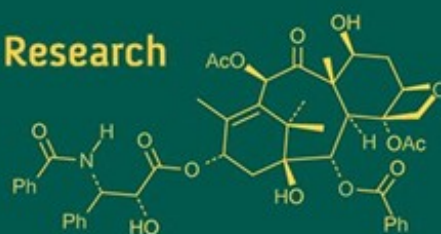


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Nanotechnology, biotechnology and artificial intelligence in soil management: New sustainable strategies and approaches to improve modern viticulture farming

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ABSTRACT

Vineyard soils are a finite and increasingly stressed resource, subject to erosion, organic-carbon depletion, compaction and, in many regions, salinisation and heavy-metal accumulation from decades of conventional viticultural practice. Because the terroir concept links soil condition directly to grape and wine quality, sustainable soil management is not merely an environmental imperative for viticulture but a determinant of product identity and economic value. This review synthesises three converging technological domains being applied to vineyard soil management: nanotechnology (nanofertilisers, nanosensors and nanoremediation agents), biotechnology (plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, biochar and biostimulants), and artificial intelligence (IoT sensor networks, UAV-based remote sensing, and machine-learning-driven precision zoning). Evidence compiled from recent primary studies and reviews indicates that integrating these domains can raise nutrient-use efficiency, restore soil organic carbon at rates of 2.8-11 Mg CO₂ ha⁻¹ yr⁻¹ through cover cropping and organic amendments, sustain biochar-derived fertility benefits for up to seven years from a single application, and enable data-driven variable-rate irrigation and fertigation informed by ensemble machine-learning models. We present a comparative synthesis of these technologies, an integrated conceptual framework for their combined deployment, and a critical discussion of persisting challenges, including nanoparticle ecotoxicity, inoculant field-performance variability, model transferability across terroirs, and the cost of sensor infrastructure for smallholder growers. We conclude that the convergence of nano-, bio- and AI-based tools, embedded within regenerative practices such as cover cropping and reduced tillage, offers the most promising pathway toward climate-resilient, terroir-preserving viticulture.

Keywords: Nanotechnology, Biotechnology, Artificial intelligence, Sustainable soil management, Viticulture

1. Introduction

Soil is the foundation of the terroir concept that underlies wine identity and quality, and its condition directly influences grapevine vigour, water and nutrient status, and the sensory and chemical profile of the resulting fruit and wine. Conventional viticultural management, characterised by intensive tillage, high agrochemical input and limited organic-matter return, has, over decades, contributed to soil erosion, compaction, loss of organic carbon and declining microbial biodiversity across many wine-growing regions.

At the same time, viticulture faces mounting pressure from climate change, including shifting precipitation patterns, rising temperatures, and increased frequency of drought and extreme rainfall events, all of which interact with soil condition to affect vine performance and long-term sustainability (Vélez *et al.*, 2024; Villat *et al.*, 2024) [1, 2]. These converging pressures have accelerated interest in technologies capable of improving soil management precision, restoring soil biological function, and reducing the environmental footprint of vineyard operations without compromising yield or wine quality.

Three technological domains have emerged as particularly transformative in this context. Nanotechnology offers controlled-release nutrient delivery, real-time in-field sensing, and remediation tools operating at the nanoscale. Biotechnology harnesses beneficial soil microorganisms, organic amendments such as biochar, and biostimulant formulations to restore soil biological function and enhance plant stress tolerance. Artificial intelligence, encompassing the Internet of Things (IoT), remote sensing and machine learning, enables the aggregation and interpretation of large, heterogeneous soil and vine datasets to support precise, spatially targeted management decisions.

This review synthesises current evidence on the application of these three domains to vineyard soil management, situates them within the broader context of regenerative and sustainable viticultural strategies such as cover cropping and reduced tillage, and critically examines the technical and practical challenges that must be addressed for widespread adoption.

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2. Nanotechnology in vineyard soil management

Nanotechnology applies materials with at least one dimension below 100 nanometres to agricultural problems, exploiting their disproportionately high surface-area-to-volume ratio, tunable reactivity and capacity for targeted delivery. In soil management, three nano-enabled tool classes are most relevant to viticulture: nanofertilisers, nanosensors/nanobiosensors, and nanoremediation agents.

