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Unveiling terroir: evaluating the magnitude of the heterogeneity and its main drivers in the Canary Islands wines

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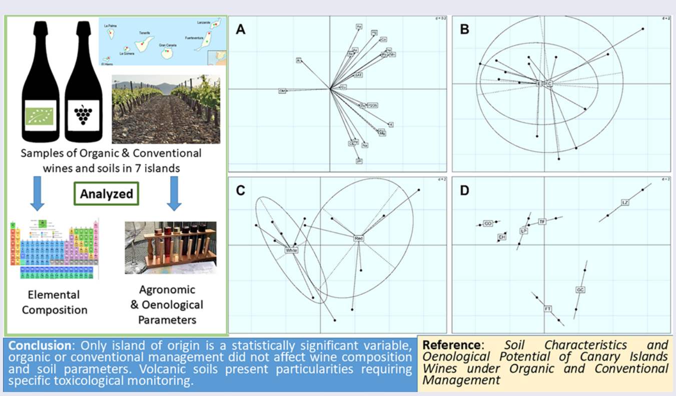
ABSTRACT

The Canary Islands are a Spanish archipelago of volcanic origin in the Atlantic Ocean near the Saharan coast. The extensive intricacy and multitude of variables inherent in the Canary Islands winemaking tradition have posed a substantial challenge, preventing comprehensive research on the main factors contributing to the character of local wine, thus, far. This challenge arises from a convergence of factors including the presence of 14 different grape varieties, and radically different climatic, soil and geographic conditions. This investigation sought to start unraveling this complexity by discerning the impacts of various geographical (specifically, island-related) and management factors (namely, organic vs. conventional practices) on soils and wines within the Canary Islands. Additional variables, such as wine type (red and white) and island of origin, were explored and correlated with the chosen management system. Pairs of organic and conventional wine and soil samples, possessing similar characteristics, were systematically collected from each of the seven wine-producing islands in the Canary archipelago. An examination of elemental composition, oenological attributes and fertility parameters was conducted, followed by comprehensive statistical analysis. Among the variables examined, only the island of origin emerged as statistically significant within the sample. Concerning soil fertility, organic samples exhibited elevated levels of organic matter compared to their conventional counterparts. No notable disparities were observed between the two production methods in terms of soil metal composition and other fertility parameters. However, it is noteworthy that four soil samples surpassed the legally permissible limits for Nickel (Ni) and Mercury (Hg), with three of these instances originating from Lanzarote.

GRAPHICAL ABSTRACT



HIGHLIGHTS

- Differences between organic and conventional vineyard management in wines remains unexplored.
- Comparative nutrient, oenological and elemental soil and wine profiles were performed.
- The study aimed to test whether volcanic soils presented specific characteristics.
- Organic and conventional management did not significantly influence wine parameters.
- Volcanic soils present certain toxic compounds in amounts requiring toxicological monitoring.

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1. Introduction

The Canary Islands, a subtropical Spanish archipelago of volcanic origin, serve as the study's focus, with a rich winemaking history dating back to the 16th century Spanish conquest (Alonso González & Parga-Dans, 2020b). Despite this history, the archipelago lacks comprehensive studies examining soil fertility and its relationship to wine characteristics, as well as comparisons between various management systems. Previous research has predominantly focused on wine oenological and sensory profiles, elemental composition and pesticide residues (Acosta-Dacal *et al*., 2021; Alonso González *et al*., 2021; Darias-Martín *et al*., 2008; López *et al*., 2003; Pérez Trujillo *et al*., 2011; Santana-Mayor *et al*., 2020). The extensive intricacy and multitude of variables inherent in the Canary Islands winemaking tradition have posed a substantial challenge, preventing comprehensive research on the main factors contributing to the character of local wine, thus, far. This challenge arises, among other issues, from factors such as the presence of 14 endemic grape varieties and the frequent incorporation of foreign grape varieties in wine blends, complicating the analysis of wines produced from a single grape variety. Additionally, each island exhibits distinct soil and climatic conditions, microclimatic regions and geographic orientations with different isolation levels, leading to largely autonomous winemaking traditions. In such a small territory, there are vineyards planted in desertic conditions in Fuerteventura and Lanzarote, and in highly wet mountainous regions over 1300 m of altitude in La Palma and Tenerife islands. Thus, this study significantly contributes to understanding soil fertility and elemental composition in volcanic island environments and comparing vineyard and wine management systems in this unique subtropical setting.

As a secondary research focus, the existing body of literature comparing organic and conventional wines remains limited, despite the global surge in organic wine production and consumption (Cravero, 2019; Döring *et al*., 2019). Further research in this domain is imperative due to varying regulations governing organic wines across countries, leading to consumer confusion (Alonso González & Parga-Dans, 2020a). Compounded by the proliferation of sustainable and health-related certifications, such as biodynamic, zero-carbon emission, integrated agriculture, vegan and *vin méthode nature* (natural wine method) (Vecchio *et al*., 2021), consumers are often misled. Hence, it is crucial to conduct studies that differentiate between different production methods (Puszka, 2020).

While regulations differ globally, conventional viticulture commonly employs agrochemical products, including synthetic pesticides and inorganic fertilizers with diverse elemental compositions (Lamichhane *et al*., 2016). In contrast, organic farming opts for natural fertilizers and minerals, avoiding chemical herbicides and utilizing techniques like tillage or mulching, along with non-synthetic pesticides (Döring *et al*., 2019). Integral to organic agriculture is the holistic management of vineyards and soils, considering soil biodiversity, erosion, compaction and contamination (Alonso González & Parga-Dans, 2018a). The connection between soil and wine quality, encapsulated in the concept of terroir, has driven many winegrowers toward organic agriculture for improved yields (Alonso González & Parga-Dans, 2018b).

The territorial and, therefore, the island factor are also key given the diversity of terroirs present in the archipelago. According to the terroir concept, originating from French viticulture and accepted worldwide, a wine's uniqueness results from environmental conditions during production, encompassing climate, soil, cultivation methods and human interventions (Lazcano *et al*., 2020). While consensus is lacking on the correlation between wine character and soil properties, studies have demonstrated distinct organoleptic properties between organic and conventional wines (Delmas *et al*., 2016; Parga Dans *et al*., 2019).

