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REVIEW ARTICLE

Natural Mineral Soil Amendments in Organic Viticulture: Traditional Practices, Local Resources, and Ecological Perspectives

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Abstract - Natural mineral soil amendments are receiving renewed attention in organic and regenerative viticulture because they can connect traditional local resources with soil remediation, soil-life restoration and climate adaptation. This partly protocol-based scoping narrative review synthesises evidence on rock powders, zeolites, clays, carbonates, gypsum, perlite, vermiculite, alginite and humic mineral materials. The review evaluates their roles in nutrient buffering, pH and cation-exchange regulation, water retention, microbial habitat formation, heavy-metal immobilisation and carbon-stabilising soil structure. It argues that mineral amendments are most effective when used with organic matter, cover crops, reduced tillage and locally adapted vineyard-floor management, rather than as stand-alone substitutes for fertilisers. Comparative tables and decision matrices are provided to link amendment choice to soil pH, texture, salinity, contamination risk, climate stress and organic certification rules. The paper highlights Central European resources, especially volcanic and organic-mineral deposits, while placing them in a global viticultural and agroecological context. The main limitations are slow and site-dependent nutrient release, potential contamination, over-mineralisation, extraction and transport impacts, cost, and uneven field evidence in vineyards. Future research should prioritise long-term replicated vineyard trials, microbial and rhizosphere indicators, life-cycle assessment and practical guidance for certified organic farms.

Keywords - organic viticulture; mineral soil amendments; soil remineralisation; soil biodiversity; microbial habitat; climate resilience; circular economy; natural resources; soil remediation

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INTRODUCTION

Viticulture is a perennial land-use system in which soil degradation, climate stress and market expectations interact over decades. In many wine regions the same vineyard soils have been exposed to repeated traffic, tillage, erosion, copper accumulation, low organic matter return and simplified vegetation cover. These pressures reduce aggregate stability, rooting depth, infiltration, microbial activity and the capacity of soils to buffer drought, heat waves and intense rainfall (Visconti et al., 2024; Cataldo et al., 2021; García-Navarro et al., 2023; Giffard et al., 2022; Pagano and Dhar, 2016).

Application of synthetic fertilisers carry numerous environmental and even health risks. Care should be taken when using synthetic fertilisers, as they can easily lead to one-sided nutrient replenishment and nutrient imbalances (Ames and Dufour, 2017; Dufour, 2006; Villette et al., 2020). For instance, too much phosphorus will cause symptoms of zinc deficiency on shoots and inflorescences. Magnesium deficiency, which causes a serious decrease in yield can be detected as chlorosis, a sign of reduced photosynthetic capacity (Bai et al., 2024). Furthermore, among the N-fertilisers, ammonium salts and urea acidify the soil, as the nitrification of ammonium ions produces H+ ions (transformation acidity). Excessive nitrogen fertilisation can increase the yeast assimilable nitrogen (YAN) in must, which results in increased formation of ethyl carbamate (urethane), which is a potentially carcinogenic compound, ethyl acetate and protein haze (Bell and Henschke, 2005). For organic viticulture, the problem is particularly important because synthetic soluble fertilisers and many plant-protection tools are restricted, while soil health is expected to support vine nutrition, water supply, disease resilience and terroir expression (Nogales et al., 2021; OIV, 2020; O'Brien et al., 2025).

Even natural mineral-based soil improvers have often been discussed narrowly as sources of potassium, calcium, magnesium, silicon or trace elements. This nutrient-centred view, rooted in industrial agriculture, is insufficient. In living soils, mineral particles also provide surfaces for microbial biofilms, influence pore networks, modify pH and cation exchange capacity, stabilise organic matter and microbial necromass, affect water retention and may immobilise toxic elements (De Corato, 2020; Garbowski et al., 2023; Syed et al., 2021; Pan et al., 2023). Their agronomic value therefore depends not only on chemical composition, but also on particle size, weathering rate, soil pH, soil moisture, rhizosphere organic acids, microbial activity and the presence of organic amendments (Swoboda et al., 2022; Benevides Filho et al., 2023). The review addresses five gaps:

1. Local Central European mineral resources such as alginite, rhyolitic tuffs, zeolitised tuffs, volcanic rock powders, bentonites and humic mineral materials are rarely evaluated in the same framework as international studies on rock powders, zeolites, compost-mineral blends and enhanced weathering (Solti, 1987; Szepesi et al., 2024; Cataldo et al., 2023; Swoboda et al., 2022; Skov et al., 2024).
2. Existing descriptions often list geological characteristics without linking them to measurable vineyard functions, to measurable outcomes such as water retention, rooting depth, aggregate stability, nutrient buffering, microbial activity, drought resilience, or toxic-element immobilisation (Garbowski et al., 2023; Firat, 2024).
3. The literature on regenerative viticulture, soil microbiology, circular winery by-products and organic regulations is fragmented, although growers need integrated decision rules (Brito et al., 2024; O'Brien et al., 2025; European Parliament and Council, 2018; USDA Agricultural Marketing Service, 2026; Commission Implementing Regulation (EU) 2021/1165, 2021).
4. Insufficient vineyard-scale evidence. Many claims may come from laboratory, pot, or non-viticultural studies. Producers need evidence from real vineyards under different soil types, climates, slopes, organic systems, and management histories (Cataldo et al., 2023; Nagy et al., 2020; Richardson, 2025).
5. Unclear long-term effects. Viticulture is perennial and decisions affect soils over decades. There is a need for long-term evidence on cumulative benefits, possible accumulation of unwanted elements, effects on copper mobility, soil carbon stabilisation, and resilience under drought or intense rainfall (Tiecher et al., 2018; Manaljav et al., 2021; Swoboda et al., 2022).

