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RESEARCH ARTICLE

Soil biological activity and nutrient dynamics under contrasting vineyard management systems

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ABSTRACT

Cultural management practices in vineyards (*Vitis* spp.) significantly influence soil quality. Nevertheless, the impact of these practices on soil quality within Chile’s heritage vineyards remains largely unexplored. This study sought to assess the effects of two distinct management practices—organic and conventional—on soil quality in vineyards located in the Itata Valley, Ñuble Region. The investigation focused on microbiological variables, including microbial biomass, basal respiration, and enzymatic activities associated with the C, N, P, and S cycles, as well as chemical variables such as pH, organic matter, available nutrients, and total soil trace elements. Additionally, the study examined the influence of varying durations of organic management (2 to 11 yr) on soil quality parameters. Organic management was found to significantly enhance soil biological activity, as indicated by increased basal respiration, microbial biomass, and key enzymatic activities related to the C, N, P, and S cycles, with improvements ranging from two- to 3.2-fold ($P < 0.05$) compared to conventional management. Conversely, conventionally managed vineyards exhibited higher soil nutrient availability, including nitrate (58%) and sulfate (95%), than their organically managed counterparts. Soil quality has improved with extended periods of organic management. Over the span of 2 to 11 yr of organic management, there were significant increases in pH and Ca ($P < 0.05$), while Cd levels decreased by 25%. Consequently, organic management is superior for the sustainability of heritage vineyards, as it increases soil biological activity by up to 3.2-fold and reduces heavy metals such as Cd by 25% after 11 years of implementation.

Key words: Heavy metals, microbial biomass, soil enzymatic activity, soil quality, sustainable management, *Vitis* spp.

INTRODUCTION

The global area devoted to vineyards (*Vitis* spp.) is 7.1 million hectares, making it one of the most important sectors (OIV, 2024). Latin America has become a center of wine production because of its ancestral importance, agroecological practices, and implementation of climate change adaptation strategies (Gutiérrez-Gamboa and Fourment, 2025). The Itata Valley, located in the Ñuble Region of Chile, is one of the oldest valleys and covers an area of 3660.10 km^2. This valley is associated with the lower basin of the Itata River and has a wine appellation of origin. Wine production in this sector has great historical value, with the largest number of vineyards in Chile, averaging 2 ha, with traditional grape (*Vitis vinifera* L.) varieties such as 'País', 'Cinsault', and 'Muscat of Alexandria', grown on slopes and head-trained vines (Serra et al., 2024). In terms of soil and climate characteristics, the Itata Valley presents challenging conditions, such as dryland areas, typically clay soils with slow infiltration, and steep slopes of 20% to 30%, making them highly susceptible to erosion (Serra et al., 2024). On the other hand, these vineyards stand out for their high variations in management practices, such as fertilization, weed control, cover crops, and pest and disease control. In this regard, it has been widely demonstrated that maintaining vineyards with better-quality soils supports berry yield and quality (Visconti et al., 2025). Despite this, the study of different management systems on soil health has been scarcely evaluated in Itata Valley vineyards.

Organic and conventional vineyard management systems have been widely compared worldwide due to their contrasting effects on soil fertility, biodiversity, and ecosystem services. In terms of production and ecosystem services, organic management in vineyards has been shown to promote soil quality and C sequestration compared to conventional systems. For example, a recent study comparing organically and conventionally managed vineyards found that soils under organic fertilization stored around 33 Mg ha^{-1} C in 1 yr and exhibited approximately twice the labile C stocks compared to conventional vineyard soils (Fracetto et al., 2024). Similarly, after the transition from a conventional to an organic system, there was a significant increase in the activity of soil enzymes related to the C and P cycles, such as α-, β-glucosidase, β-1,4-glucosidase, β-D-cellobiohydrolase, β-xylosidase, and phosphomonoesterase (Serrano-Grijalva et al., 2024). In addition to improving the nutrient cycle, organic management can modify soil chemical conditions in ways that influence the behavior and distribution of trace elements (Shen et al., 2025). Consequently, soil improvements under organic management can enhance grapevine growth by supporting plant water status and photosynthetic performance (Gutiérrez-Gamboa and Fourment, 2025). However, organic vineyard management may also involve certain challenges, such as higher labor requirements, lower initial yields, and increased input costs (Merot and Smits, 2020).

In vineyard systems, conventional and organic management practices can differentially influence soil health; however, comparative assessments remain limited, particularly regarding the effects of long-term organic management. Therefore, this study evaluated the impact of contrasting vineyard management systems (conventional *vs*. organic) on soil chemical fertility and biological activity, including basal soil respiration and enzymatic activities associated with the C, N, P, and S cycles. In addition, the influence of the duration of organic management (2, 3, and 11 yr) on soil quality indicators was assessed.

We hypothesized that (i) organic management enhances soil biological activity relative to conventional systems, (ii) soil enzymatic activity increases with longer periods under organic management, and (iii) conventionally managed vineyards exhibit higher short-term nutrient availability.