Given the widespread adoption of organic certification in the past decade (Migliorini *et al*., 2018), a strong tradition of comparing organic and conventional farming practices has emerged. Studies encompass various cultivars, incorporating long-term trials with diverse variables. Generally, organic farming exhibits higher soil organic matter, topsoil depth, biological activity and biodiversity, coupled with lower soil erosion and bulk density (Seufert *et al*., 2017). In academic literature, the assessment of soil and wine quality and sustainability relies on key physical, chemical and biological parameters (Hendgen *et al*., 2020).

Commonly employed soil indicators include pH and organic matter content, influencing soil water holding capacity, promoting soil aggregation and representing available nutrient pools (Garcia & Teixeira, 2017; Maioli *et al*., 2021; Morlat, 2008; Probst *et al*., 2008) Additionally, parameters like electrical conductivity (EC), phosphorous oxide (P_2O_5), soil paste saturation percentage (SP) and the presence of main nutrients and heavy metals are crucial. Heavy metal concentrations, if high, can lead to toxicity, necessitating consideration of factors such as pH, SP and electrical conductivity (Preston *et al*., 2016).

Soil characteristics influence wine quality parameters, including color percentage, color intensity, tonality, polyphenols, tannins, protein stability, tartaric, citric, lactic, malic and acetic acids, sugar, glycerol, dry extract, glucose + fructose, volume mass, alcohol volume, pH and total, free and molecular sulfites (Mackenzie & Christy, 2005). Analytical methods, such as comparisons of oenological parameters, polyphenolic and antioxidant profiles, elemental composition, volatile and aromatic compounds and pesticide and toxic compound content, have been employed to distinguish between organic and conventional wines (Čepo *et al*., 2018; Drava & Minganti, 2019; Dutra *et al*., 2018; Hopfer *et al*., 2015; Picchi *et al*., 2020; Saurina, 2010; Urdapilleta *et al*., 2021; Vrček *et al*., 2011).

This study adopts an exploratory approach to characterize the wines from the Canary Islands regarding soil fertility, elemental composition and oenological properties with the aim of defining the magnitude of its heterogeneity and identifying the role of potential main factors driving it (i.e., island origin, wine type and management). It addresses a gap in the literature by exploring the reality of wine production on islands, specifically volcanic islands. The study seeks to ascertain whether the production method variable is more significant in identifying soil and wine samples than the island variable or wine type variable.

2. Material and methods

2.1. Vineyard and sampling conditions

Samples were gathered from 14 distinct wines, with 14 corresponding locations—two per each wine-producing island—selected during the 2019–2020 vintage (see Table 1). For privacy reasons, the sample names were encoded based on islands and production methods, while their original names and geolocation remain undisclosed in this study. The sampling approach involved the selection of pairs of organic and conventional wines within a proximity of less than 5 km from each other to minimize variations in soil and climate characteristics (see Figure 1).

Based on Köppen's climate classification, samples from the eastern islands of Fuerteventura, Gran Canaria and Lanzarote were categorized as hot desert climates (BWh), whereas samples from the western islands of Tenerife, El Hierro, La Gomera and La Palma were identified as temperate with Hot-summer

Table 1. Sample description including codification, island of provenance, type of wine, production method, harvest, grape variety, location and soil type.

Sample	Island	Type	Production	Harvest	Variety	Region	Vineyard soil
TF1	Tenerife	Red	Organic & Biodynamic	2019	Listán Negro	La Perdoma	Basaltic lava flows
TF2	Tenerife	Red	Conventional	2019	Listán Negro	La Perdoma	Basaltic lava flows
LP1	La Palma	White	Organic	2019	Albillo Criollo	Puntagorda	Basaltic lava flows
LP2	La Palma	White	Conventional	2019	Albillo Criollo, Listán Blanco	Tijarafe	Basaltic lava flows
GC1	Gran Canaria	Red	Organic	2019	Listán Negro, Castellana	Vega de Gáldar	Basanitic-nephelineitic, basaltic and olivine-pyroxenic basaltic lavas
GC2	Gran Canaria	Red	Conventional	2019	Listán Negro	Vega de Gáldar	Basanitic-nephelineitic, basaltic and olivine-pyroxenic basaltic lavas
LG1	La Gomera	White	Organic	2019	Forastera Gomera	Igualero	Basaltic and trachybasaltic lava flows
LG2	La Gomera	White	Conventional	2019	Forastera Gomera	El Cercado	Basaltic and trachybasaltic lava flows
FT1	Fuerteventura	White	Organic	2019	Marmajuelo, Malvasía	Casillas de Morales	Colluvium and slope deposits
FT2	Fuerteventura	White	Conventional	2019	Malvasía	Lajares	Basaltic lava flows
EH1	El Hierro	White	Organic	2019	Verijadiego, Pedro Ximenez, Listán Blanco	Frontera	Basaltic, basanitic and tephritic lava flows
EH2	El Hierro	White	Conventional	2019	Verijadiego	Frontera	Basaltic, basanitic and tephritic lava flows
LZ1	Lanzarote	Red	Organic	2019	Listán Negro, Syrah	La Geria	Dispersion pyroclasts
LZ2	Lanzarote	Red	Conventional	2019	Listán Negro, Syrah, Tintilla, Merlot	La Geria	Dispersion pyroclasts

Geological data retrieved from the Geological Map of the Canary Islands, 2010 version.