The working hypothesis is that natural mineral soil amendments contribute most to organic viticulture when they are used as components of a multifunctional soil ecosystem strategy: mineral reservoirs and reactive surfaces must be combined with organic matter inputs, living roots, reduced disturbance, cover crops, composted winery residues, careful water management and certification-compliant monitoring (Mrunalini et al., 2022; Cataldo et al., 2021; O'Brien et al., 2025; Silvestroni et al., 2024). The objectives are therefore to:

1. synthesise the main amendment groups and their mechanisms;
2. link material choice to soil and climate constraints;
3. integrate mineral amendments with soil-life, remediation and climate-resilience concepts;
4. address regulatory, economic and environmental trade-offs; and
5. identify research gaps relevant to ecological cycle processes and international organic viticulture.

METHODOLOGY

Review design

This paper was designed as a partly protocol-based scoping narrative review. A quantitative meta-analysis was not appropriate because the evidence base includes heterogeneous material types, soil contexts, field trials, pot experiments, agronomic reports, regulatory documents, local geological descriptions and author-provided unpublished conceptual manuscripts. The review structure follows the logic of PRISMA-ScR and JBI scoping guidance (Page et al., 2021; Tricco et al., 2018; Peters et al., 2020): explicit questions, transparent search strings, eligibility screening, evidence charting and thematic synthesis. Narrative interpretation was then used to connect mechanisms, trade-offs and place-based recommendations.

The scope was intentionally broader than nutrient supply. Evidence was charted for soil physical functions, organic matter and carbon stabilisation, humus formation, microbial and faunal habitat, arbuscular mycorrhizal fungi, plant-growth-promoting rhizobacteria, pathogen suppression, soil remediation, water balance, climate resilience, circular economy, organic certification and economic feasibility (FAO et al., 2020; De Corato, 2020; Giffard et al., 2022).

Search strategy and information sources

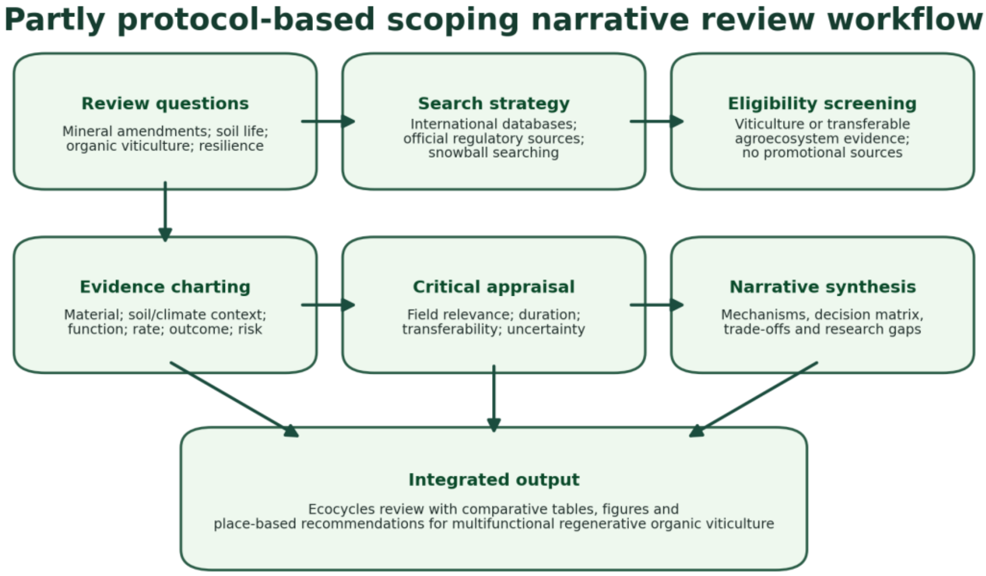
Searches were organised around six evidence domains: (1) mineral soil amendments and rock dust fertilisers; (2) vineyard soil health, microbiome and rhizosphere symbioses; (3) organic and regenerative viticulture; (4) soil remediation and heavy-metal immobilisation; (5) circular use of vineyard and winery by-products; and (6) organic production regulations. The update used international scientific databases and publisher platforms accessible through open web search, including ScienceDirect, PubMed/PubMed Central, AGRIS/FAO records, Google Scholar indexed pages, SpringerLink, MDPI, Frontiers, OENO One and official OIV, FAO, EUR-Lex and USDA sources (OIV, 2020; FAO et al., 2020; European Parliament and Council, 2018; USDA Agricultural Marketing Service, 2026). The protocol can be replicated in Scopus and Web of Science using the same strings.

Core search strings combined: (viticulture OR vineyard OR grapevine OR wine) AND (mineral amendment OR rock dust OR silicate rock powder OR remineralisation OR zeolite OR bentonite OR perlite OR alginite OR gypsum OR limestone OR dolomite); (vineyard soil health OR soil biodiversity OR arbuscular mycorrhiza OR rhizosphere OR microbial necromass); (organic viticulture OR regenerative viticulture OR cover crops OR compost OR circular economy); and (soil remediation OR heavy metal immobilisation OR salinity OR sodicity OR contamination). The main evidence window covered 2000-May 2026, while older historical sources were retained where they were foundational for traditional mineral amendment practice (Barton, 2018; Keating, 2007).

Eligibility, appraisal and synthesis

Sources were included when they provided direct evidence for viticulture or transferable evidence for perennial horticulture, soil remediation, mineral weathering, organic certification or soil biology. Purely promotional webpages, uncited product claims and public images without academic or technical documentation were excluded from the revised synthesis. Local geological descriptions were retained only when linked to agronomic performance, soil function, terroir or resource availability.

Each included source was charted by material, composition, particle-size relevance, soil pH and texture context, climate context, amendment rate where available, co-application with organic matter, measured or proposed outcomes, risks and transferability to organic vineyards. Greater weight was given to peer-reviewed field studies, multi-year experiments, vineyard-specific evidence, transparent regulatory documents and reviews with explicit methods. The synthesis distinguishes evidence-based recommendations from plausible hypotheses requiring field validation (Page et al., 2021; Peters et al., 2020; Tricco et al., 2018).