MATERIAL AND METHODS

Vineyard selection and soil sampling

Vineyards producing wine grapes (*Vitis vinifera* L.) in the Itata Valley were selected under two management systems: Conventional and organic (Figure 1). Four vineyards were selected for conventional management practices. The selection criteria for conventional vineyards included inorganic fertilization, weed control with chemical herbicides, and phytosanitary control with synthetic products, with a management continuity of ≥ 36 yr (Table 1). Three vineyards were selected for organic management. The organic vineyards have implemented organic fertilization, mechanical weed control, phytosanitary control with certified organic products, and additional organic management practices, such as green corridors and the introduction of animals. The organic treatments had certified continuity of management for 2, 3, and 11 yr (Table 1). The number of vineyards reflects the limited availability of certified organic vineyards in the study area.

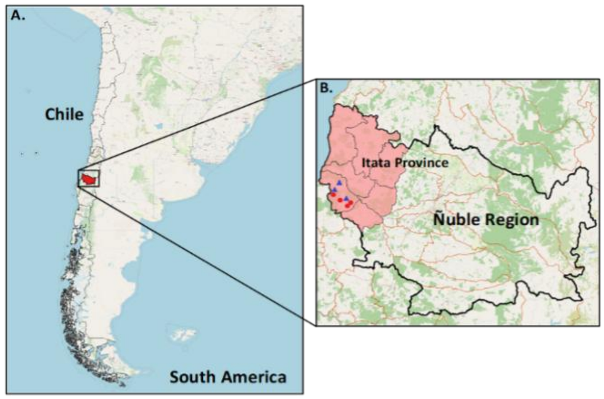

Figure 1. A) Map of Chile in South America; B) Itata Province in the Ñuble Region, Chile, with study sampling areas, conventional management (blue triangle) and organic management (red circle).

Table 1. Characteristics of selected vineyards in the Itata Valley, Ñuble Region, Chile.

Cultivar	Rootstock	Planting year	Coordinates	Management type	Duration of management	Specific management practices
Cinsault	Ungrafted	1950	-36.580492, -72.691952	Organic	2 yr	Control organic fertilization, natural weed cover, phytosanitary with certified organic products, and additional organic management practices
Cinsault	Ungrafted	1960	-36.585062, -72.672746	Organic	3 yr	Organic fertilization, lupine cover, phytosanitary control with certified organic products, and additional organic management practices
Cinsault	Ungrafted	1986	-36.576766, -72.655199	Organic	11 yr	Organic fertilization, mechanical weed control mix with natural cover, phytosanitary control with certified organic products, and additional organic management practices, green corridors and the introduction of animals
Cinsault	Ungrafted	1990	-36.562204, -72.664528	Conventional	36 yr	Inorganic fertilization, plowed soil, pest and disease management based on synthetic phytosanitary products, under conventional viticultural management
Cinsault	Ungrafted	1986	-36.576454, -72.651469	Conventional	40 yr	Inorganic fertilization, weed control with chemical herbicides, pest and disease management based on synthetic phytosanitary products, under conventional viticultural management
Cinsault	Ungrafted	1985	-36.577094, -72.697435	Conventional	41 yr	Inorganic fertilization, plowed soil, pest and disease management based on synthetic phytosanitary products, under conventional viticultural management
Cinsault	Ungrafted	1950	-36.580068, -72.689598	Conventional	76 yr	Inorganic fertilization, weed control with chemical herbicides, pest and disease management based on synthetic phytosanitary products, under conventional viticultural management

Each soil sample consisted of four subsamples collected within each vineyard and subsequently homogenized. Soil samples were collected on 15 October 2024 from seven vineyards (four conventional and three organic) (Kovács et al., 2020). In each vineyard, three composite samples were collected between vine rows at a depth of 0-0.3 m, resulting in a total of 21 samples (12 conventional and 9 organic). After collection, soil samples were placed in sterile plastic bags and stored in a cooler with ice packs during field transport. The soils were classified as Alfisols according to USDA Soil Taxonomy (Soil Survey Staff, 2006). Each composite sample was homogenized and divided into two subsamples of 500 g each for microbiological and chemical analyses. Soil samples for microbiological analysis were stored at 4 °C until further analysis.

Microbiological analyses of soil

The activity of six soil enzymes related to the C (protease and β-glucosidase), N (dehydrogenase and urease), P (phosphatase), and S (arylsulfatase) cycles was measured. Dehydrogenase activity was determined following García et al. (1997) by incubating soil samples with iodonitrotetrazolium chloride (INT) and quantifying the formation of iodonitrotetrazolium formazan (INTF) colorimetrically. Results were expressed as μg INTF g^{-1} dry soil.

The enzymatic activities of protease, β-glucosidase, urease, and acid phosphatase were determined according to Nannipieri et al. (1980). Briefly, soil samples were incubated with specific substrates under controlled temperature and time conditions, and the products released during the enzymatic reactions were quantified spectrophotometrically. Urease and protease activities were expressed as μmol NH_4^+ g^{-1} h^{-1}, while β-glucosidase and phosphatase activities were expressed as μmol *p*-nitrophenol (PNP) g^{-1} h^{-1}.

Arylsulfatase activity was determined following Tabatabai and Bremner (1970) by incubating soil with *p*-nitrophenyl sulfate and measuring the *p*-nitrophenol released during the reaction. Results were expressed as μmol PNP g^{-1} h^{-1}.