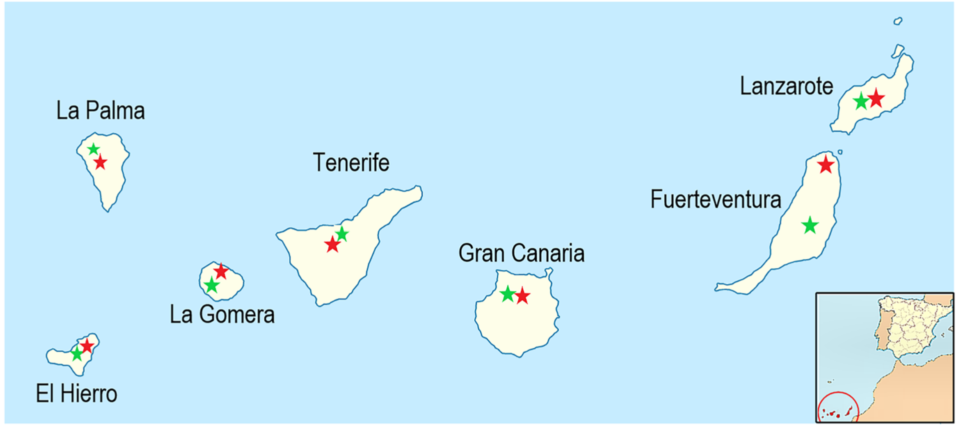

Figure 1. Location of samples collected in each of the Canary Islands. Organic samples are shown in green and conventional samples in red.

Mediterranean climate (CSA) (Mestre & Felipe, 2012) (see Table 1).

Various winemaking methods were also taken into account, resulting in a total of 6 red and 8 white wines being selected. Listán Blanco was the grape varietal for whites and Listán Negro for reds. The sampling process also prioritized pairs of wines with similar profiles in terms of alcohol volume, residual sugar, vintage year, grape variety and aging tanks used. In general, most wines were dry, with the exception of the conventional sample from El Hierro, which was a sweet wine. This sample was chosen as alternative wine samples were not available in the region.

The samples were personally collected at wineries, representing marketed bottles rather than wines stored in cellars before commercialization. All organic wines were certified by the Canary Institute of Agrofood Quality (ICCA) under the EU organic agriculture scheme (see Alonso González & Parga-Dans, 2018a). Organic wine samples were collected in Tenerife and La Gomera during the second year of the mandatory transition period to organic agriculture. After opening the original bottles, all three subsamples (see below) were transferred to plastic containers and stored at 4–5 °C until analysis. The wines under consideration differ from those in a previous paper published by the group (Alonso González *et al*., 2022). Wines originate from the same cellars but from a different harvest year. Selecting the same cellars for the analysis was a pragmatic approach due to the scarcity of pairs of organic and conventional wine samples in the Canary Islands and aimed to build on our previous research in the region.

Soil samples were collected on all islands between May and July 2020, during the dry season. The average area from which the vines were produced was 2 hectares. Soils were sampled at each location by obtaining three composite samples, each consisting of four subsamples, using a gouge auger from different rows, always between inter-vines and throughout the vine root zone.

Bulk density was measured in advance to ensure consistency in sample collection. Soil samples were collected from the top 20 cm, except in Lanzarote, where the specific cultivation system of La Geria did not permit this and samples were taken within the characteristic Geria's vine pits and below the volcanic ash layer. The collected soil volume was one liter per sample, mixed and stored at 6 °C in a refrigerator.

2.2. Sample analysis

2.2.1. Characterization of soil samples

The soil sample analysis involved the creation of three composite subsamples, each combining four individual soil samples from a given vineyard. These subsamples were subsequently subjected to air-drying, a process that took three to seven days depending on the soil type and initial moisture content. Following air-drying, the samples were ground and passed through a 2 mm sieve. For each soil subsample, a total of 21 variables were measured (see Supporting Information Table S2).

To measure pH, a soil–water mixture with a 1:2.5 ratio was prepared, shaken and left to stand for 10 min. pH measurements were then taken using a pH electrode in a 2:1 soil extract. The available cations, including Calcium (Ca), Potassium (K), Phosphorus pentoxide (P_2O_5), Magnesium (Mg) and Sodium (Na), were extracted using a 1 M solution of ammonium acetate at pH 7 (10 g of soil in 50 mL of ammonium acetate), following the official methods of the Spanish Ministry of Agriculture (MAPA, 1994). The concentration in the extract was determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP OES) Perkin Elmer Avio 500. Available Phosphorous (P), as per Olsen's method, was extracted with sodium bicarbonate at pH 8.5 (5 g of soil in 100 mL of extractant) (Olsen & Sommers, 1982). Saturated pastes were prepared by using 350 g of air-dried soil and the soil pastes were left to equilibrate for 24 h following the standard method (Rhoades, 1982). Subsequently, 20 mL of water was added to 100 g of soil, stirred and more water was added until saturation, after which the liquid was extracted using a vacuum system.

Following the collection of extracts under vacuum, the electrical conductivity of the extracts was measured using a conductivity meter (WTW, Cond 315i). To determine the soil paste saturation percentage (SP), a subsample of each paste was oven-dried for 24 h at 104 °C. The total heavy metal content was extracted with EDTA and analyzed using ICP OES Perkin Elmer Avio 500 (Perkin Elmer, Waltham, Massachusetts, USA), following the standards set by the Spanish Ministry of Agriculture (MAPA, 1994).

2.2.2. Wine samples characterization

The examination of wine samples involved the analysis of three sub-samples (bottles) for each vineyard. A comprehensive assessment was conducted, encompassing 56 variables for each wine subsample (see Supporting Information Tables S2–S4). The determination of total sulfur dioxide employed the Ripper potentiometry method with a double platinum electrode, utilizing a Crisson SO2-Matic 23 (Crisson, Barcelona, Spain). Protein stability was assessed by heating and subsequent cooling of the wine as reported by Vincenzi *et al.* (2011), samples were heated at 80 °C for 6 h and were then cooled at 0/+4 °C for 16 h. The difference in turbidity before and after heating was assessed after equilibration at room temperature. A Hanna HI98713 turbidity meter (Hanna Instruments, Smithfield, Rhode Island, USA) was employed for this purpose.