The workflow increases transparency while retaining narrative synthesis, because the evidence base includes heterogeneous field trials, reviews, regulations and local resource descriptions.

Figure 1. Structured workflow used for the partly protocol-based scoping narrative review. Source: own design based on PRISMA-ScR and JBI scoping-review principles (Tricco et al., 2018; Page et al., 2021; Peters et al., 2020).

NATURAL MINERAL AMENDMENTS: FUNCTIONS BEYOND NUTRIENT SUPPLY

Natural mineral soil amendments include ground silicate rocks, carbonate rocks, gypsum, zeolites, clay minerals, volcanic tuffs, perlite, vermiculite, alginite and humic mineral materials (Garbowski et al., 2023; Swoboda et al., 2022; Syed et al., 2021). They differ fundamentally in solubility, reactivity and ecological function. Carbonates and dolomite mainly regulate acidity and supply calcium and magnesium; gypsum supplies calcium and sulphur without strong liming; zeolites and bentonites increase cation retention and water-holding capacity; basaltic and other silicate rock powders release nutrients slowly and may support enhanced weathering; alginite and humic mineral materials combine mineral and organic functions (Fig. 2).

Natural mineral amendments should be evaluated beyond nutrient balance. Their effects are organised here into four overlapping functions. The first is chemical buffering: pH regulation, cation exchange, slow nutrient release and reduced nitrate or ammonium leaching. The second is physical habitat formation: improved aggregation, pore continuity, aeration, water retention and root exploration. The third is biological stimulation: microbial colonisation of mineral surfaces, rhizosphere weathering, AMF-supported nutrient uptake and microbial necromass stabilisation. The fourth is remediation and resilience: immobilisation of some potentially toxic elements, reduction of sodicity constraints, erosion resistance, carbon protection and drought buffering (Garbowski et al., 2023; Pan et al., 2023; Syed et al., 2021; Illera et al., 2003).

These functions are context-specific. A carbonate amendment that benefits an acidic sandy soil may induce iron, manganese or zinc deficiency in a calcareous vineyard. A basalt powder that is useful on highly weathered tropical soils may release nutrients too slowly for immediate correction of deficiency in a temperate vineyard. Zeolite may reduce leaching and improve water storage, but it cannot substitute for organic matter inputs or living roots. Consequently, the appropriate unit of analysis is not the amendment alone, but the amendment-soil-biota-vine-management system (Shaaban et al., 2015; Swoboda et al., 2022; Campisi et al., 2016; Cataldo et al., 2023).

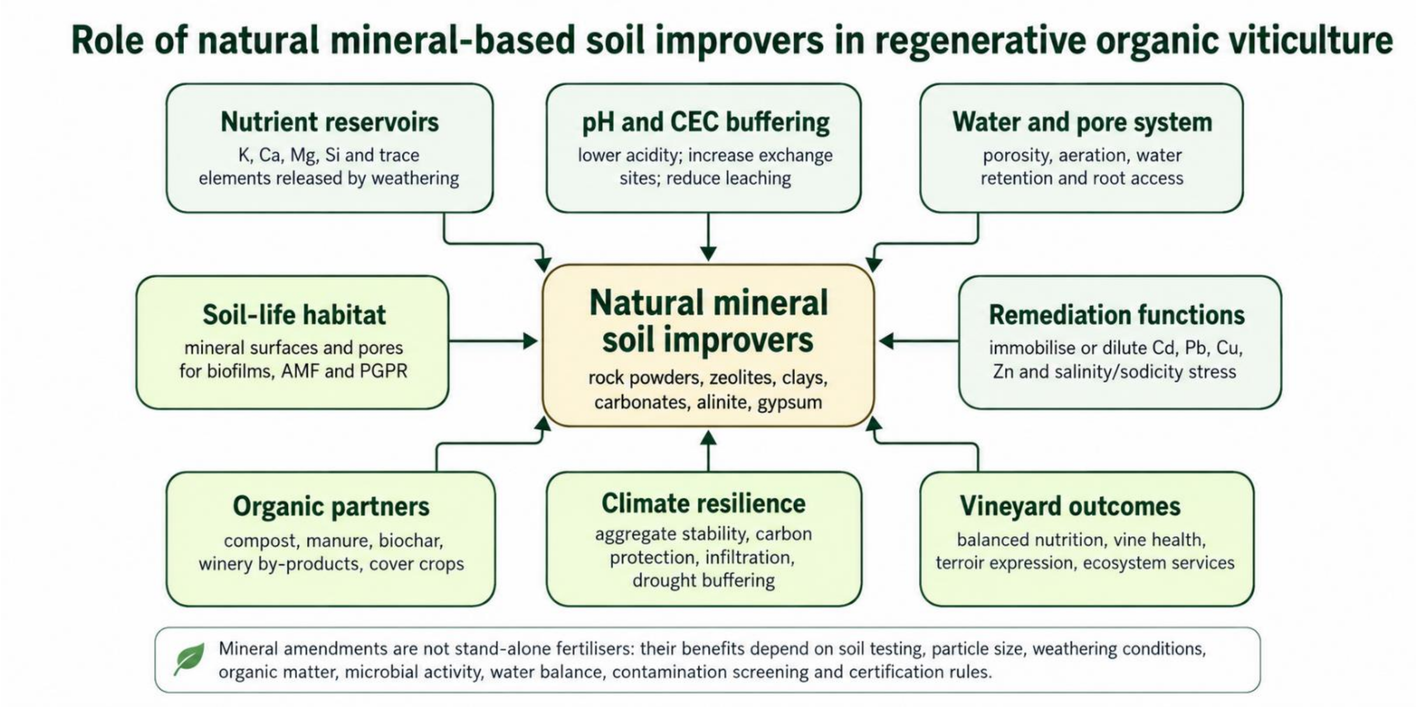


Figure 2. Functional role of natural mineral-based soil improvers in soil nutrition and ecosystem performance in multifunctional regenerative organic viticulture. Source: own design.