Basal soil respiration was determined as described by Joergensen (1995) and expressed as μg CO_2 g^{-1} h^{-1}. Soil microbial C biomass was assessed using the substrate-induced respiration (SIR) method after glucose was added to the soil. The conversion of the amount of CO_2 emitted into microbial biomass C was performed using the equation developed by Anderson and Domsch (1978). Soil respiration and soil microbial biomass C were determined using an automatic analyzer (μ-TRAC 4200, SY-LAB, Purkersdorf, Austria).

Bulk density, available and total elements in the soil

Soil bulk density was measured using the core method described by Sandoval et al. (2012), in which undisturbed soil samples of known volume were collected, oven-dried, and weighed to calculate soil mass per unit volume (g cm^{-3}).

Soil chemical analyses were performed according to the standardized procedures described by Sadzawka et al. (2006). Briefly, soil samples were extracted using appropriate chemical extractants to determine available nutrients. Nitrate (NO_3^-), ammonium (NH_4^+), available N, available P, and available K were expressed in mg kg^{-1}, whereas exchangeable K and exchangeable Al were expressed in $cmol_{(+)}$ kg^{-1}. Organic matter content was determined as a percentage (%) using the standard oxidation method. Soil pH was measured in a soil-water suspension (1:5, w/v) using a digital pH meter (Hanna Instruments, Woonsocket, Rhode Island, USA).

Dissolved organic C (DOC) was determined using a total organic C (TOC) analyzer (TOC-L, Shimadzu, Kyoto, Japan) after aqueous extraction of soil samples. Anions such as Cl^-, NO_2^-, NO_3^-, and SO_4^{2-} were quantified by ion chromatography using a Dionex ICS-1100 system (Thermo Fisher Scientific, Sunnyvale, California, USA).

Total elemental concentrations in the soil were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) using an iCAP 6300 DUO radial spectrometer equipped with a CETAC ASX-520 autosampler (Thermo Fisher Scientific, Illkirch, France) after acid digestion of soil samples. Seventeen elements were quantified, including macronutrients (P, K, Mg, S, Ca), micronutrients (Cu, Fe, Mn, Zn, Ni, B), and non-essential elements and heavy metals (As, Cd, Pb, Ti, Co, Cr).

Statistical analysis

The data were subjected to an ANOVA. Means were compared using Fisher's least significant difference (LSD) test at a significance level of 0.05. To discriminate between the chemical and microbiological variables of the soil between vineyard management practices, principal component analysis (PCA) and correlations were performed using RStudio software, version R 4.5.1 with the FactoMineR and ggplot2 packages (R Foundation for Statistical Computing, Vienna, Austria). To analyze the effect of years of organic management on the variables (soil chemical and microbiological), a linear regression was performed, selecting those with a coefficient of determination (R^2) ≥ 0.4. The R^2 was used to assess the extent to which the duration of organic management explains the observed variability in soil quality indicators. Permutational multivariate analysis of variance (PerMANOVA) was performed to analyze differences in variables between the vineyard management practices.

RESULTS

Soil microbiological activity

Soil microbiological activity was significantly influenced by vineyard management practices (Figure 2). Organic management consistently exhibited higher values across all evaluated enzymatic indicators, with activities of dehydrogenase, urease, protease, phosphatase, β-glucosidase, and arylsulfatase being 3.2-, 2.7-, 2.0-, 2.0-, 2.2-, and 2.7-fold greater, respectively, than those observed under conventional management. Additionally, basal soil respiration and microbial biomass were markedly enhanced under organic management, showing increases of 2.0- and 2.7-fold, respectively, compared to the conventional system.