Color intensity and hue were analyzed following European Union methods applicable to the wine sector (Madrid Vicente, 1991) through UV–Vis spectrophotometry, utilizing a Varian Cary 50 (Varian, Palo Alto, California, USA). Total polyphenol and tannins were assessed according to the Masquelier index (Weseler & Bast, 2017) using UV–Vis spectrophotometry with a Varian Cary 50. Anthocyanin content was determined via the Ribèreau–Gayon method (Ribéreau-Gayon *et al.*, 2006), involving bisulfite decolorization analysis through UV–Vis spectrophotometry with a Varian Cary 50. The remaining oenological parameters (tartaric acid, acetic acid, sugars, dry extract and alcohol) were scrutinized using Fourier transform infrared spectrometry (FTIR), employing a TDI Bacchus 3 apparatus (TDI, Barcelona, Spain) with a Thermo Nicolet IS5 interferometer (Waltham, Massachusetts, USA), using the methods established by the International Organisation of Vine and Wine as a reference (OIV, 2022). For a comprehensive analysis of the elemental composition of wines, please refer to our earlier research (Alonso Gonzalez *et al.*, 2021).

2.3. Statistical analysis

The mean for each measured variable within each of the 14 vineyards (consisting of three subsamples per vineyard) was calculated. To explore associations, Spearman correlation coefficients were used to test correlations between all pairs of the 21 wine variables and 56 soil variables. Following this, Wilcoxon rank-sum and signed-rank tests were conducted, employing 'island' as the pairing factor. These tests aimed to identify significant differences between samples from conventional and organic production methods for each of the measured variables.

A Principal Component Analysis (PCA) of the standardized measurements was then executed separately for the soil and wine variables. This analysis served to establish a multivariate ordination of the vineyard samples and visualize their correspondence to the origin of these samples based on island (El Hierro, La Palma, La Gomera, Tenerife, Gran Canaria, Fuerteventura or Lanzarote), wine type (red or white) and production method (conventional or organic). Subsequently, to assess significant differences between groups of vineyard samples based on their soil and wine profiles, permutational ANOVAs were conducted on a Euclidean distance matrix derived from the standardized measurements. A total of 999 permutations were considered, with geographical origin, wine type and production method serving as grouping factors. All data analyses and visualizations were performed using the R-packages corrgram, corrplot, vegan and ade4 by the R Development Core Team.

3. Results and discussion

We begin by presenting the results related to soil samples, followed by wine samples and conclude with a statistical analysis highlighting potential correlations and key variables. In terms of the measured soil variables, no significant differences are identified between conventionally and organically managed vineyard samples based on Wilcoxon rank-sum and signed-rank tests ($p < .05$). Only P_2O_5 showed marginal significance ($p = .07$), with higher values observed for conventionally managed vineyards (see Figure 2). The first two Principal Component Analysis (PCA) axes of the soil profiles for the vineyard samples collectively accounted for 54% of the total variance. PC1 exhibited a strong positive correlation with K, Mn, Ni and Pb, and a negative correlation with organic matter (MO). PC2 was negatively correlated with pH and positively correlated with Fe (see Figure 3).

Scatter plots based on PC1 and PC2 pairs in the ordination did not reveal any apparent differentiation between samples based on the production method. Conversely, when considering the wine type and island of origin, the ordinations displayed a clustering of vineyards consistent with these factors. Consequently, permutational ANOVAs indicated non-significant differences in the soil profiles of the vineyard samples between production methods ($p = .998$, $r2 = 0.023$). However, significant differences were observed between red and white wine types ($p = .002$, $r2 = 0.233$) and among the islands ($p = .001$, $r2 = 0.781$). This suggests distinct vineyard management systems for white and red wines, as well as variations between different islands.

3.1. Comparative analysis of soil characteristics per island

We begin by presenting the results related to soil samples, followed by wine samples and conclude with a statistical analysis highlighting potential correlations and key variables. Notably, the island of origin emerges as the most significant variable. The mean values for both organic and conventional samples were calculated for each island (see Table 3). The analysis reveals distinct differences between the western and eastern islands of the archipelago, indicating fundamental disparities in terroirs.

The eastern islands, including Lanzarote, Fuerteventura and Gran Canaria, exhibit semiarid and arid conditions with elevated salinity levels and

