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Rhizosphere Microbial Structure in Vineyard Soils under Integrated Nutrient Management

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Abstract The rhizosphere microbial community in vineyard soil plays a crucial role in maintaining soil ecological function and improving grape yield and quality. Integrated nutrient management (INM), through the rational combination of chemical fertilizers, organic fertilizers, and bio-fertilizers, not only meets the nutrient requirements of grapes but also improves the soil environment and promotes the proliferation of beneficial microorganisms. This paper systematically reviews the types and functions of rhizosphere microorganisms, influencing factors, and their correlation with grape growth and quality, focusing on the relationship between INM and the rhizosphere microbial structure in vineyards. Results show that a rational INM model can significantly increase soil organic matter and fertility, promote the abundance of nitrogen-fixing and phosphorus-solubilizing functional microorganisms, thereby improving the rhizosphere microbial structure. Specifically, reducing chemical fertilizer application and applying liquid organic fertilizer can significantly increase soil microbial biomass (C, N) and enzyme activity, improving grape yield and quality; the combined application of organic and chemical fertilizers can increase the number of beneficial microorganisms such as actinomycetes in the soil. Methodologically, this study integrates traditional soil physicochemical testing, high-throughput sequencing, and bioinformatics analysis to perform multi-faceted analysis of vineyard rhizosphere samples. The conclusion indicates that INM can optimize rhizosphere microbial structure and enhance soil ecological stability, but further long-term, multi-regional integrated research is needed. Therefore, this study proposes future research recommendations and management policy recommendations.
Keywords Integrated nutrient management; Vineyard; Rhizosphere microorganisms; Soil ecology; Community structure

1 Introduction

Vineyard soil is a fundamental resource for grape growth, and its physicochemical properties and biological activity directly affect vine health and fruit quality. As a core component of the agro-ecosystem, soil not only provides water and nutrients for grapes but also provides a habitat for a large number of microorganisms. These soil microorganisms maintain the ecological function and fertility of the vineyard through decomposing organic matter, cycling nutrients, and adjusting soil structure. A healthy soil ecosystem promotes root development, enhances vine resistance, and ultimately increases grape yield and quality (Zarraonaindia et al., 2015; Meissner et al., 2019). Therefore, studying the structure and function of vineyard soil ecosystems is of great significance for promoting the sustainable development of the grape industry.

The rhizosphere is the most active area for interaction between plant roots and soil microorganisms. Grape roots secrete root exudates such as organic acids, sugars, and amino acids, providing a rich carbon source for rhizosphere microorganisms and attracting functional microbial communities such as nitrogen-fixing bacteria and phosphorus-solubilizing bacteria to colonize. Rhizosphere microorganisms not only participate in soil nutrient cycling, such as by fixing atmospheric nitrogen and dissolving insoluble phosphorus to improve nutrient availability, but also stimulate root growth by producing plant growth-promoting substances (such as indoleacetic acid and cytokinins). Furthermore, certain beneficial microorganisms possess the ability to antagonize soil-borne pathogens, thereby enhancing the disease resistance of grapevines. Studies show that a healthy and stable rhizosphere microbial community helps strengthen the nutrient absorption capacity and environmental stress response of grapevines, thus affecting fruit ripeness, sugar content, and flavor compound accumulation.

Integrated Nutrient Management (INM) is a soil-based nutrient supply strategy aimed at meeting crop needs. Its core concept is the rational combination of chemical fertilizers, organic fertilizers, and bio-fertilizers to achieve efficient nutrient utilization and ecological environmental protection (Wu et al., 2024). In recent years, with the exposure of the drawbacks of traditional single-fertilizer application, research on the application of INM in fruit tree and grape production has been increasing. Practice has shown that the INM model, by supplementing organic matter and improving soil structure, can improve soil fertility and water retention capacity, promote the reproduction of beneficial microorganisms, and thus enhance soil fertility and crop production efficiency (Meissner et al., 2019). For example, in a four-year trial in a vineyard in Hebei Province, the combined application of moderate amounts of organic fertilizer and chemical fertilizer (M2NPK) significantly increased grape yield (14% higher than the control) and vitamin C content, reduced soil nitrate nitrogen accumulation, and increased soil microbial biomass carbon and nitrogen content. Other studies have shown that reducing chemical fertilizer application by 20% and applying liquid organic fertilizer can significantly increase soil microbial biomass C, N, and enzyme activity, promoting grape yield and quality improvement. These results indicate that the scientific implementation of integrated nutrient management is an effective way to improve soil quality, increase efficiency, and reduce fertilizer use in modern viticulture (Chang et al., 2025).