SOIL LIFE, MINERAL WEATHERING AND CLIMATE RESILIENCE

A vineyard soil is a living ecosystem formed by mineral particles, organic matter, water, air, roots, microbes, mesofauna and macrofauna (Fig. 3). Bacteria, fungi, archaea, protozoa, nematodes, mites, springtails, earthworms and arthropods form interacting food webs. These organisms decompose residues, transform nutrients, produce extracellular polymers, stabilise aggregates, build biopores and influence plant immunity. Soil minerals are not inert background material in this system; they are reactive surfaces on which organic compounds, enzymes, microbial cells and necromass are adsorbed and protected (FAO et al., 2020; Giffard et al., 2022; De Corato, 2020).

Arbuscular mycorrhizal fungi are especially important in grapevines because they extend the effective root system, improve phosphorus and micronutrient uptake, influence water relations and interact with root-associated bacteria. Plant-growth-promoting rhizobacteria, saprotrophic fungi and nitrogen-fixing bacteria support nutrient cycling and disease suppression. Mineral amendments can support these processes when they improve pH, reduce toxicity, supply limiting trace elements or provide porous habitats. They can also disrupt soil life if over-applied, contaminated, excessively alkaline or used as a substitute for organic matter and vegetation cover (Trouvelot et al., 2015; Nogales et al., 2021; Pagano and Dhar, 2016).

Climate resilience arises from this biological-mineral-organic coupling. Soils with stable aggregates, protected carbon, continuous pores and active biota infiltrate rainfall faster, store more plant-available water, resist crusting and erosion, and maintain rhizosphere function under drought and heat. Mineral amendments can contribute to these outcomes by improving structure, pH, CEC and water retention, but only within a management system that returns carbon through cover crops, mulches, compost, manure, biochar or winery by-products and reduces unnecessary disturbance (O'Brien et al., 2025; Mrunalini et al., 2022; Silvestroni et al., 2024; Pan et al., 2023).

COMPARATIVE EVALUATION OF AMENDMENT GROUPS

Table 1 replaces isolated material descriptions with a comparative synthesis. The comparative synthesis shows that natural mineral soil improvers should be understood not as interchangeable fertilisers, but as site-specific ecosystem amendments selected according to soil pH, texture, salinity/sodicity, organic-matter status, nutrient balance, microbial activity and local resource availability. Carbonate materials such as limestone, marl, calcareous tuff and dolomite mainly serve pH correction, Ca/Mg supply and structural improvement; gypsum is more appropriate for sodic or saline-sodic soils where Ca is needed without strong pH increase; silicate and volcanic materials such as basalt, rhyolite tuff, pumice and zeolites support slow remineralisation, cation exchange, water retention, microbial habitats and long-term resilience; while clay minerals, alginite and humic lignite products strengthen colloidal buffering, moisture storage, nutrient retention and remediation potential, especially when combined with compost, cover crops or winery by-products.

Application rates should therefore be treated as indicative ranges reported in practice or trials, not universal prescriptions: certified organic use requires local soil testing, product analysis, contaminant screening and certifier approval before field application (Garbowski et al., 2023; Swoboda et al., 2022; Cataldo et al., 2023; Chaganti et al., 2015; Al-Taey et al., 2023; Brindza et al., 2021; Mehrez et al., 2011).