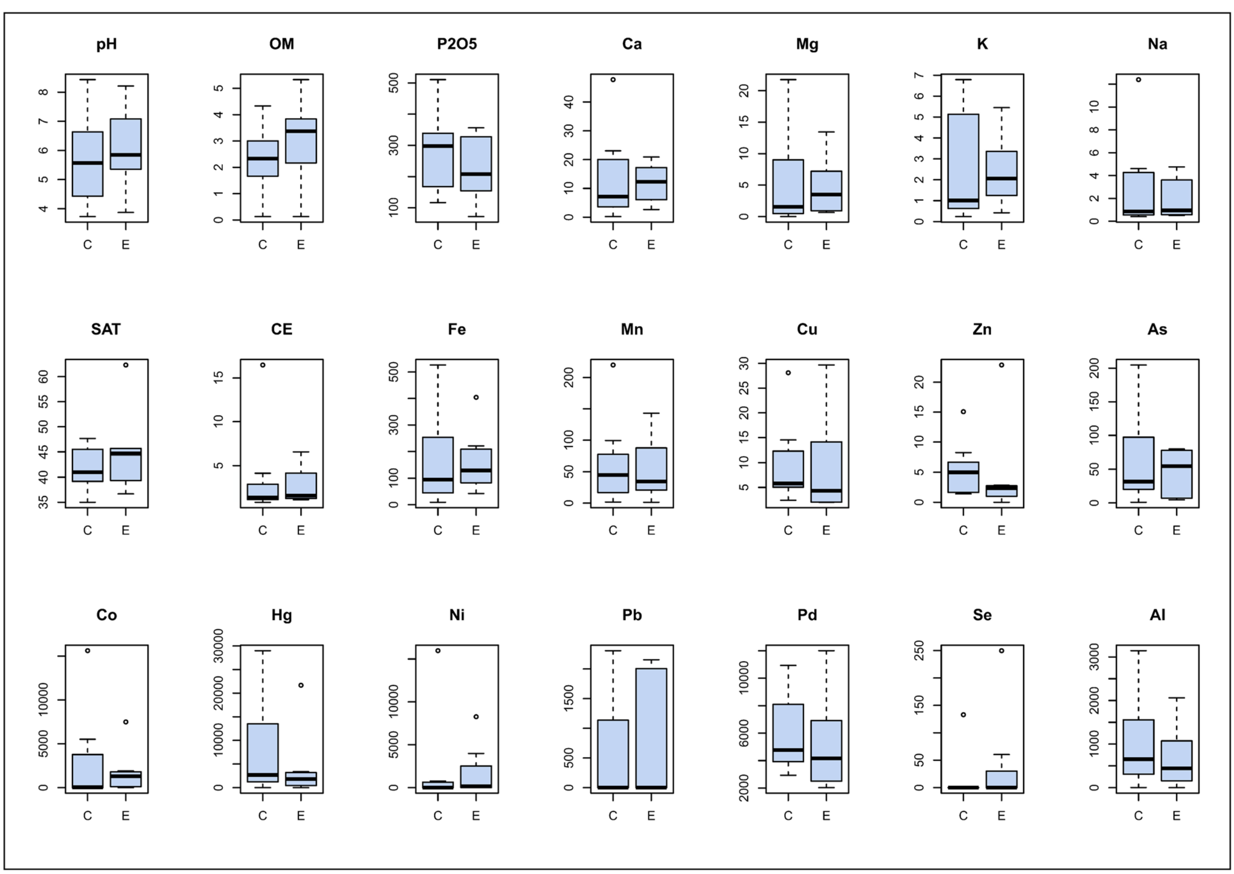

Figure 2. Variation in the soil variables measured from conventional management (C) and organic management (E) vineyards. See Table 2 for codes and concentration units of each variable.

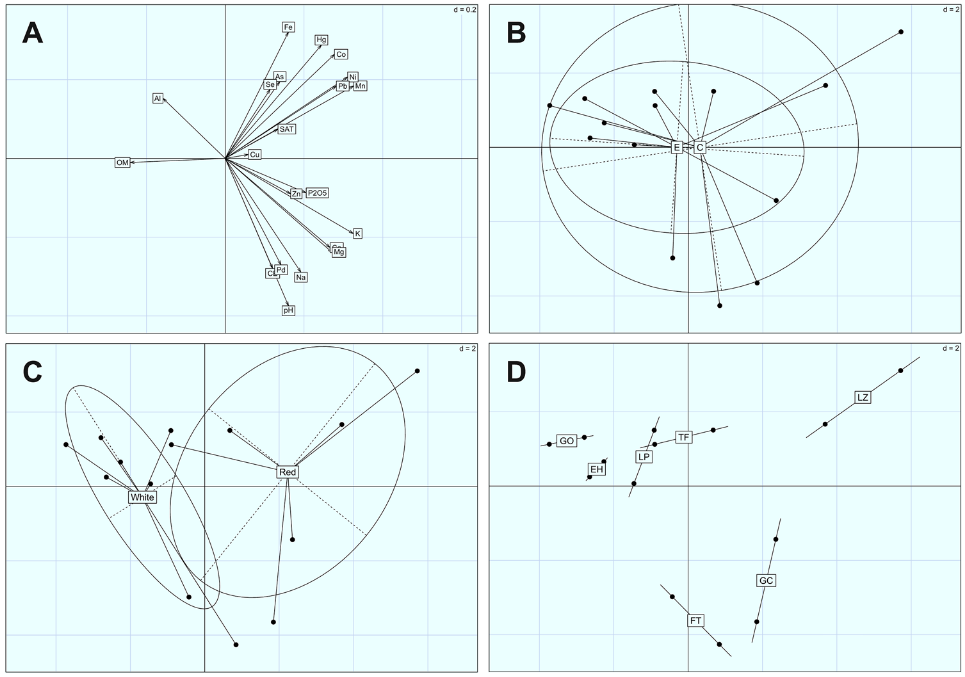

Figure 3. Principal components analyses ordinations of the vineyard samples according to the variation in the soil variables measured. (A) variable contribution to two main principal components and (B–D) vineyard samples ordinations grouped by management type (conventional, C; organic, E), type of wine (Red; White) and the island of origin (El Hierro, EH; La Palma, LP; La Gomera, LG; Tenerife, TF; Gran Canaria, GC; Fuerteventura, FT; Lanzarote, LZ) respectively. See Supporting Information Table S1 for variable codes in A.

Table 2. Average values of soil parameters per island comprising both organic and conventional management systems.

	pH	%OM	P_2O_5	%SP	EC	Ca	Mg	K	Na	Fe	Mn	Cu	Zn	As	Co	Hg	Ni	Pb	Pd	Se	Al
TF	5.14	4.33	433.50	42.50	1.23	9.24	2.53	1.54	0.90	373.67	44.88	28.88	7.53	0.41	1.13	0.08	0.47	1.92	6.69	0.12	1655.67
LP	6.05	2.85	186.61	45.00	1.19	7.41	0.96	1.37	0.55	115.05	75.08	7.05	1.97	1.41	3.71	0.02	0.00	0.00	3.61	0.00	655.60
GC	8.03	2.50	244.00	51.67	2.68	33.18	17.60	5.62	3.37	32.78	74.92	17.25	15.55	0.41	0.87	0.08	2.24	1.22	9.31	0.00	723.70
LG	3.80	3.33	94.24	37.83	1.05	1.45	0.33	0.33	0.46	111.95	16.28	2.22	2.12	0.04	0.64	0.02	0.54	0.00	3.06	0.00	2602.55
FT	7.90	2.33	349.67	36.67	11.52	16.45	6.63	3.60	8.58	25.80	30.88	3.88	3.07	0.01	0.00	0.00	0.00	0.00	9.56	0.00	2.93
EH	4.93	3.00	148.67	44.00	1.46	2.77	0.45	0.50	0.58	135.17	1.50	6.00	1.33	0.00	0.00	0.07	0.00	0.00	3.15	0.00	196.50
LZ	5.49	0.13	312.78	45.67	4.20	21.98	9.58	5.38	4.50	397.67	181.50	4.33	3.83	0.09	11.55	0.25	12.12	0.00	4.46	0.10	416.58

Concentrations of Ca, Mg, K and Na are expressed in meq/100g and for the rest of the elements and P_2O_5 in µg/g. Island: TF: Tenerife, LP: La Palma, GC: Gran Canaria, LG: La Gomera, FT: Fuerteventura, EH: El Hierro, LZ: Lanzarote. %OM: Organic Matter percentage; %SP: Soil Paste Saturation Percentage; EC: Electric Conductivity (dS/m).