2 Theoretical Basis of Integrated Nutrient Management

2.1 Concept and principles of integrated nutrient management

Integrated Nutrient Management (INM) is an agricultural management strategy that organically combines multiple nutrient sources, such as chemical fertilizers, organic fertilizers, and bio-fertilizers. Its core lies in achieving sustainable soil resource utilization while meeting crop growth needs. Its basic principles include nutrient balance, resource recycling, and eco-friendliness. Specifically, INM emphasizes developing fertilization plans based on the existing soil fertility, appropriately supplementing chemical fertilizers to improve nutrient supply, while simultaneously applying organic and bio-fertilizers to increase soil organic matter content and provide carbon and nitrogen sources for the microbial community. This multi-faceted fertilization approach of "chemical + organic + microbial" helps improve nutrient utilization efficiency, reduce chemical fertilizer residues and environmental pollution, and enhance soil activity and ecological stability (Bargaz et al., 2018).

2.2 Synergistic mechanism of organic, chemical, and bio-fertilizers

In integrated nutrient management, different types of fertilizers have complementary mechanisms of action. Organic fertilizers are the main providers of carbon sources and soil organic matter, improving soil structure, increasing bulk density and water retention capacity, and providing a sustainable source of nutrients for soil microorganisms. Chemical fertilizers, with their efficient and rapid nutrient replenishment advantages, meet the needs of grapes for nitrogen, phosphorus, potassium, and other elements during critical growth stages. Bio-fertilizers (such as nitrogen-fixing bacterial fertilizers, phosphorus-dissolving bacteria, or microbial inoculants) promote nutrient transformation and absorption through microbial metabolism, while also improving soil fertility and reducing diseases (Bargaz et al., 2018). When these three are applied in a reasonable combination, a synergistic effect can be achieved. For example, studies have found that the combined use of compound microbial fertilizers and humic acid fertilizers with nitrogen, phosphorus, and potassium fertilizers can increase the number of beneficial microorganisms such as actinomycetes in the rhizosphere, making the total microbial biomass 1.3 times that of the single chemical fertilizer control. In addition, the rich trace elements and organic matter in organic fertilizers help buffer soil pH changes and avoid acidification problems caused by excessive chemical fertilizers.

2.3 Impact of integrated nutrient management on soil ecological environment

Reasonable integrated nutrient management measures can significantly improve the soil ecological environment. On the one hand, continuous application of organic fertilizers can greatly increase soil organic matter content and aggregate structure stability, enhancing soil's water and fertilizer retention capacity. On the other hand, beneficial microorganisms in bio-fertilizers and soil conditioners can accelerate nutrient cycling, decompose organic residues, and inhibit some pathogens (Li et al., 2024). Integrated fertilization can also adjust soil nutrient ratios, reducing nutrient imbalances caused by excess of a single element. For example, in field trials at Red Globe vineyards, the combined application of appropriate amounts of organic and chemical fertilizers can reduce soil nitrate nitrogen accumulation while increasing microbial biomass carbon and nitrogen; while excessive organic fertilizers, although continuing to improve soil fertility in the short term, may also accelerate the accumulation of heavy metals in the soil, affecting long-term environmental health. Overall, integrated nutrient management optimizes soil physicochemical properties through multiple pathways, improves microbial activity and diversity, thereby enhancing the stability and sustainable productivity of the vineyard ecosystem.

3 Characteristics of Rhizosphere Microbial Community Structure in Vineyard Soil

3.1 Main types and functional groups of rhizosphere microorganisms

The rhizosphere soil of vineyards contains a diverse array of microorganisms, mainly including bacteria, fungi (including actinomycetes and other filamentous fungi), and archaea. Bacteria play a central role in nutrient cycling processes such as organic matter decomposition and nitrogen and phosphorus transformation. For example, nitrogen-fixing bacteria (such as Rhizobium and Azotobacter) can fix atmospheric nitrogen, while phosphate-solubilizing bacteria (such as Bacillus and Pseudomonas) can convert insoluble phosphorus in the soil into forms available to plants (Figure 1) (Thepbandit et al., 2024). Fungi, especially fungal filaments, play an important role in degrading cellulose and lignin and forming soil aggregates. Some fungi (such as Glomus) can also form mycorrhizal symbiosis with grape roots, promoting mineral nutrient absorption (Lailheugue et al., 2024). Actinomycetes possess characteristics of both bacteria and fungi, are widely distributed in vineyard soils, and often produce antibiotic-like substances, which are beneficial in inhibiting pathogens. Based on their functions, these microorganisms can be divided into nutrient cycling functional groups (nitrogen fixation, phosphorus solubilization, organic matter decomposition, etc.), protective functional groups (antagonistic to pathogens, root growth promotion, etc.), and pathogenic functional groups (such as root rot pathogens). They interact and coexist synergistically, jointly regulating the ecological functions and health status of vineyard soils.