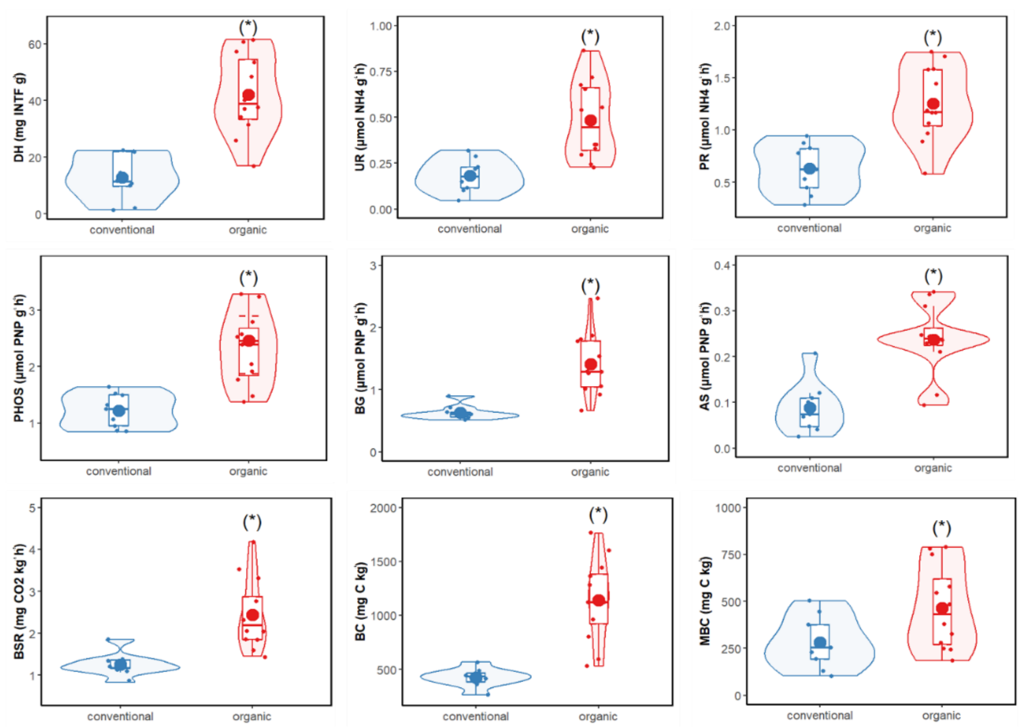

Figure 2. Boxplot of soil biological parameters under two vineyard management systems (conventional n = 9; organic n = 12). In the boxplot, Q1 to Q3: Interquartile range; middle line: median; whiskers: range of non-outlier data; jitter points: individual data values; large dot: group mean; violin: distribution density; DH: dehydrogenase; UR: urease; PR: protease; PHOS: phosphatase; BG: β-glucosidase; AS: arylsulfatase; BSR: basal soil respiration; BC: biomass C; MBC: microbial biomass C; INTF: iodonitrotetrazolium formazan; PNP: p-nitrophenol. *Significant differences between management systems ($p < 0.05$).

Available and total soil elements

The nutrient availability and soil anions (Table 2) were significantly influenced by vineyard management practices. Organic management led to a notable increase in pH (+15%), organic matter (+32%), exchangeable K (+29%), and available K (+19%) compared to conventional management. Conversely, conventional management exhibited significantly higher levels of available N, approximately double, due to elevated NO_3^- levels (+58%). Additionally, conventional management resulted in a significantly higher available S (+95.0%). There were nonsignificant differences in bulk density, dissolved organic C, and other soil nutrients (available NH_4^+, available P, assimilable NO_2^-, and NO_3^-) between the vineyard management practices ($P > 0.05$). The total soil elements remained largely unchanged due to vineyard management. Among the total soil elements assessed (Table 3), most elements (P, K, Mg, S, Cu, Fe, Mn, Zn, Ni, B, As, Cd, Pb, Co, and Cr) did not exhibit significant differences between management practices ($P > 0.05$). However, the organic vineyard treatment demonstrated significantly higher concentrations ($P < 0.05$) of Ca and Ti than the conventional treatment, with increases of +48% and +21%, respectively.

Table 2. Bulk density, available nutrients, and anions in soils from vineyards in the Itata Valley under conventional and organic management system. Different letters indicate significant differences between treatments according to Fischer's LSD test ($P < 0.05$). Mean ± standard error.

	Conventional	Organic
Bulk density, g cm^{-3}	1.8 ± 0.03[a]	1.8 ± 0.03[a]
Dissolved organic C, mg kg^{-1}	349.0 ± 36.7[a]	285.0 ± 39.8[a]
pH (water)	5.0 ± 0.1[b]	5.9 ± 0.1[a]
Organic matter, %	2.5 ± 0.2[b]	3.7 ± 0.2[a]
Nitrate availability (N-NO_3^-), mg kg^{-1}	8.3 ± 1.4[a]	3.5 ± 0.3[b]
Ammonium availability (N-NH_4^+), mg kg^{-1}	4.2 ± 1.0[a]	3.0 ± 0.4[a]
N availability, mg kg^{-1}	12.4 ± 1.9[a]	6.5 ± 0.6[b]
Olsen P, mg kg^{-1}	50.0 ± 10.4[a]	28.0 ± 7.5[a]
Exchangeable K, $cmol_+$ kg^{-1}	0.5 ± 0.03[b]	0.7 ± 0.04[a]
K availability, mg kg^{-1}	210.0 ± 11.3[b]	258.0 ± 15.6[a]
S availability, mg kg^{-1}	30.0 ± 7.9[a]	1.5 ± 0.6[b]
Cl assimilable (Cl^-), mg L^{-1}	4.9 ± 0.2[a]	4.5 ± 0.04[b]
Nitrogen dioxide (NO_2^-), mg L^{-1}	0.09 ± 0.03[a]	0.07 ± 0.01[a]
Nitrate assimilable (NO_3^-), mg L^{-1}	9.03 ± 1.0[a]	7.85 ± 0.5[a]
S assimilable (SO_4^{2-}), mg L^{-1}	18.7 ± 2.1[a]	9.8 ± 0.3[b]

Table 3. Analysis of total elements in soils from vineyards in the Itata Valley under conventional and organic management system. Different letters indicate significant differences between treatments according to Fischer's LSD test ($P < 0.05$). Mean ± standard error.