Table 3. Average values of wine parameters per island comprising both organic and conventional management systems.

	(TPI)	Tannins (mg/L)	Tartaric acid (g/L)	Acetic acid (g/L)	Sugars (g/L)	Dry extract (g/L)	Alcohol %	Total sulphites (mg/L)	pH
TF (r)	57.17	3.98	2.15	0.74	3.53	54.33	13.24	10.67	3.66
LP (w)	15.83	1.13	2.63	0.46	1.50	33.67	13.55	102.50	3.32
GC (r)	63.67	4.50	1.03	0.63	3.83	58.00	12.97	30.67	3.75
LG (w)	14.50	1.00	3.58	0.30	2.73	38.83	13.49	77.67	3.14
FT (w)	13.50	0.93	3.30	0.19	2.52	35.33	12.71	70.50	3.26
EH (w)	16.83	1.18	2.53	0.74	14.60	65.83	14.57	103.67	3.13
LZ (r)	49.50	3.47	1.72	0.47	3.00	52.50	12.59	66.83	3.75

Island: TF: Tenerife; LP: La Palma; GC: Gran Canaria; LG: La Gomera; FT: Fuerteventura; EH: El Hierro; LZ: Lanzarote; TPI: Total Polyphenol Index.

relatively low annual rainfall compared to the western or 'green' islands of Tenerife, La Gomera, La Palma and El Hierro, which experience cooler climates associated with the trade winds. In the eastern islands, mean values for pH, phosphorous and electrical conductivity are higher, while organic matter content is lower. The percentage of soil paste is not significantly different. Notably, the pH values for four samples from Gran Canaria and Fuerteventura exceed the optimal range for vine cultivation in the archipelago (ranging between 5.2 and 7.5). Conversely, samples from La Gomera exhibit relatively low pH levels, averaging 3.8.

The acidic pH of La Gomera's soils, combined with elevated levels of aluminum, poses potential long-term challenges to the nutritional health of vines.

The pH variable indicates that the island factor is more significant in discriminating the origin of the samples than the production method or wine type. In the eastern islands, higher pH levels are attributed to arid or semiarid weather conditions and sandy loam soils, intrinsically related to the presence of alkaline carbonates and high sodium levels. Sodium, naturally present in eastern island soils, becomes more abundant in vineyard soils due to the use of irrigation water with high conductivity levels and natural sea sprays. Na levels are much higher in samples from eastern islands compared to the western islands.

Additionally, the eastern island samples show lower organic matter content, correlating with pH levels due to the absence of a humus layer and low precipitation. However, there is no correlation between low organic matter and high soil paste percentage, indicating that higher soil paste percentages result in lower water retention capacity, higher clay presence and potentially more compacted soils. Fuerteventura exhibits the lowest average soil paste percentage, followed by La Gomera, while Gran Canaria has the highest saturation percentage.

Low organic matter levels hinder water retention and percolation, contributing to soil erosion in arid and semiarid soils. To mitigate nutrient mineralization and soil erosion, especially on the eastern islands, increasing organic matter content is advisable. Tenerife displays higher levels of phosphorus pentoxide (P_2O5), which can be attributed to grapevines' increased need for phosphorus, as alkaline, calcareous and arid soils impair nutrient absorption.

The K/(Ca + Mg) ratios generally indicate an adequate balance between these cations, except for FT2, which exhibits an imbalance threatening optimal vine growth. Notably, other soil nutrients such as K, Mg and Ca also show opposing patterns between the western and eastern islands, with the latter having significantly higher levels. Gran Canaria, in particular, stands out with the highest levels overall, demonstrating substantial differences in soil composition and vineyard characteristics among the islands dedicated to grape cultivation.

3.2. Comparative analysis of soil characteristics per production method

The type of wine does not significantly impact soil composition in the analyzed samples, as fertilization and plant protection strategies remain consistent between red and white wines in the study area. Additionally, the organic or conventional production methods influence certain soil parameters, although not in a statistically significant manner. There is no consensus in the literature regarding the effects of production methods on various soil chemical parameters.

Consistent with certain prior studies, when comparing the means of all samples collectively, the production method did not influence pH levels significantly. Organic soils exhibited slightly higher pH levels than conventionally treated soils (6.12 vs. 5.69, respectively). Both levels fall within the optimal range for vine development, but conventionally treated soils may be susceptible to acidification due to low organic matter content. On average, organic matter was higher in organic agriculture, likely attributed to the application of compost amendments, which serve as the primary nutrient source in organic agriculture due to the prohibition of synthetic fertilizers.

These findings align with previous research by Coll *et al*. (2011) and Fließbach *et al*. (2001), which observed improvements in organic matter profiles under organic agriculture. In contrast, Gutiérrez-Gamboa *et al*. (2019) found no significant differences between the two production methods. P_2O_5 did not exhibit a uniform pattern, although conventional vineyards generally showed higher levels. This aligns with the findings of Penfold *et al*. (2015) and Probst *et al*. (2008), who reported no differences. Other results indicate a trend toward an initial decrease in phosphorus (P) when transitioning to organic agriculture, followed by a subsequent sustained increase, as noted in previous studies.

However, in this study, vineyards with long-standing adherence to organic agriculture (over 20 years) did not show higher levels of P_2O_5 than their conventional counterparts. In contrast, recently converted vineyards (less than 5 years) exhibited similar or higher levels. Differences in soil saturation percentage were negligible, with slightly higher values detected in organic vineyards, as reported by Coll *et al*. (2011). However, conventional vineyards presented higher levels of electrical conductivity and sodium, reflecting more saline and erosion-prone soils, along with slightly higher levels of calcium, magnesium and potassium. This contrasts with the findings of Coll *et al*. (2011), who reported increased levels of phosphorus and potassium under organic viticulture.