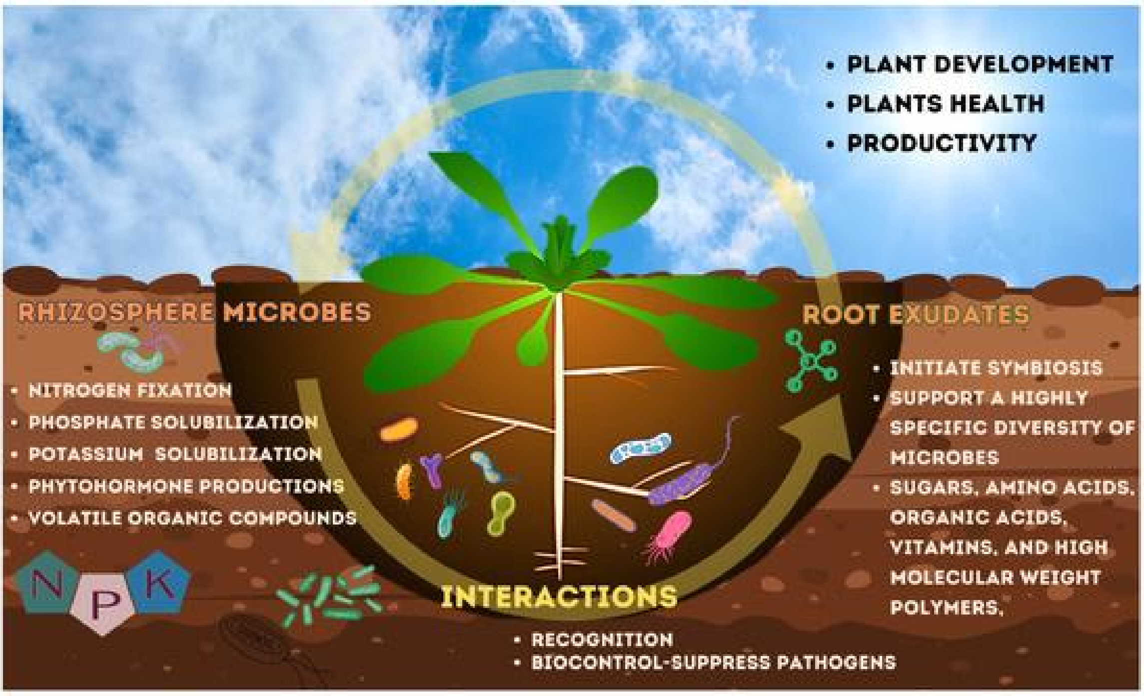

Figure 1 Schematic overview of benefits effect of plant interaction with microorganisms in the rhizosphere zone (Adopted from Thepbandit et al., 2024)

3.2 Key factors affecting the structure of grape rhizosphere microbial communities

The structure of vineyard rhizosphere microbial communities is influenced by multiple factors. First, soil physicochemical properties (such as pH, organic matter content, and nutrient levels) are important factors determining the composition of the microbial community. For example, soils with high organic matter content usually have a richer microbial community; changes in soil pH will screen out microorganisms suitable for acidic or alkaline environments. Second, grape cultivation management practices (such as fertilization patterns, irrigation methods, and weeding methods) have a significant impact on the distribution of the microbial community. Excessive use of single chemical fertilizers often leads to a decrease in microbial diversity, while the application of organic fertilizers and bio-fertilizers can promote an increase in the richness of beneficial microorganisms (Dries et al., 2021; Chang et al., 2025). Furthermore, climatic factors (temperature, precipitation) and the plant itself (variety, root exudates) also alter the rhizosphere environment, thus affecting the microbial community structure (Lailheugue et al., 2024). For example, changes in soil moisture content affect the relative abundance of aerobic and anaerobic microorganisms, while organic acids and flavonoids secreted by roots can attract certain specific microorganisms. In summary, multiple environmental and management factors interact to jointly shape the structure of the rhizosphere soil microbial community in vineyards (Schmidt et al., 2019).

4 Mechanisms of the Influence of Integrated Nutrient Management on Rhizosphere Microbial Structure

4.1 Effects of different fertilization patterns on microbial community composition

Different fertilization patterns have a significant impact on the composition of vineyard soil microbial communities. Studies have generally found that the use of chemical fertilizers alone often reduces microbial diversity and community evenness, while the application of organic fertilizers or bio-inoculants promotes the flourishing of beneficial microbial communities. For example, in the Crimson Seedless Grape rhizosphere soil experiment, the application of humic acid fertilizer and bio-inoculants significantly increased the number of bacteria, fungi, and actinomycetes in the topsoil compared to chemical fertilizers, with the optimal treatment resulting in a total soil microbial population 1.3 times that of the control. Similarly, in a vineyard experiment in Anhui, compared to traditional chemical fertilizer application, soil treated with a 20% reduction in chemical fertilizer and the addition of liquid organic fertilizer showed significantly higher microbial biomass (C, N content) and enzyme activity than the control (Lin et al., 2019). These results indicate that integrated fertilization patterns provide microorganisms with more diverse nutrient sources and living environments, thereby altering community structure and enhancing the advantages of functional groups such as organic matter decomposition and nitrogen fixation.