2.1 Nanofertilisers and controlled nutrient delivery

Nanofertilisers, typically formulated from zinc, iron, copper, molybdenum oxides or carbon-based nanomaterials, encapsulate or bind nutrients so that release is synchronised with plant demand rather than governed by bulk solubility and leaching (Ashique *et al.*, 2025; Abad *et al.*, 2021) [3, 4]. This controlled-release behaviour reduces the fraction of applied nutrient lost to leaching or volatilisation, thereby improving nutrient-use efficiency relative to conventional fertiliser formulations, an outcome particularly valuable in permeable, well-drained vineyard soils prone to nutrient leaching (Ashique *et al.*, 2025) [3].

2.2 Nanosensors and nanobiosensors for real-time soil monitoring

Nanosensors incorporating gold and silver nanoparticles, quantum dots and engineered nanostructures can detect soil moisture, pH, nutrient concentrations and plant pathogens, including viral pathogens relevant to grapevine health such as Grapevine virus A, with high sensitivity and low detection limits (Adeel *et al.*, 2025; Badeka *et al.*, 2023) [5, 6]. Deployed across a vineyard, such sensors provide near-continuous data streams that feed directly into the precision-management workflows discussed in Section 4, enabling early intervention before soil or vine stress becomes visually apparent (Adeel *et al.*, 2025) [5].

2.3 Nanoremediation of degraded and contaminated vineyard soils

Older or intensively managed vineyard soils can accumulate copper and other heavy metals from historical fungicide use, alongside general fertility decline. Nanoscale zero-valent iron and metal-oxide nanoparticles have shown capacity to immobilise or transform such contaminants, reducing their bioavailability and supporting the gradual reclamation of degraded vineyard soils (Ashique *et al.*, 2025; Bala *et al.*, 2025) [3, 7], though field-scale validation specific to viticultural contexts remains comparatively limited.