	Conventional	Organic
P, g 100 g^{-1}	0.057 ± 0.007[a]	0.055 ± 0.006[a]
K, g 100 g^{-1}	0.487 ± 0.041[a]	0.446 ± 0.031[a]
Mg, g 100 g^{-1}	0.126 ± 0.004[a]	0.138 ± 0.008[a]
S, g 100 g^{-1}	0.021 ± 0.003[a]	0.002 ± 0.001[a]
Ca, g 100 g^{-1}	0.117 ± 0.009[b]	0.225 ± 0.017[a]
Cu, mg kg^{-1}	46.0 ± 4.1[a]	47.0 ± 2.6[a]
Fe, mg kg^{-1}	40475.0 ± 3089[a]	36841.0 ± 1583[a]
Mn, mg kg^{-1}	1189.0 ± 132[a]	1193.0 ± 68[a]
Zn, mg kg^{-1}	80.0 ± 5.4[a]	84.0 ± 2.5[a]
Ni, mg kg^{-1}	11.0 ± 0.9[a]	11.0 ± 0.4[a]
B, mg kg^{-1}	9.0 ± 2.2[a]	7.0 ± 1.2[a]
As, mg kg^{-1}	6.7 ± 0.65[a]	6.7 ± 0.43[a]
Cd, mg kg^{-1}	0.56 ± 0.04[a]	0.79 ± 0.12[a]
Pb, mg kg^{-1}	46.0 ± 3.3[a]	43.0 ± 1.8[a]
Ti, mg kg^{-1}	569.0 ± 27[b]	721.0 ± 27[a]
Co, mg kg^{-1}	14.0 ± 1.1[a]	13.9 ± 0.89[a]
Cr, mg kg^{-1}	40.0 ± 2.2[a]	42.0 ± 1.4[a]

Multivariate analysis of soil properties

Principal component analysis (PCA) explained 54.8% of the total variability in the data (Figure 3). The PCA showed that organically managed vineyards had soils with greater coupling between microbiological variables and organic matter, whereas conventionally managed soils were associated with mineral nutrients and trace elements. Specifically, the variables most associated with organic management were soil enzyme activity (dehydrogenase, β-glucosidase, acid phosphatase, arylsulfatase, and protease), basal respiration, microbial biomass, pH, organic matter, Ca, and Mg. In contrast, conventionally managed samples were associated with higher concentrations of available mineral nutrients (NO_3^-, NH_4^+, Olsen P, available S, and SO_4^{2-}), dissolved organic C, Cl^-, and trace metals (Fe, Cu, Ni, Zn, Pb, and As). However, the PerMANOVA analysis did not reveal any significant differences between the vineyard management practices (P = 0.272).

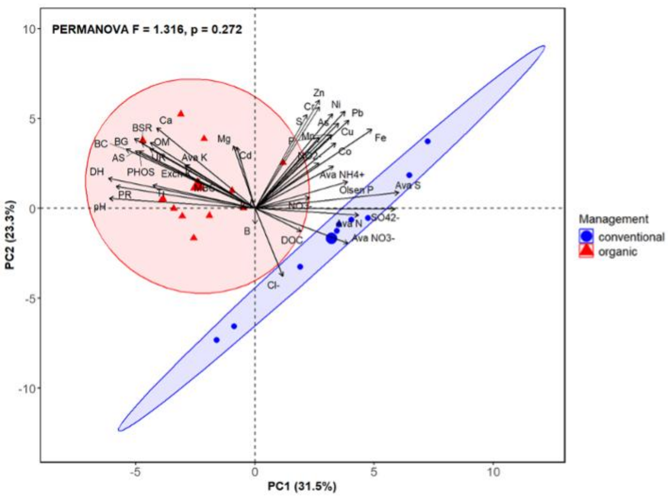

Figure 3. Principal component analysis (PCA) and PerMANOVA for vineyard management (conventional and organic), performed on the soil variables: Microbiological (DH: dehydrogenase; UR: urease; PR: protease; PHOS: phosphatase; BG: β-glucosidase; AS: arylsulfatase; BSR: basal soil respiration; BC: biomass C; MBC: microbial biomass C), total elements (P, K, Mg, S, Ca, Cu, Fe, Mn, Zn, Ni, B, As, Cd, Pb, Ti, Co and Cr), BD: bulk density, available elements (DOC: dissolved organic C; pH; OM: organic matter; Ava NO_3^-: nitrate availability; Ava NH_4^+: ammonium availability; Ava N: N availability; Olsen P; Exch K: exchangeable K; Ava K: K availability; Ava S: S availability; Cl-: Cl assimilable (Cl^-); NO2-: nitrogen dioxide (NO_2^-); NO3-: nitrate assimilable (NO_3^-); SO42-: S assimilable (SO_4^{2-})). PC1: Principal component 1; PC2: principal component 2.

Correlation between soil variables

Pearson's correlation analysis between the microbiological and chemical soil variables showed significant associations (Figure 4; $r \geq 0.5$). Microbiological variables (soil enzymes and microbial biomass) showed high positive correlations with each other, for example, dehydrogenase activity with urease (r = 0.7), phosphatase (r = 0.8), arylsulfatase (r = 0.7), protease (r = 0.8), and basal soil respiration (r = 0.8). Similarly, organic matter was positively associated with respiration (r = 0.7) and enzymes such as dehydrogenase (r = 0.7), protease (r = 0.7), and β-glucosidase (r = 0.8). In terms of nutrients, Ca was strongly and positively associated with microbiological variables such as dehydrogenase (r = 0.8), β-glucosidase (r = 0.8), arylsulfatase (r = 0.7), and basal soil respiration (r = 0.7). Available S was strongly but negatively correlated with dehydrogenase (r = -0.7), protease (r = -0.7), and phosphatase (r = -0.6) activities. pH had a high negative correlation with available soil nutrients such as N (r = -0.7), P (r = -0.6), and S (r = -0.9), but a positive correlation with organic matter (r = 0.7).