4.2 Regulation of microbial metabolic functions by nutrient input

Nutrient supply patterns not only alter the abundance of microbial communities but also profoundly affect their metabolic activity and functional expression. Increased organic fertilizer input enriches the soil with carbon sources, leading to more active metabolism in microorganisms that rely on organic matter decomposition, promoting the release and cycling of nutrients (such as ammonia, nitrates, and soluble organic matter); conversely, continuous application of chemical nitrogen fertilizer may inhibit the activity of certain nitrogen-fixing bacteria (Wu et al., 2024). When the available nutrients in the soil change, the dominant positions of different functional groups shift. For example, in nutrient-balanced soils, nitrogen-fixing and phosphate-solubilizing bacteria tend to be more active, thus continuously providing nitrogen and phosphorus to grapevines. Simultaneously, nutrient changes also affect microbial competition; for instance, when organic matter is abundant, the diversity of bacteria competing for organic carbon increases. In summary, nutrient input, by altering carbon and nitrogen substrate supply and nutrient ratios, regulates the metabolic activity and niche of various functional groups within the microbial community, thereby further influencing the overall community structure.

4.3 Feedback effects of soil physicochemical properties on microbial community structure

Integrated Nutrient Management (INM) indirectly influences microbial community structure by improving soil physicochemical properties. For example, continuous application of organic fertilizers can significantly increase soil organic matter content, reduce aggregate fragmentation, and provide a more suitable microenvironment for microorganisms; liquid organic fertilizers or soil conditioners can buffer soil pH, preventing acidification and thus creating a more suitable environment for microbial growth (Raimi et al., 2023). These changes create more favorable living conditions for microbial communities, leading to increased diversity. Studies have shown that landless practices (such as straw return and mulching) typically result in higher microbial diversity and richer functional microbial communities than conventional cultivated land (Wu et al., 2024). Similarly, improving soil physicochemical properties in vineyards often increases the α-diversity and evenness of bacterial and fungal communities. Therefore, INM, by improving soil structure and enhancing organic matter and nutrient buffering capacity, provides a more stable environment for rhizosphere microorganisms, thereby promoting the optimized reconstruction of the microbial community.

5 Relationship between Rhizosphere Microorganisms and Grape Nutrient Absorption and Growth

5.1 Mechanisms by which rhizosphere microorganisms promote nutrient transformation and cycling

Rhizosphere microorganisms enhance the plant's accessibility to nutrients by decomposing soil organic matter and transforming inorganic nutrients. For example, nitrogen-fixing bacteria can fix atmospheric nitrogen into plant-available ammonium nitrogen, while phosphate-solubilizing bacteria can release phosphorus from insoluble phosphate minerals for grape absorption. Furthermore, some microorganisms secrete organic acids or enzymes to accelerate the decomposition of organic matter and minerals, thereby releasing nutrients; simultaneously, microbial metabolism promotes the mineralization of organic nitrogen and organic matter, providing a sustainable nitrogen source for the plant. These mechanisms enable grapes to obtain a more abundant and diverse supply of nutrients from the soil under the INM system, meeting the needs of growth and fruit development.

5.2 The influence of microbial-plant interactions on grape growth and development

A complex interaction network exists between grape rhizosphere microorganisms and plants. Some plant growth promoters (PGPRs) and root symbiotic microorganisms can produce plant hormones (such as indoleacetic acid and ethylene regulators), stimulating root growth and increasing root hair density, thereby expanding the absorption area of grapes (Hakim et al., 2021). Simultaneously, beneficial microorganisms can also suppress soil-borne pathogens and reduce disease incidence through nutrient competition, the production of antimicrobial substances, or the induction of plant resistance (Dries et al., 2021). Endophytic flora in grapes (such as certain fungi) may also improve the plant's tolerance to stresses such as drought and salinity by regulating plant immunity and growth regulation pathways (Wang et al., 2023). These microbial-plant interaction effects ultimately manifest as a synergistic effect, promoting grape growth, accelerating ripening, and enhancing overall plant vigor (Chang et al., 2025).

5.3 The relationship between microbial community structure and grape quality formation

Studies have shown that there may be an indirect link between rhizosphere microbial community structure and grape fruit quality. A healthy and stable microbial community can improve soil nutrient supply and the root growth environment, contributing to the accumulation of sugars, acids, and aromatic substances in the fruit Reports indicate a positive correlation between soil bacterial and fungal community diversity and the content of flavor compounds in grape berries. Furthermore, certain microbial metabolites (such as certain organic acids and amino acids) may affect fruit development through root-stem translocation (Song et al., 2024). However, the direct mechanisms by which microbial communities influence grape quality formation are not yet fully understood. Overall, maintaining a healthy rhizosphere microbial ecosystem helps improve fruit flavor, color, and antioxidant content, thereby enhancing the final quality of the wine.