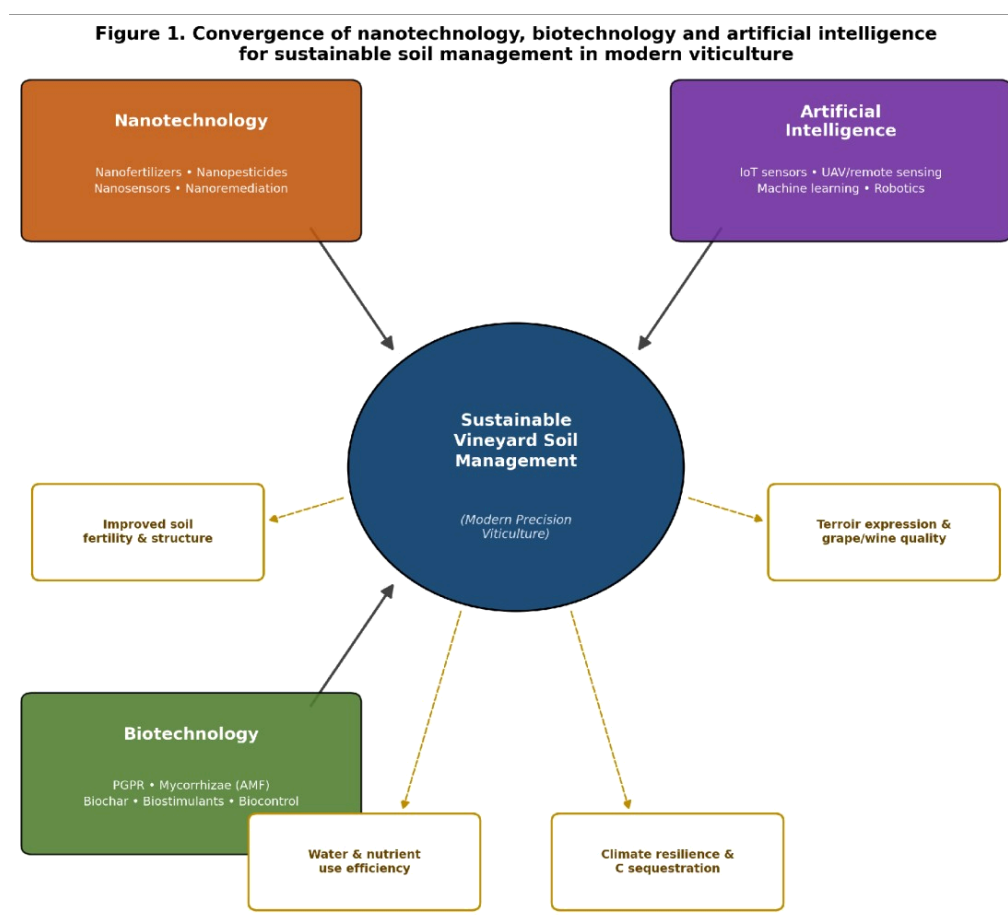


Figure 1. Convergence of nanotechnology, biotechnology and artificial intelligence for sustainable soil management in modern viticulture, and their downstream contributions to soil fertility, resource-use efficiency, climate resilience and terroir expression.

3. Biotechnology in vineyard soil management

Biotechnological approaches to vineyard soil management centre on harnessing living organisms and organic amendments to restore and enhance soil biological function, in contrast to the engineered-material basis of nanotechnology.

3.1 Plant growth-promoting rhizobacteria (PGPR)

PGPR typically comprise 2-5% of the rhizosphere microbial population and influence plant growth through both direct mechanisms, such as phytohormone production (indole-3-acetic acid, cytokinins, gibberellins) and nutrient solubilisation, and indirect mechanisms, including induced systemic resistance and antagonism toward soil-borne pathogens (Deis *et al.*, 2025) [8]. In grapevine systems, PGPR inoculation has been associated with improved nutrient uptake and enhanced tolerance to both biotic and abiotic stress (Das *et al.*, 2024; Deis *et al.*, 2025) [9, 8].

3.2 Arbuscular mycorrhizal fungi (AMF)

AMF form mutualistic associations with grapevine roots, extending the effective root-absorptive surface area and substantially improving nitrogen and phosphorus acquisition (Deis *et al.*, 2025; El-Ramady *et al.*, 2024) [8, 10]. Mycorrhizal grapevines exhibit higher root organic-acid content than non-colonised vines and show enhanced drought tolerance (El-Ramady *et al.*, 2024) [10], an increasingly valuable trait as Mediterranean and temperate viticultural regions face more frequent water-deficit periods. AMF colonisation is also promoted by reduced tillage and cover cropping (El-Ramady *et al.*, 2024) [10], linking biotechnological and agronomic strategies discussed further in Section 5.

3.3 Biochar as a soil-biological and structural amendment

Biochar, a pyrogenic carbon-rich material produced from biomass pyrolysis, improves cation exchange capacity, water-holding capacity and microbial habitat structure when incorporated into vineyard soils (Das *et al.*, 2024; Elsayed *et al.*, 2025) [9, 11]. Notably, the positive effects of biochar on vineyard soil fertility have been shown to persist for at least seven years following a single application (Elsayed *et al.*, 2025) [11], and its co-application with PGPR or AMF has demonstrated synergistic benefits for nutrient fortification and stress tolerance in other cropping systems, a combination with clear potential for viticultural adaptation (Elsayed *et al.*, 2025) [11].

3.4 Biostimulants and biological control agents

Protein hydrolysates, seaweed extracts and humic substances act as biostimulants that promote root development, nutrient assimilation and activation of plant stress-signalling pathways (Das *et al.*, 2024) [9], while biological control agents offer a lower-impact alternative to conventional agrochemicals for managing soil-borne and foliar pathogens (Das *et al.*, 2024) [9]. Careful attention to application timing is required to optimise the efficacy of both PGPR and AMF inoculants under field conditions (Das *et al.*, 2024) [9].

4. Artificial intelligence and precision soil management

Artificial intelligence, robotics and the Internet of Things are transforming viticulture by enabling continuous, spatially resolved monitoring and data-driven decision-making at a scale unattainable through traditional soil sampling and visual inspection alone.