3.3. Comparative analysis of toxic elements in soils

Metal toxicity was assessed based on the most stringent maximum concentration limits established by the legislation of any European country for Hg, Ni, Cu, Zn and Pb (European Commission, 2018). For Co and As, limits were evaluated following the lowest guideline values defined by Denmark and those provided by the Finnish Ministry of the Environment (MEF, 2007). According to the official method, Mo and Se could not be detected, while Al does not have a limit imposed on soils and will not be discussed.

Since the Canary Islands lack data on most elements, comparisons with natural soils and other agricultural crops are not possible. The concentration of elements occurred in the following order: Al > Fe > Mn > Co > Ca > Cu > Pd > Mg > Zn > Na > K > Ni > Pb > As > H > Se. Only four samples exceeded the legal limits in Ni and Hg, three of them from Lanzarote. LZ2 exceeded the Danish legal limit for Ni of 15 ppm with 15.97 ppm, while LP2, LZ1 and LZ2 exceeded the Finnish legal limits for Hg of 0.2 ppm, with 0.26 ppm, 0.21 ppm and 0.28 ppm, respectively. These infringements are likely caused by the elemental composition of the volcanic soils of the islands, notably in Lanzarote, where vines are grown in volcanic ash using the La Geria cultivation system.

According to recent EU studies, Ni in soils is primarily due to natural factors, particularly in arid or semi-arid areas (Mendoza et al., 2006; Tóth *et al*., 2016). High levels of Ni were detected in Lanzarote but below the detection limit in La Palma, La Gomera and El Hierro. The mean Ni content of all samples was 2.20 ppm, which is below data reported in other studies. Lanzarote also presented high levels of Mn and relatively high levels of Hg, which has been shown to be present in high amounts in geothermally active areas around the world (Peña-Rodríguez *et al*., 2012). Compared to the 0.26 ppm found in a sample from La Palma and 0.21 ppm and 0.28 ppm from Lanzarote, Hg concentrations in natural soils in the Canary Islands range between 0.34 ppm and 0.001 ppm, with an average content of 0.04 ppm.

Conventional samples averaged more Hg (0.08 and 0.04 ppm) and Ni (1.93 and 2.46 ppm) than their organic counterparts. These results confirm that soils from volcanic areas can show significant enrichment in Hg and become a source of this element in the food chain. However, no correlation was found between Hg, Fe and Al, as reported by other authors in tropical environments.

In all samples, all other elements were below the legal threshold limits. Generally, there were no significant differences between conventional and organic samples. Conventional samples showed higher concentrations of Mn, Cu, Zn, As, Hg, Ni, Pd and Al, while organic samples were higher in Co and Pb. As levels were low, showing much lower levels than averages reported elsewhere in Europe and mainland Spain. Co levels were elevated in volcanic ash soils of Lanzarote with 11.55 ppm followed by Tenerife with 3.71 ppm but were below detection limits in El Hierro and Fuerteventura.

Zn values were higher in Gran Canaria (15.5 ppm) followed by Tenerife (7.53 ppm). Overall levels are relatively low when compared to European averages. There is a strong correlation between Zn increases and the use of phosphate fertilizers, and their levels are generally associated with intensive land exploitation. This may explain the higher levels found on Tenerife and Gran Canaria, historically the most intensively exploited islands.

Following a similar pattern like Zn, Cu levels were the highest in Tenerife (28.88 ppm) followed by Gran Canaria (17.25 ppm), well ahead of La Palma (7.05 ppm). Once again, the island factor was more determinant than the production method, as organic vineyards showed only slightly lower Cu levels (9.76 vs. 10.13 ppm). As a result of its prolonged use as a fungicide, Cu normally accumulates in soils at higher levels in areas where traditional agricultural methods are practiced. In fact, high Cu levels are often considered a negative outcome of organic viticulture. High Cu levels have been found in Spain with averages ranging from 179 to 579 ppm, France with 398 ppm or Brazil with 3216 ppm. There is, however, no direct correlation between Cu in soil and plant bioavailability.

Both Pb and Fe were below the maximum permissible limits. Pb was higher in organic management, and Fe in conventional cultivars, although not significantly. In contrast to previous studies in volcanic areas, Pb concentrations were low and below average in both agricultural and vineyard soils. Only Tenerife (1.92 ppm) and Gran Canaria (1.22 ppm) reported Pb, which again correlates with a more intensive long-term exploitation of agricultural soils. Fe levels showed significant differences between islands. Lanzarote was the highest (397.67 ppm) followed by Tenerife (373.67 ppm), while Gran Canaria (32.78 ppm) and Fuerteventura (25.80 ppm) were the lowest. As with other elements, these values are much lower than those reported in other areas such as Castellón with 56.1 ppm or the Douro basin with 28.8 ppm.

3.4. Comparative analysis of wine oenological profiles

The mean concentrations of most of the wine variables measured in wine samples from conventional production were higher (with the exception of some variables, e.g., volatile acidity, Zn, Cd, Hg, Pb or Bi), as well as heterogeneity of the measurements compared to wine samples from organic management (See Figure 4). However, significant differences in concentrations (Wilcoxon rank-sum and signed-rank tests, $p < .05$) between conventionally and organically managed wine samples were only observed for polyphenols and tannins, with significantly higher concentrations in conventionally managed vineyards ($p = .015$ and $p = .016$, respectively). This contrasts with most of the literature describing higher polyphenol content under organic and biodynamic management (Döring *et al*., 2019; Maioli *et al*., 2021). The first two PCA axes of the wine profiles for the vineyard samples accounted for 52% of the total variance. PC1 correlated positively and strongly with Sb, Ga, Yb, Se, Al or Y, among others; and PC2 correlated positively with polyphenols and tannins and negatively with Th and total sulphites (See Figure 5).