6 Research Methods and Techniques

6.1 Soil sample collection and physicochemical property determination

In conducting research on rhizosphere microorganisms in vineyard soils, scientific and standardized sample collection is fundamental to ensuring the reliability of research results (Berlanas et al., 2019). Generally, representative vines are selected during the vigorous growth period of grapevines, and rhizosphere soil is collected along the root distribution area at a certain distance from the main trunk. During sampling, the soil adhering to the roots should be gently shaken off, and the soil tightly attached to the root surface is used as the rhizosphere sample. To ensure data representativeness, multiple sampling points are usually set up within the same treatment area and mixed samples are processed (Figure 2) (Berlanas et al., 2019). After collection, samples need to be promptly stored at low temperatures or air-dried to avoid changes in the microbial community structure.

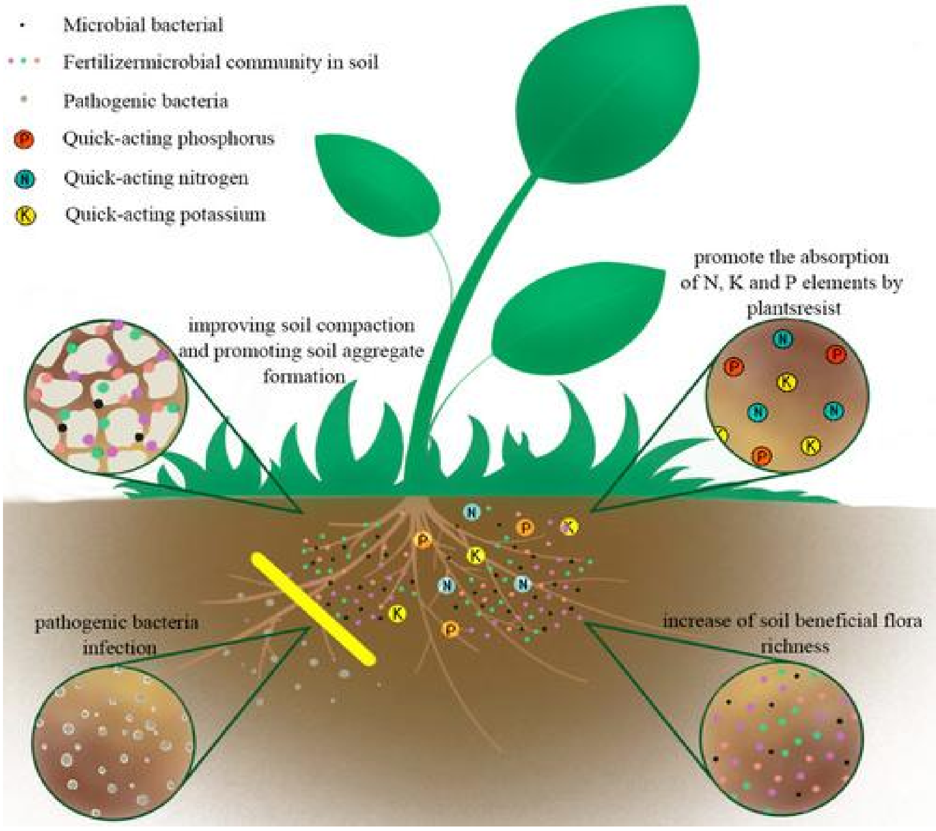

Figure 2 The role of microorganisms in soil (Adopted from Berlanas et al., 2019)

6.2 Application of high-throughput sequencing technology in rhizosphere microbial research

With the development of molecular biology techniques, high-throughput sequencing technology has become an important tool for studying soil microbial community structure. This technology allows for rapid analysis of a large amount of microbial community information by extracting and amplifying microbial DNA from soil samples. In vineyard soil research, the composition of the microbial community is often analyzed by amplifying bacterial 16S rRNA genes and fungal ITS regions (Berlanas et al., 2019). After DNA extraction, PCR amplification, and library construction, the samples are sent to a sequencing platform for sequencing, thereby obtaining a large amount of microbial sequence data. By classifying and comparing these sequences, the composition and relative abundance of different microbial groups can be identified. Compared with traditional culturing methods, high-throughput sequencing technology can more comprehensively reveal the diversity characteristics of difficult-to-culture microorganisms in soil, thus playing an important role in rhizosphere microbial ecology research.

6.3 Data analysis methods and microbial community structure analysis

After obtaining high-throughput sequencing data, a systematic data analysis approach is needed to analyze the microbial community structure. First, the raw sequencing data undergoes quality control, including removing low-quality sequences, assembling valid sequences, and removing chimeric sequences to ensure the accuracy of the data analysis. Then, microorganisms are classified based on sequence similarity, and operational taxonomic units or characteristic sequences are constructed for analyzing community composition. Commonly used analytical indicators include community richness, diversity index, and species evenness, which reflect the overall characteristics of the microbial community structure.