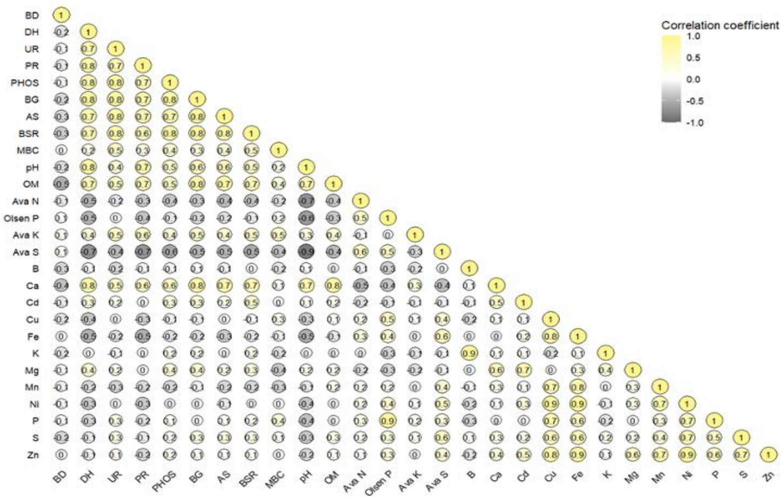

Figure 4. Correlation matrix performed on soil variables: Microbiological (DH: dehydrogenase; UR: urease; PR: protease; PHOS: phosphatase; BG: β-glucosidase; AS: arylsulfatase; BSR: basal soil respiration; BC: biomass C; MBC: microbial biomass C), total elements (P, K, Mg, S, Ca, Fe, Mn, Zn, Ni, B and Cd), BD: bulk density and available elements (pH; OM: organic matter; Ava N: N availability; Olsen P; Ava K: K availability; Ava S: S availability).

Effect of organic management time on vineyards

Linear regression analysis of soil variables analyzed in different years of organic management showed eight variables with significant regressions in relation to time ($R^2 \geq 0.4$; Figure 5). Likewise, these variables were significantly affected by the years of organic management ($P \leq 0.05$; Figure 6). Among the microbiological variables, only dehydrogenase enzyme activity showed a significant relationship ($R^2 = 0.54$), increasing from 34.2 mg INT g^{-1} in year 2 to 49.7 mg INT g^{-1} in year 11. Among the total element variables associated with time, B ($R^2 = 0.80$), Ca ($R^2 = 0.49$), and K ($R^2 = 0.44$) increased by 67.4%, 33.3%, and 20.0% from 2 to 11 yr, respectively. In contrast, Cd showed a less pronounced downward trend ($R^2 = 0.46$), decreasing by 25% from 2 to 11 yr of organic management.

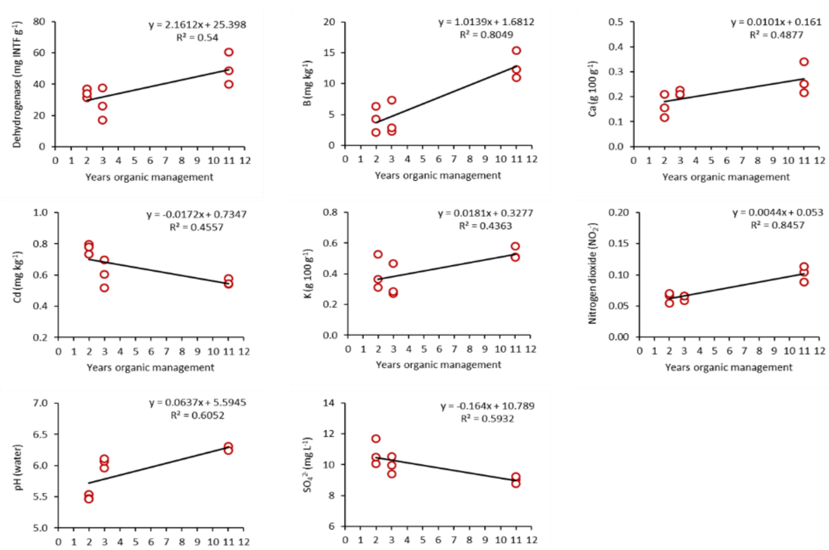

Figure 5. Linear regression of soil variables at different years of organic management (2, 3, and 11 yr). In the equation of the line: x = independent variable (yr); y = dependent variable (measured soil variable); a: slope; b: intercept; R^2: coefficient of determination. INTF: Iodonitrotetrazolium formazan.