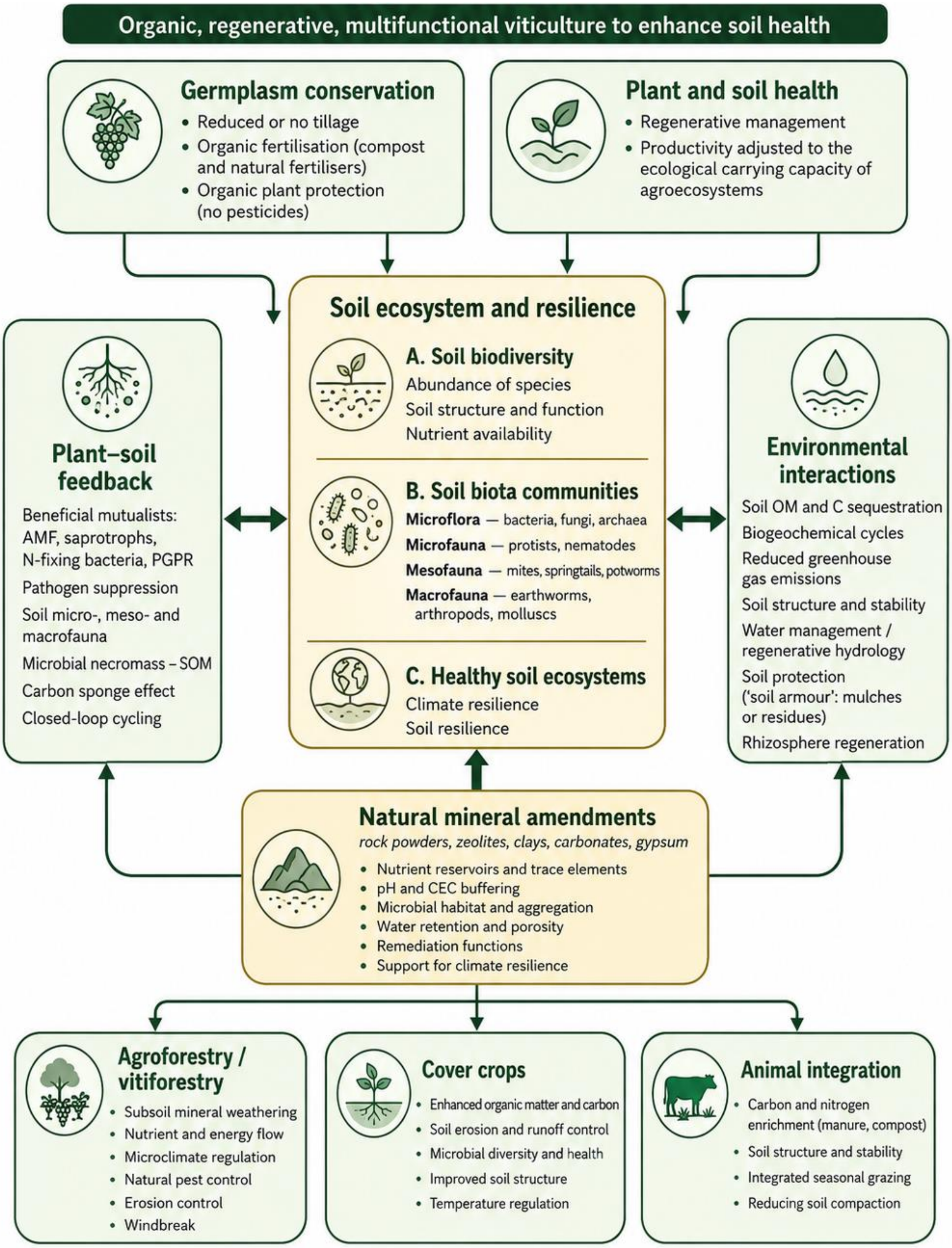


Figure 3. Soil-life feedbacks in organic and regenerative multifunctional viticulture, showing interactions among soil biota, cover crops, vitiforestry, animal integration, organic fertilisation, with particular emphasis on natural mineral amendments, soil structure, water management and climate resilience. Source: own design based on cited literature (FAO et al., 2020; Giffard et al., 2022; Trouvelot et al., 2015; O'Brien et al., 2025).

Table 1. Comparative functions, suitable contexts and cautions for natural mineral soil amendments in organic viticulture.

Amendment group	Main constituents / properties	Primary ecosystem functions	Best-fit vineyard contexts	Cautions and trade-offs	Application logic
Limestone, marl, calcareous tuff	$CaCO_3$; neutralising value; variable texture	Raise pH, supply Ca, improve aggregation in acid soils, reduce Al/Mn toxicity	Acidic sandy or leached soils; low Ca status; pH correction before planting	Over-liming can induce Fe, Mn, Zn and B deficiency; low relevance on calcareous soils	Based on pH, buffer capacity and lime requirement; incorporate before planting or apply in maintenance doses
Dolomite	$CaMg(CO_3)_2$; liming plus Mg	pH correction, Mg supply, structural improvement; possible N_2O mitigation in acid soils	Acidic soils with Mg deficiency or low Ca/Mg balance	Avoid where Mg is already excessive or soil is calcareous; slow reaction if coarse	Use after soil and petiole diagnosis; monitor K-Mg-Ca antagonisms
Gypsum and anhydrite	$CaSO_4$; soluble Ca and S with limited pH increase	Improve sodic soil structure, supply Ca/S, support infiltration	Sodic or saline-sodic soils; crusting or dispersion; some subsoil Ca needs	Not a general fertiliser; requires drainage/leaching; may increase salinity temporarily	Combine with water management, organic matter and monitoring of EC/SAR
Basalt, mafic and ultramafic rock powders	Silicate minerals; Ca, Mg, Fe, Si, trace elements; alkaline potential	Slow remineralisation, pH buffering, potential enhanced weathering, micronutrient supply	Highly weathered or nutrient-poor soils; compost blends; long-term soil building	Variable weathering; possible Ni, Cr, Co or other contaminants; mining/transport footprint	Use fine particle sizes with compost or cover-crop rhizospheres; require heavy-metal analysis
Rhyolite tuff, volcanic ash, pumice	Silica-rich pyroclastics; alkali feldspar, glass, pumice; variable zeolitisation	Improve texture, porosity, water retention; slow K and trace-element release	Sandy, drought-prone or low-CEC soils; local volcanic terroirs	Slow nutrient release; excessive local geological detail is not agronomic evidence	Use where locally available; evaluate CEC, water retention and vine response
Natural zeolite / clinoptilolite	Porous aluminosilicate with high CEC and molecular channels	Retain NH4+, K+ and water; reduce leaching; provide microbial pore habitat	Light-textured soils; nutrient leaching; compost-mineral blends; drought buffering	May immobilise nutrients temporarily; quality varies; not a substitute for organic matter	Apply alone at modest rates or co-compost with winery waste/compost; monitor N and K
Bentonite and clay minerals	Montmorillonite-rich clays; high swelling and CEC	Increase CEC, water retention, aggregate stability and nutrient retention	Sandy soils, low colloid content, low water-holding capacity	Sodium bentonite can disperse soil; handling and swelling affect structure	Prefer Ca-bentonite where dispersion risk exists; combine with compost and soil testing
Perlite and vermiculite	Expanded volcanic glass or phyllosilicate; high porosity/water retention	Improve aeration, drainage, rooting media and water storage	Nursery substrates, young vines, container production, localised planting pits	Energy cost of expansion; limited field-scale feasibility; not nutrient-rich	Use mainly in propagation or targeted establishment zones rather than broadacre vineyard application
Alginite and humic mineral materials	Organic-mineral sediment; humic substances, clay, Ca/Mg, trace elements; variable NPK	Water retention, organic-mineral colloids, microbial activity, slow nutrient buffering	Local Central European resources; sandy or low-organic-matter soils; compost blends	Composition varies by deposit; avoid product claims without independent analysis	Use as local resource after chemical, microbiological and contaminant testing
Humic lignite products (e.g., Dudarit-type)	Humic acids with mineral nutrients; lignite-derived organic-mineral matrix	CEC and nutrient buffering, carbon input, remediation support in blends	Local use where independently tested; degraded soils needing humic colloids	Alkaline activation and product claims require peer-reviewed or certified data; contamination control essential	Treat as site-specific organic-mineral amendment; verify pH, EC, heavy metals and field response

DECISION MATRIX BY SOIL CONSTRAINT

A practical recommendation should start from diagnosis rather than from product availability. Effective soil management must always prioritize diagnostic data over marketing promises. Selecting amendments based on current product availability rather than real soil deficiencies leads to wasted money, nutrient imbalances, and potential crop damage. Vineyard soil analysis, petiole or leaf analysis, infiltration tests, aggregate stability, organic matter, pH, electrical conductivity, exchangeable sodium, potentially toxic elements and biological indicators should guide amendment choice. Table 2 summarises a diagnostic decision matrix (Ames and Dufour, 2017; Dufour, 2006; Cataldo et al., 2021; García-Navarro et al., 2023).