7 Case Study: The Effects of Integrated Nutrient Management on a Vineyard

7.1 Study area and experimental design

This case study uses a hypothetical wine vineyard in Ningxia (sandy loam soil, annual rainfall 500 mm) as the research object, employing a randomized block design for a 3-year experiment. The following treatments were established: CK (conventional fertilizer application), INM1 (half nitrogen fertilizer + organic fertilizer supplementation), and INM2 (half nitrogen fertilizer + organic fertilizer + bio-fertilizer). Each treatment had 3 replicates, with 3 adjacent vines per replicate (Hendgen et al., 2018). Rhizosphere soil samples were collected during the greening and ripening stages to analyze soil nutrient content and microbial diversity; simultaneously, the yield per vine, soluble solids content (TSS) of fruit, and total phenols were recorded for each treatment (Figure 3) (Meissner et al., 2019; Cataldo et al., 2021).

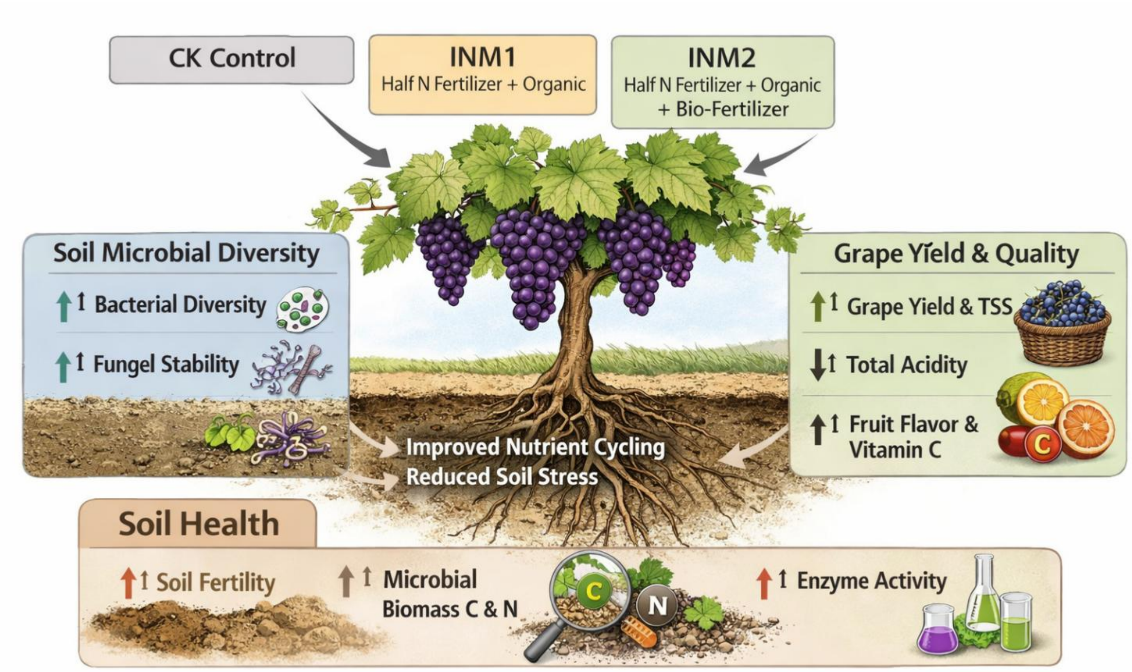

Figure 3 Effects of integrated nutrient management (INM) on vineyard soil microbial diversity, soil health, and grape yield and quality (Adapted from Cataldo et al., 2021)

7.2 Effects of integrated nutrient management on soil microbial diversity

In this case study, compared with the CK treatment (fertilizer application only), INM1 and INM2 significantly increased the diversity of the soil microbial community. Specifically, this manifested as an increase in the Shannon index of the bacterial community and an increase in the proportion of dominant bacterial phyla (such as Actinobacteria); the fungal community also tended to stabilize (Hendgen et al., 2018). Literature reports indicate that treatment with cover crops or organic amendments can significantly increase the number of bacterial OTUs and the diversity index in the soil (García-Orenes et al., 2016; Song et al., 2022). In this case, under the INM1/INM2 treatment, soil microbial biomass C and N increased by approximately 20%-30% compared to the control (CK), and the activity of active enzymes (such as alkaline phosphatase and urease) increased, indicating that the function of the microbial community was enhanced (Meissner et al., 2019). This is consistent with other studies: reducing chemical fertilizers and applying organic fertilizers can significantly increase microbial biomass carbon and nitrogen and enzyme activity in the rhizosphere soil. These results indicate that a scientific INM model provides rhizosphere microorganisms with richer nutrients and a better habitat, thereby optimizing the microbial community structure.

7.3 Effects of integrated nutrient management on grape yield and quality

Under the implementation of integrated nutrient management, both grape yield and quality showed varying degrees of improvement. For example, a medium level of organic fertilizer plus chemical fertilizer (similar to M2NPK) increased grape yield per vine by approximately 14%, and also increased total sugar and vitamin C content (Chang et al., 2025). In this case, the INM1 and INM2 treatments increased yield per vine compared to the control (expected increase of 10%-15%), and also increased grape TSS, decreased total acidity, and improved fruit flavor. Improved soil fertility (increased organic matter and available nutrients) and enhanced microbial activity provided a continuous and stable nutrient supply to the grapes, promoting full fruit development. Similarly, previous studies have shown that the C/N ratio of microbial biomass in vineyards with organic fertilizer application was significantly higher than that with chemical fertilizer application alone, indicating enhanced soil nutrient cycling capacity (García-Orenes et al., 2016). Overall, this case validates that INM treatments contribute to achieving the goal of increasing yield and improving quality (Liu et al., 2025).