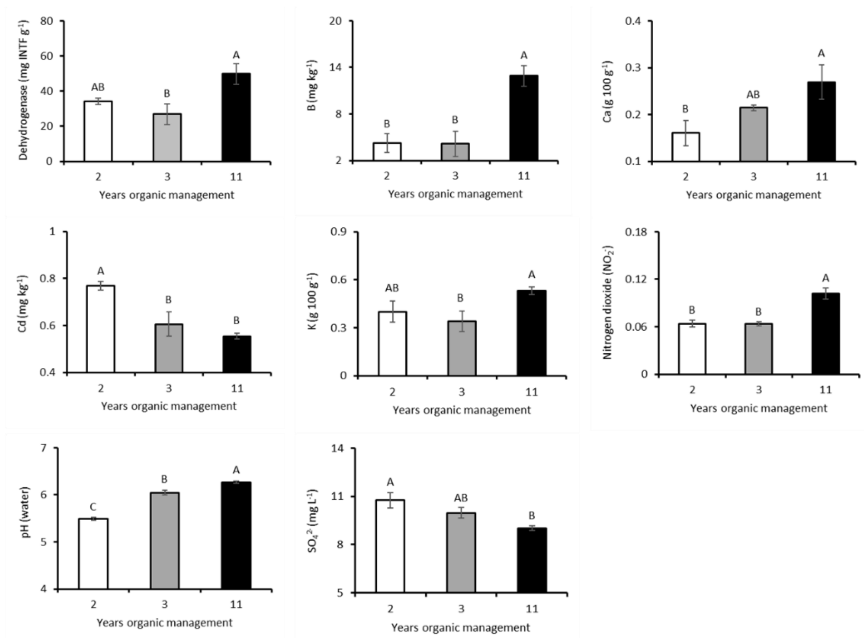

Figure 6. Soil variables with different years of organic management. Different capital letters indicate significant differences between years of organic management (2, 3, and 11 yr) according to Fischer's LSD test ($p < 0.05$). Mean ± standard error ($n = 3$). Bars correspond to the experimental error for each treatment. INTF: Iodonitrotetrazolium formazan.

Among the variables of available elements associated with time, NO_2^-, pH, and SO_4^{2-} were identified. In the case of NO_2^- and pH, a strong positive relationship was observed (R^2 = 0.85 and 0.61, respectively), with concentrations increasing by 40% and 12.7%, respectively, between the second and eleventh years of organic management. In contrast, the SO_4^{2-} content showed a linear decrease (R^2 = 0.59) of 15.9% from the beginning to the end of the evaluation period.

DISCUSSION

This study compared the impact of conventional *vs*. organic management practices on the chemical and microbiological properties of soil in ancestral vineyards located in the Itata Valley, Ñuble Region, Chile. Our findings confirm that vineyard management strongly influences soil functionality, affecting both microbial processes and nutrient availability for plants. In particular, organic management promoted higher biological activity and improvements in several soil quality indicators, whereas conventional management was associated with greater availability of readily soluble mineral nutrients. (Suarez-Fernandez et al., 2025). Organic management notably enhanced the levels of the assessed enzymes, including dehydrogenase, urease, protease, phosphatase, β-glucosidase, and arylsulfatase, as well as basal respiration and soil microbial biomass. Organic vineyards also demonstrated broader and less compact data distributions, indicating greater variability in soil microbiological responses than those managed conventionally. Over the years of organic wine practice, there was an increase in elements considered beneficial for plant nutrition, such as Ca and B, while Cd, which poses potential risks, decreased. Conversely, conventionally managed vineyards exhibited a greater availability of mineral nutrients, specifically N, P and almost S, which are readily absorbed by plants. Multivariate analysis revealed distinct trends associating organic management with microbiological variables and conventional management with chemical variables; however, nonsignificant differences were observed ($P = 0.272$), likely due to the spatial heterogeneity of the soils. These patterns reveal a trade-off between systems. Conventional management favors immediate nutrient availability, whereas organic management promotes biological processes that regulate nutrient cycling and support long-term soil functionality.

Effect of management on soil microbiological variables

Our results showed that organic vineyard management resulted in more microbiologically active and functional soil. This trend was reflected in the multivariate analysis, which showed an association between organic management and microbiological variables (enzymes, soil basal respiration, and C microbial biomass), pH, and soil organic matter (OM), although this association was nonsignificant. Higher enzymatic activities and microbial biomass under organic management indicate a more active microbial community and a greater potential for nutrient cycling in these soils. In addition, soil OM and pH were significantly higher than those under conventional management. Soil pH is a key factor regulating microbial community structure, enzymatic activity, and nutrient availability in soils (Liu et al., 2025). This indicates that soil under organic management has a greater capacity for the mineralization of N compounds, greater P availability, more efficient decomposition of carbohydrates and S compounds, and a higher content of labile C (Krause et al., 2025). These results are consistent with our hypothesis and are supported by previous studies showing that organic management promotes favorable physicochemical conditions at the microhabitat level, enhancing soil microbial biomass and microbial activity (Lori et al., 2017). Specifically, it has been shown that OM serves as a substrate and nutrient source for soil microorganisms, as well as improving soil physical properties such as lower bulk density and higher porosity, stimulating their activity and production of extracellular enzymes (Cui et al., 2023; Liu et al., 2025). In our study, higher soil organic matter was associated with improved soil physical conditions and stronger microbiological responses, supporting the role of organic inputs in promoting microbial activity and soil biological functioning. Conversely, the high availability of inorganic nutrients observed under conventional management may have reduced microbial activity, as evidenced by the negative correlation between available nutrients (especially S) and soil biological indicators (Suarez-Fernandez et al., 2025). This inhibition of microbial and enzymatic activity with conventional management can be attributed to a lower need for enzyme production, changes in the composition of the microbial community, and indirect effects such as soil acidification (Li et al., 2025). However, further studies on the taxonomic and functional composition of soil microbial communities are still needed to gain an in-depth understanding of the mechanisms that regulate the sustainability of vineyards with high heritage importance.