Table 2. Soil-constraint-based decision matrix for mineral amendments in organic vineyards.

Dominant constraint	Priority diagnostics	Mineral amendment options	Regenerative partners	Expected outcome	Monitoring
Acidic, leached soil	pH, exchangeable acidity, Al/Mn, Ca/Mg, CEC	Limestone, dolomite, marl; selected basalt if contaminant-safe	Compost, cover crops, reduced tillage	pH buffering, Ca/Mg supply, improved root environment	pH, micronutrients, vine vigour, petiole Mg/K/Ca
Calcareous soil with micronutrient limitation	pH, active lime, Fe/Mn/Zn/B, chlorosis	Avoid additional carbonates; use compost-mineral blends, zeolite or clay only if justified	Organic matter, rootstock choice, microbial inocula where evidence supports	Better micronutrient availability through biological cycling rather than liming	Leaf chlorosis, Fe/Zn/Mn, yield and quality
Sandy low-CEC soil	Texture, CEC, organic carbon, water retention	Bentonite, zeolite, alginite, fine volcanic tuff	Compost, biochar, mulches, permanent or seasonal cover crops	Higher CEC, water storage, microbial habitat and nutrient retention	CEC, infiltration, plant-available water, microbial activity
Compaction and low infiltration	Bulk density, penetration resistance, aggregate stability, infiltration	Gypsum if sodic; porous volcanic amendments where locally available	Deep-rooted covers, reduced traffic, organic mulches, compost	Improved pore continuity and erosion resistance	Infiltration, runoff, root depth, earthworms
Saline-sodic conditions	EC, SAR/ESP, pH, drainage, irrigation water quality	Gypsum/anhydrite; sometimes acidifying organic inputs; avoid indiscriminate liming	Leaching, drainage, salt-tolerant covers, organic matter	Ca-driven flocculation and reduced dispersion where drainage exists	EC/SAR, infiltration, vine stress, salt ions
Heavy-metal legacy or contamination	Total and bioavailable Cu, Zn, Cd, Pb, Ni, Cr; pH; organic matter	Zeolite, bentonite, Fe/Mn-rich minerals, lime or gypsum depending on pH	Biochar, compost, phytostabilising covers, erosion control	Reduced bioavailability and leaching risk; immobilisation rather than removal	Bioavailable metals, soil biota, cover-crop establishment
Drought-prone vineyard	Soil depth, plant-available water, infiltration, vapour-pressure deficit	Zeolite, bentonite, alginite, perlite in establishment zones, tuff where local	Mulch, cover-crop timing, compost, vitiforestry where water competition is controlled	Improved water buffering and root-zone stability	Stem water potential, yield stability, soil moisture, carbon
Nutrient-poor but biologically active soil	Petiole nutrients, pH, CEC, organic matter, microbial respiration	Rock dusts, zeolite-compost blends, alginite/humic minerals	Compost, winery residues, legumes, AMF-supportive management	Slow nutrient release and tighter nutrient cycling	Petiole nutrients, microbial biomass, yield/quality

LOCAL RESOURCES AND INTERNATIONAL RELEVANCE

Hungary and the Carpathian-Pannonian region are treated here as a case of local resource availability rather than as the whole scope of the review. The region has important volcanic and sedimentary resources, including rhyolitic tuffs, zeolitised tuffs, basaltic materials, bentonites, alginite and humic lignite-derived products. These materials are relevant because local sourcing can reduce transport impacts and connect vineyard soil management to regional terroir, but local occurrence alone does not prove agronomic value (Solt et al., 2007; Solti, 1987; Szepesi et al., 2024; Manaljav et al., 2021; OIV, 2010; van Leeuwen et al., 2018).

Alginite is therefore presented as an organic-mineral sediment with potential benefits for water retention, colloid supply and nutrient buffering, not as a uniquely Hungarian material (Solti, 1987; Brindza et al., 2021). Deposits or analogous algal/humic mineral sediments occur in several regions; what matters for organic viticulture is independent analysis of organic matter, carbonate content, CEC, nutrient composition, water-holding capacity, contaminant levels and field response (Osman, 2018; Convention on Wetlands, 2021; van der Merwe et al., 2022). Similarly, Dudarit-type humic lignite products are treated as local humic mineral amendments whose claims require transparent product composition and vineyard trials (Nagy et al., 2020).

International studies broaden the relevance of the review. Zeolite and compost combinations have been tested in Sangiovese vineyards, where clinoptilolite and winery-waste compost improved soil management and grapevine eco-physiology (Cataldo et al., 2023). Silicate rock powders have been evaluated in Brazil, temperate Europe and North America, with evidence that benefits depend strongly on rock type, weathering environment and particle size (Ramos et al., 2014; Benevides Filho et al., 2023; Luchese et al., 2023; Skov et al., 2024; Richardson, 2025; Tetsopgang and Tagne, 2024). Perlite, vermiculite and bentonite studies in horticultural and sandy soils show water-retention and leaching-control mechanisms that can be transferred cautiously to vineyard establishment or targeted soil improvement (Mehrez et al., 2011; Güneri and Yukselen-Aksoy, 2022; Alshamary et al., 2021; Alobaidy et al., 2024; Al-Taey et al., 2023; Hussain et al., 2022). These examples show why comparative mechanisms are more useful than isolated descriptions of single deposits.