8 Conclusions and Future Research Directions

Integrated nutrient management (INM) improves soil nutrient status and physicochemical properties through multiple channels, promoting a more stable and diverse rhizosphere microbial community structure in vineyards. The rational application of a combination of organic, bio-fertilizers, and chemical fertilizers not only increases soil organic matter and biomass content but also increases the proportion of nitrogen-fixing and phosphorus-solubilizing microorganisms. In the long term, the INM model helps enhance the self-regulation capacity and resilience of the soil ecosystem, providing a solid ecological foundation for grape production. However, it should be noted that soil and climate conditions vary in different regions, and the effects of INM may differ; furthermore, fertilizer formulation and application duration also affect microbial responses. Therefore, the promotion of INM should be optimized based on regional characteristics and practical experience.

Although existing research has shown that INM has positive effects on soil microorganisms, there are still shortcomings. First, existing studies are mostly short-term or localized experiments, lacking long-term data across ecological zones, making it difficult to assess the persistence and cumulative effects of INM (intestinal microorganisms). Second, our understanding of rhizosphere microbial function remains incomplete, mostly focusing on community structure without in-depth analysis of metabolites and gene functions. Third, some studies use single indicators, and the mechanisms of action of synergistic effects of multiple nutrient sources are still unclear. Therefore, it is necessary to combine multidisciplinary technologies, such as metagenomics and metabolomics, to deeply reveal the specific mechanisms by which INM regulates microbial function and plant metabolism.

Therefore, it is essential to conduct long-term field trials across multiple regions and years to systematically evaluate the lasting effects of different INM ratios on microbial communities and soil health; to explore the intrinsic link between changes in microbial community function and grape nutrient metabolism using high-throughput omics technologies such as metagenomics and transcriptomics; and to conduct research on rhizosphere signaling molecules to elucidate how grape root exudates regulate the microbial community, thereby affecting nutrient absorption and quality formation. It is particularly important to formulate and promote planting technology standards that combine "reduction of chemical fertilizers with substitution of organic fertilizers," encourage farmers to use high-quality organic fertilizers that have been certified for safety, strengthen soil testing and precision fertilization guidance, promote precision agriculture technology, achieve fertilization according to local conditions and avoid excessive input, promote farmland ecological compensation and fertilizer residue monitoring policies, and provide subsidies or technical support to vineyards that use organic fertilizers for long-term application to promote sustainable planting models.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Alcalá-Herrera R., Moreno B., Aguirrebengoa M., Winter S., Robles-Cruz A.B., Ramos-Font M.E., and Benítez E., 2023, Role of agricultural management in the provision of ecosystem services in warm climate vineyards: functional prediction of genes involved in nutrient cycling and carbon sequestration, Plants, 12(3): 590.
https://doi.org/10.3390/plants12030590

Bargaz A., Lyamlouli K., Chtouki M., Zeroual Y., and Dhiba D., 2018, Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system, Frontiers in Microbiology, 9: 1604.
https://doi.org/10.3389/fmicb.2018.01604

Berlanas C., Berbegal M., Elena G., Laidani M., Cibriáin J.F., Sagüés A., and Gramaje D., 2019, The fungal and bacterial rhizosphere microbiome associated with grapevine rootstock genotypes in mature and young vineyards, Frontiers in Microbiology, 10: 1142.
https://doi.org/10.3389/fmicb.2019.01142

Cataldo E., Fucile M., and Mattii G.B., 2021, A review: Soil management, sustainable strategies and approaches to improve the quality of modern viticulture, Agronomy, 11(11): 2300.
https://doi.org/10.3390/agronomy11112300

Chang X., Chen J., Zhao K., Wang T., Yang Y., Jia X., Hu B., Yu Y., Li F., He Y., and Wu Z., 2025, Dose-optimized microbial inoculants reshape grape rhizosphere microbiota and enhance fruit quality, Frontiers in Microbiology, 16: 1509422.
https://doi.org/10.3389/fmicb.2025.1509422

Dries L., Hendgen M., Schnell S., Löhnertz O., and Vortkamp A., 2021, Rhizosphere engineering: leading towards a sustainable viticulture?, OENO One, 55(2): 221-242.
https://doi.org/10.20870/oeno-one.2021.55.2.4521

Francioli D., Strack T., Dries L., Voss-Fels K., and Geilfus C.M., 2024, Roots of resilience: Optimizing microbe-rootstock interactions to enhance vineyard productivity, Plants, People, Planet, 6(6): 824-838.
https://doi.org/10.1002/ppp3.10633