4.1 Sensing and data acquisition

IoT networks of soil-moisture, electrical-conductivity, temperature and humidity sensors provide round-the-clock data collection, forming the backbone of data-driven vineyard management (Izquierdo-Bueno *et al.*, 2024; Jindo *et al.*, 2022) [12, 13]. Complementing ground-based sensors, unmanned aerial vehicles (UAVs) equipped with multispectral and hyperspectral cameras deliver high-resolution imagery for assessing vine vigour, water stress and disease status, including detection of *Esca disease* symptomatology, across large vineyard areas in short survey times (Kroodsma *et al.*, 2006; Martín-Pablo *et al.*, 2026) [14, 15]. Automatic resistivity profiling has similarly been used to generate high-resolution soil electrical-resistivity maps that correlate with vine trunk circumference and yield, supporting delineation of within-vineyard management zones (Moganapathi *et al.*, 2025) [16].

4.2 Machine learning for prediction and zonation

Machine-learning ensembles combining random forest, extreme gradient boosting and cubist algorithms have been applied to model nutrient availability across vineyard soils, as demonstrated in the Lodi American Viticulture Area of California, where such ensemble models integrated multiple soil and environmental covariates to generate spatially explicit nutrient-availability predictions (Miguel-Rojas *et al.*, 2023) [17]. Deep-learning architectures, including convolutional neural networks and YOLO-based object detectors, are additionally used for grape-maturity assessment and disease classification (Zain *et al.*, 2023; Zhang *et al.*, 2021) [18, 19], extending AI's role from soil-focused analytics into integrated vineyard decision support.

4.3 From prediction to action: variable-rate management

The practical value of AI-driven analytics lies in closing the loop from data to action: GPS and GIS-based mapping of soil, topography and vine-vigour variability enables variable-rate irrigation, fertigation and amendment application tailored to delineated management zones, rather than uniform, vineyard-wide treatment (Izquierdo-Bueno *et al.*, 2024; Moganapathi *et al.*, 2025) [12, 16]. This targeted approach reduces resource wastage while supporting more consistent grape quality across spatially heterogeneous vineyard blocks. Key barriers to wider adoption include the need for terroir-specific model calibration and the fragmentation of datasets across different sensor platforms and vineyard operations, which currently limits interoperability (Kroodsma *et al.*, 2006) [14].

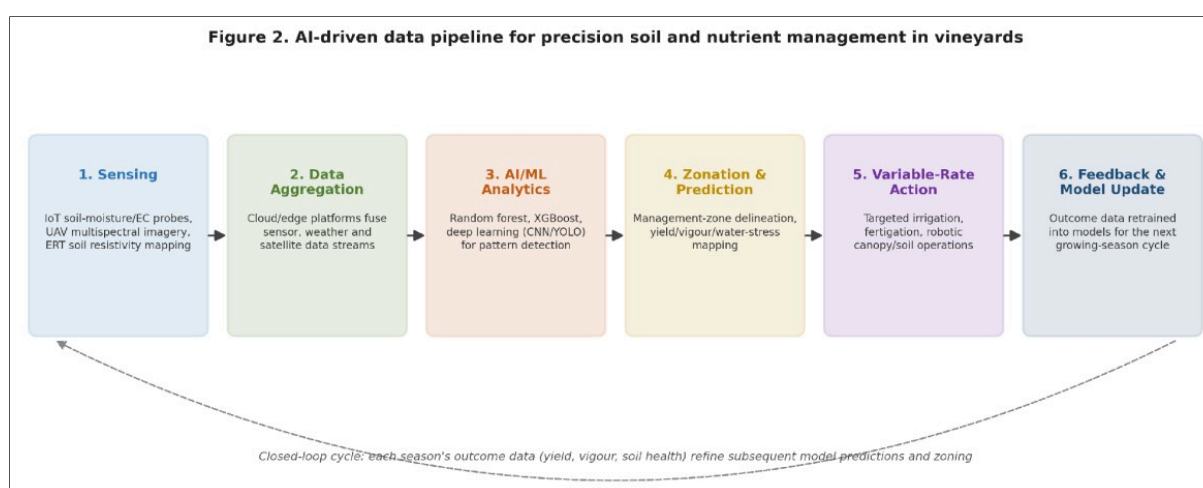


Figure 2. AI-driven data pipeline for precision soil and nutrient management in vineyards, from multi-source sensing through machine-learning analytics to variable-rate action and closed-loop model refinement.