MINERAL AMENDMENTS, SOIL REMEDIATION AND CARBON

Carbon terminology is important in evaluating mineral amendments. Soils do not sequester CO_2 as gas in the ordinary agronomic sense; they store carbon in organic matter, microbial necromass, mineral-associated organic matter and, in some contexts, inorganic carbonates. Silicate weathering can consume CO_2 and may contribute to inorganic carbon pathways, but the magnitude and permanence depend on mineralogy, climate, hydrology and verification methods. In vineyard practice, the most immediate climate-resilience benefit is often improved soil carbon protection, aggregation and water buffering rather than claimable carbon dioxide removal (Swoboda et al., 2022; Skov et al., 2024; Richardson, 2025; Syed et al., 2021).

Remediation is another important function. Lime, gypsum, zeolite, bentonite, biochar and compost-mineral mixtures can reduce the mobility or bioavailability of Cd, Pb, Cu, Zn and other elements by pH adjustment, sorption, ion exchange, precipitation or complexation. In vineyards this is relevant to long-term copper accumulation from fungicide use, contamination from mining or industrial dust, and erosion-driven movement of contaminated particles. Immobilisation should not be presented as removal; it reduces exposure and leaching risk only while soil conditions remain stable (Illera et al., 2003; Chaganti et al., 2015; Tiecher et al., 2018; Brunetto et al., 2024; Manaljav et al., 2021).

Aluminium toxicity should be interpreted in its proper context. In calcareous and moderately neutral vineyard soils, soluble aluminium is generally not a practical constraint. It becomes relevant mainly in strongly acidic soils, where liming, organic matter and rootstock choice can reduce risk (Shaaban et al., 2015; Christensen et al., 2003; Pou et al., 2022). Aluminium-related statements should therefore not be generalised to most Mediterranean or continental vineyards.

CIRCULAR BIOECONOMY: WINERY BYPRODUCTS AS ORGANIC PARTNERS

Mineral amendments become more effective when combined with organic inputs that feed soil biota and drive rhizosphere weathering. Viticultural and winery residues provide a practical circular-economy pathway (Brito et al., 2024; Lampraki et al., 2023; Trooien and Hills, 2007). Vine shoots supply lignocellulosic biomass and minerals; grape stalks contain lignified tissues and tannins; grape pomace contributes skins, seeds, residual sugars, phenolics and fibre; wine lees contain dead yeast cells, polysaccharides, proteins, tartaric compounds and inorganic material. These residues can be composted, vermicomposted, co-composted with zeolite or transformed into biochar, while higher-value extraction of phenolics, other bioactive compounds or grape-seed oil can precede the return of residues to soil (Szmidt and Ferguson, 2004; Li et al., 2020).

Co-composting with zeolite or rock powders can reduce nutrient losses during composting, retain ammonium, improve moisture conditions and create organo-mineral complexes. This is especially consistent with ecological cycles because it links waste valorisation, local resource use, soil biodiversity and reduced off-farm input dependence. However, the approach requires hygienisation, salt and copper monitoring, maturity assessment, weed-seed and pathogen control, and logistics adapted to small and medium-sized wineries (Campisi et al., 2016; Cataldo et al., 2023; Szmidt and Ferguson, 2004; Li et al., 2020).

ORGANIC CERTIFICATION, ECONOMICS AND IMPLEMENTATION

Organic certification does not automatically approve every natural mineral amendment. EU organic production is governed by Regulation (EU) 2018/848 and implementing lists of authorised inputs, while USDA organic production requires a soil fertility and crop nutrient management plan that maintains or improves the physical, chemical and biological condition of soil and uses allowed materials under the National List (European Parliament and Council, 2018; Commission Implementing Regulation (EU) 2021/1165, 2021; USDA Agricultural Marketing Service, 2026; Ames and Dufour, 2017). In practice, growers must document the source, processing, additives, contamination status and purpose of each material. Mined minerals and natural substances may still be restricted if they are chemically treated, contaminated, highly soluble in a prohibited way or not listed by the certifier.

Economic feasibility depends on local availability, transport distance, grinding or activation cost, application equipment, labour, organic certification documentation and expected time to benefit. The slow release of many mineral amendments means that immediate yield responses may be small, while benefits may appear through risk reduction, soil structure, drought buffering or reduced nutrient loss. For this reason, economic assessment should include avoided erosion, improved vine longevity, lower leaching, reduced irrigation demand, waste valorisation and resilience value, not only short-term fertiliser substitution (OIV, 2020; Brito et al., 2024; Garbowski et al., 2023; O'Brien et al., 2025).

Application logistics matter in vineyards. Steep slopes, narrow rows, erosion risk, machinery access and the perennial root system limit incorporation. Maintenance applications should avoid dust drift, compaction and runoff (Faraone and Hillier, 2020; Ames and Dufour, 2017). Pre-planting offers the best opportunity for deeper incorporation, while established vineyards often require surface application with mulch, compost, undervine vegetation or targeted bands. Foliar fertilisers may correct acute deficiencies, but they do not replace soil rebuilding (Dufour, 2006; van Leeuwen et al., 2018; Cataldo et al., 2021).

