., & Singh, B. K. (2016). Microbial diversity drives multifunctionality in terrestrial ecosystems. *Nature Communications, 7*, 10541.
5. Hartmann, M., Frey, B., Mayer, J., Mäder, P., & Widmer, F. (2015). Distinct soil microbial diversity under long-term organic and conventional farming. *The ISME Journal, 9*, 1177–1194.

6. Rillig, M. C., Ryo, M., Lehmann, A., Aguilar-Trigueros, C. A., Buchert, S., Wulf, A., Iwasaki, A., Roy, J., & Yang, G. (2019). The microbiome and new principles of plant–soil interactions. *Nature Ecology & Evolution, 3*, 1139–1150.
7. Toju, H., Peay, K. G., Yamamichi, M., Narisawa, K., Hiruma, K., Naito, K., Fukuda, S., Ushio, M., Nakaoka, S., & Onoda, Y. (2018). Core microbiomes for sustainable agroecosystems. *Nature Plants, 4*, 247–257.
8. Trivedi, P., Leach, J. E., Tringe, S. G., Sa, T., & Singh, B. K. (2020). Plant–microbiome interactions: From community assembly to plant health. *Nature Reviews Microbiology, 18*, 607–621.
9. Compant, S., Samad, A., Faist, H., & Sessitsch, A. (2019). A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. *Journal of Advanced Research, 19*, 29–37.
10. Banerjee, S., Walder, F., Büchi, L., Meyer, M., Held, A. Y., Gattinger, A., Keller, T., Charles, R., & van der Heijden, M. G. A. (2019). Agricultural intensification reduces microbial network complexity and the abundance of keystone taxa in roots. *The ISME Journal, 13*, 1722–1736.
11. Leff, J. W., Jones, S. E., Prober, S. M., Barberán, A., Borer, E. T., Firn, J. L., Harpole, W. S., Hobbie, S. E., Hofmockel, K. S., Knops, J. M. H., McCulley, R. L., Lauber, C. L., & others. (2015). Consistent responses of soil microbial communities to elevated nutrient inputs in grasslands across the globe. *Proceedings of the National Academy of Sciences, 112*(35), 10967–10972.
12. Wagg, C., Bender, S. F., Widmer, F., & van der Heijden, M. G. A. (2014). Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proceedings of the National Academy of Sciences, 111*(14), 5266–5270.
13. Bowles, T. M., Jackson, L. E., & Cavagnaro, T. R. (2018). Mycorrhizal fungi enhance plant nutrient acquisition and soil carbon stabilization in agricultural systems. *Agriculture, Ecosystems & Environment, 254*, 1–10.
14. Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science, 296*(5573), 1694–1697.
15. Van der Heijden, M. G. A., Bardgett, R. D., & van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecology Letters, 11*(3), 296–310.
16. Altieri, M. A., Nicholls, C. I., & Montalba, R. (2017). Technological approaches to sustainable agriculture at a crossroads: An agroecological perspective. *Sustainability, 9*(3), 349.
17. Drinkwater, L. E., Schipanski, M., & others. (2019). Managing soil microbial communities for sustainable agricultural production. *Soil Biology and Biochemistry, 129*, 1–10.
18. Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and microbial biomass. *Soil Biology and Biochemistry, 129*, 1–12.
19. Schreefel, L., Schulte, R. P. O., de Boer, I. J. M., Schrijver, A. P., & van Zanten, H. H. E. (2020). Regenerative agriculture—The soil is the base. *Global Food Security, 26*, 100404.
20. Newton, P., Civita, N., Frankel-Goldwater, L., Bartel, K., & Johns, C. (2020). What is regenerative agriculture? A review of farmer-led initiatives and definitions. *Sustainability, 12*(16), 6500.