Table 1. Representative applications of nanotechnology, biotechnology and artificial intelligence in vineyard soil management

Technology domain	Tool / agent	Soil-management function	Reported outcome
Nanotechnology	Nanofertilizers (Zn, Fe, Cu, Mo, carbon nanotubes)	Controlled, slow-release nutrient delivery to root zone	Improved nutrient-use efficiency and reduced fertiliser wastage vs. conventional formulations
Nanotechnology	Nanosensors / nanobiosensors (Au, Ag, quantum dots)	Real-time monitoring of soil moisture, pH, nutrient status and pathogens (incl. Grapevine virus A)	Enables early, in-field detection of soil and vine stress for precision decision-making
Nanotechnology	Nanoremediation agents (nZVI, nano-oxides)	Immobilisation/removal of heavy metals and organic contaminants from degraded vineyard soils	Reduces contaminant bioavailability and supports reclamation of marginal soils
Biotechnology	Plant growth-promoting rhizobacteria (PGPR)	Biofertilisation, phytohormone production (IAA, cytokinins), induced systemic resistance	Enhanced nutrient uptake, improved abiotic/biotic stress tolerance in grapevine
Biotechnology	Arbuscular mycorrhizal fungi (AMF)	Extension of root-absorptive surface area; N and P acquisition; drought buffering	Improved water/nutrient uptake and drought tolerance; higher root organic-acid content
Biotechnology	Biochar (pyrogenic soil amendment)	Increases cation exchange capacity, water retention and microbial habitat	Soil-fertility benefits sustained for up to 7 years after a single application
Biotechnology	Biostimulants (protein hydrolysates, seaweed extracts, humic substances)	Stimulate root growth, nutrient assimilation and stress signalling pathways	Improved vine physiological performance under climatic and edaphic stress
Artificial Intelligence	IoT soil-moisture/EC sensor networks	Continuous 24/7 in-field data collection on soil and microclimate variables	Supports variable-rate irrigation and fertigation, reducing resource wastage
Artificial Intelligence	UAV multispectral/hyperspectral imaging + deep learning	Canopy vigour, water-stress and disease mapping (e.g., <i>Esca</i> disease detection)	High-resolution spatial delineation of management zones across the vineyard
Artificial Intelligence	Machine-learning ensembles (random forest, XGBoost, cubist)	Prediction of nutrient availability and spatial variability in vineyard soils (e.g., Lodi AVA, California)	Improved accuracy in mapping soil nutrient status for targeted amendment
Artificial Intelligence	Electrical resistivity profiling (ARP) with GIS/regression analysis	Spatial mapping of soil texture/moisture linked to vine vigour and yield	Delineation of uniform management units matching vigour and yield patterns

5. Complementary sustainable soil management strategies

Nano-, bio- and AI-based technologies are most effective when embedded within a broader framework of regenerative agronomic practice rather than deployed as isolated interventions.

5.1 Cover cropping and reduced tillage

Cover cropping with legumes, grasses or diverse native species reduces soil erosion, increases soil organic carbon and improves water infiltration and aggregate stability, while also fostering above- and below-ground biodiversity that benefits beneficial insects and soil microbial communities (Qasim *et al.*, 2026; Rossi *et al.*, 2013) [20, 21]. A systematic review spanning two decades of viticultural research found consistent positive effects of cover cropping on soil organic carbon, aggregate stability and erosion reduction across diverse wine-growing regions (Setyawan *et al.*, 2026) [22]. Combining cover crops with no-tillage further benefits mycorrhizal fungal development, since reduced soil disturbance allows fungal hyphal networks to persist between growing seasons (El-Ramady *et al.*, 2024; Rossi *et al.*, 2013) [10, 21].