Effect of management on available and total soil elements

In terms of nutrient dynamics, conventional management was mainly associated with greater availability of mineral nutrients, which likely reflects the frequent use of inorganic fertilizers in these systems. This trend was reflected in the multivariate analysis, which showed an association between conventional management and soil mineral nutrients (NO_3^-, NH_4^+, and P), but without significance. These results were expected because conventional vineyard management in the Itata Valley includes frequent and sometimes excessive application of inorganic macronutrient fertilizers to the soil. This pattern likely reflects the application of sulfate-based fertilizers commonly used in conventional vineyard management. Although nutrient levels in conventional management were moderate for vines, it is important to note that, in environmental terms, higher fertility can lead to more leaching, especially for nitrate, owing to the challenging soil and climate conditions in the Itata Valley, with its slow-infiltrating clay soils and steep slopes (Serra et al., 2024). In contrast, organic management produced significantly higher levels of available K than conventional management, with both management systems providing adequate levels for the vines. It has been shown that the application of organic amendments increases the release of available K in the soil because OM competes for binding sites in clays, favoring its release to the soil exchange complex (Bader et al., 2021). As for the total soil elements, most did not vary with vineyard management. These results are consistent with those reported by Liu et al. (2017), who stated that mineralogical composition remains relatively stable in the face of soil management in the short term (decades), since the processes that transform minerals operate on much longer time scales. However, organic management produced significantly higher total Ca and Ti than conventional management. Specifically, Ca was 48% higher than that of conventional management. Calcium can generate structural improvements in the soil and raise the pH, which also explains the microbiological improvements in our study, with high positive correlations between Ca and pH and the microbiological variables evaluated. In turn, Ca promotes the formation of organo-mineral complexes and stable aggregates, which improves soil structural stability and creates favorable microhabitats for microorganisms (Shabtai et al., 2023). Titanium is associated with parental material in minerals such as ilmenite, rutile, and anatase. Likewise, organic management, by increasing OM, stabilizes the fine fractions (clay and silt), retaining and reducing the loss of Ti.

Effect of organic management duration on soil quality

The duration of organic management showed a cumulative effect on soil quality, progressively enhancing biological activity and several beneficial chemical properties while reducing elements associated with potential environmental risks. Dehydrogenase activity showed the greatest increase over time (steepest slope), demonstrating an increase in functional microbial activity with more years of OM management. In line with these results, it has been shown that organically managed agricultural systems increase dehydrogenase activity rates, which are linked to higher labile C content and better soil structure (Kwiatkowski et al., 2020). The NO_2^- and B were the most consistent variables over time under organic management ($R^2 > 0.80$). Although transient, nitrite is a highly reactive intermediate in microbial N transformation processes; thus, its behavior reflects an active N cycle dynamic (Song et al., 2024). In contrast, B is an essential micronutrient for plant growth and development and is involved in cell wall synthesis, membrane stability, and metabolite regulation (Li et al., 2023). Similarly, widely documented beneficial chemical changes have been observed in long-term organic systems, such as increases in Ca, K, and pH, which contribute to improving soil fertility and conditions for biological activity (Wen et al., 2025). Although with a moderate coefficient of determination ($R^2 = 0.46$), Cd progressively decreased over the years of organic management. Given that Cd is a non-essential and highly toxic heavy metal, this trend represents an improvement in soil quality and food safety. Cadmium is mainly anthropogenic in origin, associated with the use of phosphate fertilizers; consequently, organic farming restricts its entry into the soil by limiting the use of mineral fertilizers. In addition, Cd reduction in the soil is likely controlled by multiple factors, including increased OM, pH, Ca, and improved soil structure (Galan-Freyle et al., 2025). The SO_4^{2-} also decreased with years of organic management, which can be attributed to increased microbial immobilization and conversion of sulfate to organic forms incorporated into active microbial biomass (Malik et al., 2021). In this context, although organic management promotes improvements in microbiological activity and several soil quality indicators, long-term nutrient balance—particularly for S—should be considered to avoid potential limitations for crop nutrition in these vineyards.

CONCLUSIONS

Overall, our results reveal clear differences between vineyard management systems. Organic management enhanced soil biological activity and several indicators of soil quality, highlighting its potential to improve soil functioning in traditional vineyards of the Itata Valley. In contrast, conventional management was mainly associated with greater short-term availability of mineral nutrients. Although organic management promoted important improvements in soil biological processes, the decline in available S observed over time suggests that nutrient balance should be considered in long-term organic systems. Future research should further explore how management practices influence nutrient dynamics and microbial functioning to support sustainable soil management in these culturally significant vineyards.

Author contribution

Conceptualization: G.P., M.S., T.L. Methodology: A.R., F.C. Software: M.B. Validation: M.S., G.P. Formal analysis: A.R., F.C., T.L. Investigation: G.P., G.T., J.H. Resources: M.S. Data curation: F.C. Writing-original draft: M.B. Writing-review & editing: M.B., M.S. Supervision: M.S. Project administration: M.S. Funding acquisition: M.S., A.R. All co-authors reviewed the final version and approved the manuscript before submission.

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