ENVIRONMENTAL RISKS AND TRADE-OFFS

Natural mineral-based soil improvers have significant environmental risks and trade-offs, primarily involving heavy metal contamination, high carbon footprints from mining and transport, and slow ecosystem disruption. While they avoid the synthetic chemical downsides of artificial fertilizers, their "natural" label does not mean they are entirely eco-friendly (Garbowski et al., 2023; Swoboda et al., 2022; Firat, 2024). The primary environmental risks and trade-offs associated with mineral-based soil amendments:

1. Contamination screening is essential, especially for mining residues, ultramafic rocks and industrial by-products that may contain Ni, Cr, Co, Cd, Pb, As or radionuclides (Swoboda et al., 2022; Brunetto et al., 2024; Tiecher et al., 2018).
2. Over-mineralisation or over-liming can shift pH and nutrient ratios, creating micronutrient deficiency or vine imbalance (Villette et al., 2020; Bai et al., 2024).
3. Quarrying, grinding, drying, thermal expansion of perlite or vermiculite and transport have ecological footprints that must be weighed against agronomic benefits (Garbowski et al., 2023; OIV, 2020).
4. Amendment effects can be slow. A grower facing an acute deficiency cannot assume that rock powder will release nutrients in the same season (Swoboda et al., 2022; Benevides Filho et al., 2023; Richardson, 2025).
5. Mineral amendments can interact with water stress. Cover crops and organic amendments may improve soil function, but they can also compete for water in dry regions if species selection and termination are not adapted (Silvestroni et al., 2024; O'Brien et al., 2025).
6. Remediation by immobilisation may be reversible if soil pH, redox conditions or organic matter change. These trade-offs support a monitoring-based and place-specific approach rather than a universal prescription (Illera et al., 2003; Chaganti et al., 2015).

DISCUSSION

The main contribution of this review is the integration of natural mineral amendments into a living-soil and climate-resilience framework for organic viticulture. Alginite, Dudarit-type humic lignite products, zeolite and local volcanic materials are therefore not presented as isolated narratives; they are evaluated through mechanisms that can be tested across regions: pH buffering, CEC, pore habitat, water retention, organic-mineral carbon protection, microbial activity, nutrient release, remediation and certification feasibility (De Corato, 2020; Garbowski et al., 2023; Cataldo et al., 2021; Swoboda et al., 2022).

A central insight is that mineral amendments and soil organic matter should be co-designed. Minerals without carbon inputs do not regenerate soil life; organic inputs without mineral surfaces may be more vulnerable to decomposition and nutrient leaching. Their combination can support microbial necromass stabilisation, aggregate formation and slow nutrient cycling. This is why co-composting winery residues with zeolite or rock powders is particularly promising for circular organic viticulture (Syed et al., 2021; Li et al., 2020; Cataldo et al., 2023; Szmidt and Ferguson, 2004).

The review also clarifies the role of local resources. Local minerals are strategically important when they reduce dependence on imported fertilisers and connect soil management to place-based terroir (OIV, 2010; van Leeuwen et al., 2018; Szepesi et al., 2024). However, local identity must be backed by analysis and field performance. Future vineyard trials should report baseline soil properties, amendment composition, particle size, application rate, co-amendments, weather, vine water status, petiole nutrients, microbial indicators, soil fauna, yield, grape composition, economics and contamination risk (Nagy et al., 2020; Cataldo et al., 2023; Richardson, 2025).

LIMITATIONS AND FUTURE RESEARCH

This review has limitations. The evidence base is heterogeneous and many studies are outside viticulture, so transferability must be evaluated carefully. Several materials have strong mechanistic plausibility but limited replicated vineyard data. Some local products have been described in technical or regional literature but lack independent peer-reviewed trials. Application rates are often reported inconsistently, and long-term effects on wine quality, microbial communities, carbon stability and economics remain insufficiently documented (Swoboda et al., 2022; Cataldo et al., 2023; Richardson, 2025; Nagy et al., 2020).

Future research should prioritise:

1. multi-year vineyard trials across acidic, calcareous, sandy, clayey, saline and contaminated soils (Cataldo et al., 2023; Richardson, 2025);
2. standard reporting of amendment composition, particle size and contaminants (Swoboda et al., 2022; Brunetto et al., 2024);
3. combined mineral-organic treatments including composted winery residues, biochar and cover crops (Li et al., 2020; Lampraki et al., 2023; Szmidt and Ferguson, 2004);
4. microbial, AMF, soil fauna and microbial necromass indicators (FAO et al., 2020; Trouvelot et al., 2015; Nogales et al., 2021);
5. climate-resilience metrics such as infiltration, plant-available water and heat/drought response (O'Brien et al., 2025; Pan et al., 2023);
6. life-cycle assessment of mining, processing and transport (Garbowski et al., 2023; Brito et al., 2024);
7. economic analysis including ecosystem services (OIV, 2020; Mrunalini et al., 2022); and
8. clear guidance for EU, USDA and other organic certification systems (European Parliament and Council, 2018; Commission Implementing Regulation (EU) 2021/1165, 2021; USDA Agricultural Marketing Service, 2026).

CONCLUSIONS

Natural mineral soil amendments can contribute to organic viticulture when they are used as part of a soil ecosystem strategy rather than as simple fertiliser replacements. Their value lies in the interaction between mineral nutrients, reactive surfaces, organic matter, microbial life, root activity, water dynamics and climate resilience. Carbonates, gypsum, silicate rock powders, zeolites, clays, perlite, vermiculite, alginite and humic mineral materials each have specific functions and limitations; none should be recommended without soil diagnosis and material testing.

The strongest pathway for multifunctional regenerative organic viticulture is the integrated use of local mineral resources with compost, winery by-products, cover crops, reduced tillage, mulching, vitiforestry where suitable, and monitoring of soil biology and vine nutrition. Such systems can improve nutrient retention, water buffering, soil structure, microbial habitat, remediation capacity and resilience to drought and heavy rainfall. They can also reduce dependence on off-farm synthetic inputs and support circular economy in the wine sector.

Implementation requires caution. Slow nutrient release, contamination risk, over-liming, cost, logistics, certification rules and extraction impacts must be assessed. The revised framework therefore supports a practical but critical position: natural mineral soil improvers are important tools for ecological viticulture, but their success depends on evidence-based, locally adapted and biologically informed management.

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