5.2 Soil organic carbon and climate mitigation

Vineyard soil management practices, including cover crops, organic amendments and incorporation of pruning residues, can sequester soil organic carbon at rates ranging from approximately 2.8 to more than 11 Mg CO₂ ha⁻¹ yr⁻¹, depending on climate, soil type and the specific combination of practices used (Shahzad *et al.*, 2025) [23]. Separately, converting arable cropland to vineyard has been estimated to increase carbon sequestration by approximately 59 g C m⁻² yr⁻¹ (Visconti *et al.*, 2024) [24], reflecting the relatively high sequestration potential of perennial woody crops such as grapevine relative to annual cropping systems (Figure 3).

5.3 Livestock integration and agroforestry

Integrating grazing animals such as sheep into vineyard inter-rows enhances nutrient cycling, reduces herbicide reliance and contributes organic matter and carbon to the soil (O'Brien *et al.*, 2025; Villat *et al.*, 2024) [25, 2], while agroforestry systems incorporating trees alongside vines can sequester additional carbon both above and below ground, improve water retention, and provide habitat supporting broader ecosystem biodiversity (Villat *et al.*, 2024) [2].

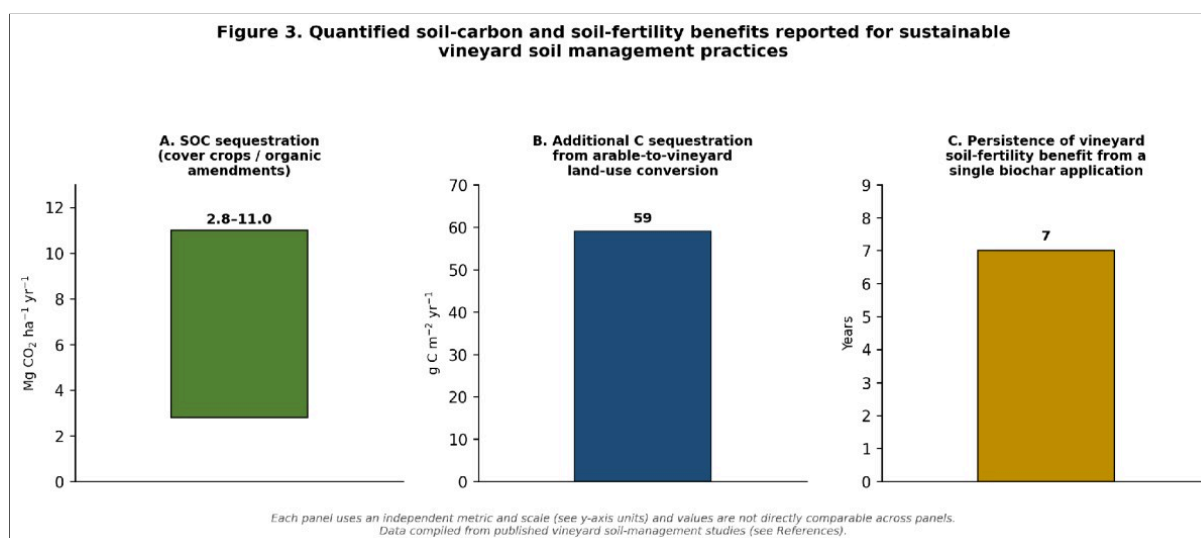


Figure 3. Quantified soil-carbon and soil-fertility benefits reported for sustainable vineyard soil management practices: (A) soil organic carbon sequestration rate from cover crops and organic amendments; (B) additional carbon sequestration from arable-to-vineyard land-use conversion; (C) persistence of soil-fertility benefit from a single biochar application.