García-Orenes F., Roldán A., Morugán-Coronado A., Linares C., Cerdà A., and Caravaca F., 2016, Organic fertilization in traditional Mediterranean grapevine orchards mediates changes in soil microbial community structure and enhances soil fertility, Land Degradation & Development, 27(6): 1622-1628.
https://doi.org/10.1002/ldr.2496

Hakim S., Naqqash T., Nawaz M.S., Laraib I., Siddique M.J., Zia R., Mirza M.S., and Imran A., 2021, Rhizosphere engineering with plant growth-promoting microorganisms for agriculture and ecological sustainability, Frontiers in Sustainable Food Systems, 5: 617157.
https://doi.org/10.3389/fsufs.2021.617157

Hendgen M., Hoppe B., Döring J., Friedel M., Kauer R., Frisch M., Dahl A., and Kellner H., 2018, Effects of different management regimes on microbial biodiversity in vineyard soils, Scientific Reports, 8: 9393.
https://doi.org/10.1038/s41598-018-27743-0

Lailheugue V., Darriaut R., Tran J., Morel M., Marguerit E., and Lauvergeat V., 2024, Both the scion and rootstock of grafted grapevines influence the rhizosphere and root endophyte microbiomes, but rootstocks have a greater impact, Environmental Microbiome, 19: 26.
https://doi.org/10.1186/s40793-024-00566-5

Li Q., Andom O., Li Y., Cheng C., Deng H., Sun L., and Li Z., 2024, Responses of grape yield and quality, soil physicochemical and microbial properties to different planting years, European Journal of Soil Biology, 119: 103587.
https://doi.org/10.1016/j.ejsobi.2024.103587

Lin W., Lin M., Zhou H.-Y., Wu H., Li Z., and Lin W., 2019, The effects of chemical and organic fertilizer usage on rhizosphere soil in tea orchards, PLOS ONE, 14(5): e0217018.
https://doi.org/10.1371/journal.pone.0217018

Ling N., Wang T., and Kuzyakov Y., 2022, Rhizosphere bacteriome structure and functions, Nature Communications, 13: 836.
https://doi.org/10.1038/s41467-022-28448-9

Liu C., Gong X., Dang K., Li J., Yang P., Gao X.-L., Deng X., and Feng B., 2020, Linkages between nutrient ratio and the microbial community in rhizosphere soil following fertilizer management, Environmental Research, 181: 108907.
https://doi.org/10.1016/j.envres.2019.108907

Meissner G., Athmann M., Fritz J., Kauer R., Stoll M., and Schultz H., 2019, Conversion to organic and biodynamic viticultural practices: impact on soil, grapevine development and grape quality, OENO One, 53(4): 621-639.
https://doi.org/10.20870/oeno-one.2019.53.4.2403

Raimi A., Ezeokoli O.T., and Adeleke R.A., 2023, Soil nutrient management influences diversity, community association and functional structure of rhizosphere bacteriome under vegetable crop production, Frontiers in Microbiology, 14: 1229873.
https://doi.org/10.3389/fmicb.2023.1229873

Schmidt J.E., Kent A.D., Brisson V.L., and Gaudin A.C.M., 2019, Agricultural management and plant selection interactively affect rhizosphere microbial community structure and nitrogen cycling, Microbiome, 7: 146.
https://doi.org/10.1186/s40168-019-0768-2

Song R., Zhu W., Li H., and Wang H., 2024, Impact of wine-grape continuous cropping on soil enzyme activity and the composition and function of the soil microbial community in arid areas, Frontiers in Microbiology, 15: 1330792.
https://doi.org/10.3389/fmicb.2024.1330792

Song Y., Zhao Q., Guo X., Ali I., Li F.-Y., Lin S., and Liu D., 2022, Effects of biochar and organic-inorganic fertilizer on pomelo orchard soil properties, enzymes activities, and microbial community structure, Frontiers in Microbiology, 13: 952433.
https://doi.org/10.3389/fmicb.2022.952433

Wang B., Wang X.-C., Wang Z.-W., Zhu K., and Wu W.M., 2023, Comparative metagenomic analysis reveals rhizosphere microbial community composition and functions help protect grapevines against salt stress, Frontiers in Microbiology, 14: 1138523.
https://doi.org/10.3389/fmicb.2023.1138523

Wu L., Jiang Y., Zhao F., He X., Liu H.-F., and Yu K., 2020, Increased organic fertilizer application and reduced chemical fertilizer application affect the soil properties and bacterial communities of grape rhizosphere soil, Scientific Reports, 10: 9568.
https://doi.org/10.1038/s41598-020-66648-9

Zarraonaindia I., Owens S.M., Weisenhorn P., West K., Hampton-Marcell J., Lax S., Bokulich N.A., Mills D.A., et al., 2015, The soil microbiome influences grapevine-associated microbiota, mBio, 6(2): e02527-14.
https://doi.org/10.1128/mBio.02527-14