Table 2. Comparative analysis of the three technology pillars for vineyard soil management

Technology pillar	Primary mechanism of action	Principal soil-management benefits	Key limitations
Nanotechnology	Nanoscale encapsulation, targeted/controlled release, high surface-area reactivity	Precision nutrient delivery, real-time sensing, remediation of contaminated soils	Cost of synthesis; nanoparticle ecotoxicity and long-term soil-biota effects remain under study
Biotechnology	Microbial symbiosis, biochemical signalling, organic-matter transformation	Improved nutrient cycling, soil structure, microbial diversity, natural stress tolerance	Efficacy is strain- and site-specific; inoculant survival and colonisation can be inconsistent
Artificial Intelligence	Sensor fusion, statistical/deep learning, spatial data analytics	Data-driven zoning, predictive decision support, resource-use optimisation	Requires terroir-specific model calibration; fragmented datasets hinder interoperability across sites

6. Integrated challenges and future outlook

Realising the combined potential of nanotechnology, biotechnology and artificial intelligence for vineyard soil management requires addressing challenges specific to each domain as well as barriers to their

integration. Table 3 summarises key sustainable strategies alongside their principal implementation challenges.

Table 3. Sustainable soil management strategies for viticulture and associated implementation challenges

Strategy	Sustainability contribution	Implementation challenge
Cover cropping (legumes, grasses, native species)	Reduces erosion and nutrient run-off; raises soil organic carbon; supports AMF colonisation under no-till	Potential competition for water/nutrients in drought-prone or young vineyards; requires site-specific species selection
Reduced/no-tillage	Preserves mycorrhizal networks and soil aggregate stability; lowers CO ₂ emission spikes associated with tillage	Weed management becomes more reliant on cover crops or mechanical alternatives
Integrated biochar-biofertiliser amendments	Synergistic improvement in nutrient availability, cation exchange capacity and microbial diversity	Optimal dosage and feedstock selection are still being standardised; risk of nutrient immobilisation
Nanoformulated slow-release fertilisers	Cuts nutrient leaching and over-application; matches nutrient release with vine phenological demand	Regulatory and cost barriers to commercial-scale adoption; nanoparticle fate in soil food webs needs further study
AI-guided variable-rate management zoning	Aligns irrigation, fertigation and amendment inputs precisely with spatial soil/vine variability	High upfront sensor/UAV investment; need for skilled data interpretation and terroir-specific model training
Livestock integration & agroforestry	Enhances nutrient cycling and carbon sequestration; diversifies vineyard ecosystem services	Logistical complexity of integrating grazing animals or trees with vineyard operations and machinery

Beyond the domain-specific limitations summarised above, cross-cutting challenges include the ecotoxicological uncertainty surrounding long-term nanoparticle accumulation in soil food webs, the site-specificity of microbial inoculant performance which complicates generali-

sation of biotechnological recommendations across terroirs, and the substantial upfront investment in sensor and UAV infrastructure that may be prohibitive for smallholder or cooperative-scale grape growers. Data interoperability across proprietary AI platforms further con-

strains the seamless integration of nano-, bio- and AI-derived data streams into a single decision-support framework.

Future research priorities include field-scale, multi-season validation of nanoremediation and nanofertiliser strategies specifically within viticultural soils; development of terroir-transferable machine-learning models trained on multi-region datasets; standardisation of biochar and PGPR/AMF co-application protocols; and open-data frameworks that allow interoperability between sensor networks, UAV platforms and farm-management software, thereby lowering adoption barriers for growers of varying scale.

7. Conclusion

Sustainable soil management is increasingly central to the long-term viability of viticulture, both as an environmental necessity and as a determinant of terroir expression and wine quality. The convergence of nanotechnology, biotechnology and artificial intelligence offers a powerful, complementary toolkit: nanotechnology enables precision nutrient delivery and real-time sensing; biotechnology restores and enhances soil biological function through beneficial microorganisms and organic amendments; and artificial intelligence integrates the resulting data into spatially precise, resource-efficient management decisions. When embedded within regenerative agronomic practices such as cover cropping, reduced tillage and livestock integration, these technologies collectively support improved soil fertility, enhanced climate resilience through carbon sequestration, and the preservation of the soil-terroir relationship that defines wine identity. Continued interdisciplinary research, field-scale validation, and attention to cost and accessibility barriers will be essential to translate these technological advances into routine practice across the diversity of the world's viticultural regions.

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