On the ordination scatter plots based on the PC1 and PC2 pairs, there was no clear ordination of the samples according to the production method. Considering the wine type, white and red wines showed a consistent aggregation within PC2. Regarding their island of origin, the ordination showed differentiation of wine samples from Gran Canaria (with high heterogeneity between the two GC wine samples) and a secondary ordination through PC1 in accordance with the other islands. Consequently, permutational ANOVAs revealed nonsignificant differences in the elemental composition profiles of the wine samples between production methods ($p = .448$, $r2 = 0.076$). However, marginally significant differences were found between wine types ($p = .056$, $r2 = 0.124$) and, as in the case of soil samples, significant differences were found between islands ($p = .011$, $r2 = 0.565$), and this result was maintained when Gran Canaria wines were excluded from the subset of wine samples ($p = .007$, $r2 = 0.574$).

Wine type presented marginally significant differences in the chemical composition of the wines due to the winemaking techniques specific to each product, including longer maceration times for red wines (and consequently, more polyphenols and tannins) and higher sulphite addition for whites. The whites had a more acidic pH than the reds (3.21 vs 3.72). As in the case of soil parameters, the island factor was more significant than the wine type and the production method (Table 3). This is despite the key confounding factor, which is the use of oenological additives that can significantly alter wine composition, especially in terms of acidity, pH, tannins and polyphenols. There were again notable differences between the eastern and western islands of the archipelago, although less significantly than in the soils. The western islands have higher alcoholic volume and tartaric acid on average than their eastern counterparts.

As mentioned, differences were observed between organic and conventional wines. Organic wines showed lower levels of polyphenols and tannins, which deviates from the literature reports showing increased levels of both compounds under organic management (Pagliarini *et al*., 2013), but also from most studies showing no appreciable differences between the two (Granato *et al*., 2015; Lante *et al*., 2004). In addition, pH, tartaric and acetic acid showed no significant differences, while organic wines displayed only lighter levels of dry extract and alcohol, consistent with most research demonstrating that these parameters do not differ between production methods (Malusà *et al*., 2002; Tassoni *et al*., 2013). Organic wines showed less sugar overall, but the average was distorted by a conventional sweet wine from El Hierro, which could be considered an outlier. Finally, organic wines were lower in sulfites than their conventional counterparts (55.62 mg/L vs 76.52 mg/L), which is in agreement with previous studies (Čepo *et al*., 2018; Cravero, 2019). This can be explained by the stricter regulations on sulphite addition under organic winemaking. An earlier publication discusses the elemental composition of wines (Alonso Gonzalez *et al*., 2021).

3.5. Correlations between soil and wine characteristics of vineyards

Statistical analysis of correlations between wine characteristics and soil properties is hindered by significant differences between islands, necessitating an inland approach in subsequent studies. Nevertheless, a correlation was found for all 21 measured soil variables (See Figure 6). Significant and strong positive correlations ($r > 0.85$) were found between Ca, Mg and K; K and Na; Na and CE; Mn, As, Co and Ni; and Pb. Al was negatively correlated ($r < -0.60$) with CE, Na and pH. For the 56 wine variables measured, an overall positive correlation was also found (See Supporting Information Figure S1). Significant and strong positive

Figure 4. Variation in the wine variables measured from conventional management (C) and organic management (E) vineyards. See Table 2 for codes and concentration units of each variable.

correlations ($r > 0.75$) were found between the rare earth elements and for As, Th, Ti, U, V, Ga and Nb. Polyphenols, tannins and pH were also strongly and positively correlated ($r > 0.85$). Hg was negatively correlated with other elements, significantly and strongly ($r < -0.75$) with Al, Cr, Mo, Ti and V.

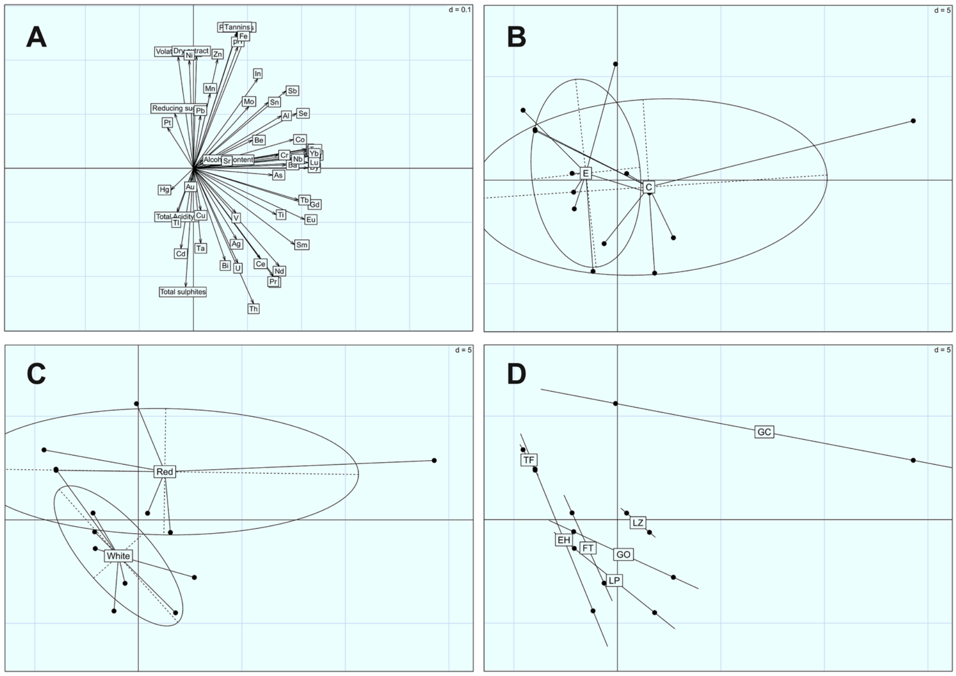

Figure 5. Principal components analyses ordinations of the vineyard samples according to the variation in the wine variables measured. (A) variable contribution to two main principal components and (B–D) vineyard samples ordinations grouped by management type (conventional, C; organic, E), type of wine (Red; White) and the island of origin (El Hierro, EH; La Palma, LP; La Gomera, LG; Tenerife, TF; Gran Canaria, GC; Fuerteventura, FT; Lanzarote, LZ) respectively. See Supporting Information Table S1 for variable codes in A.

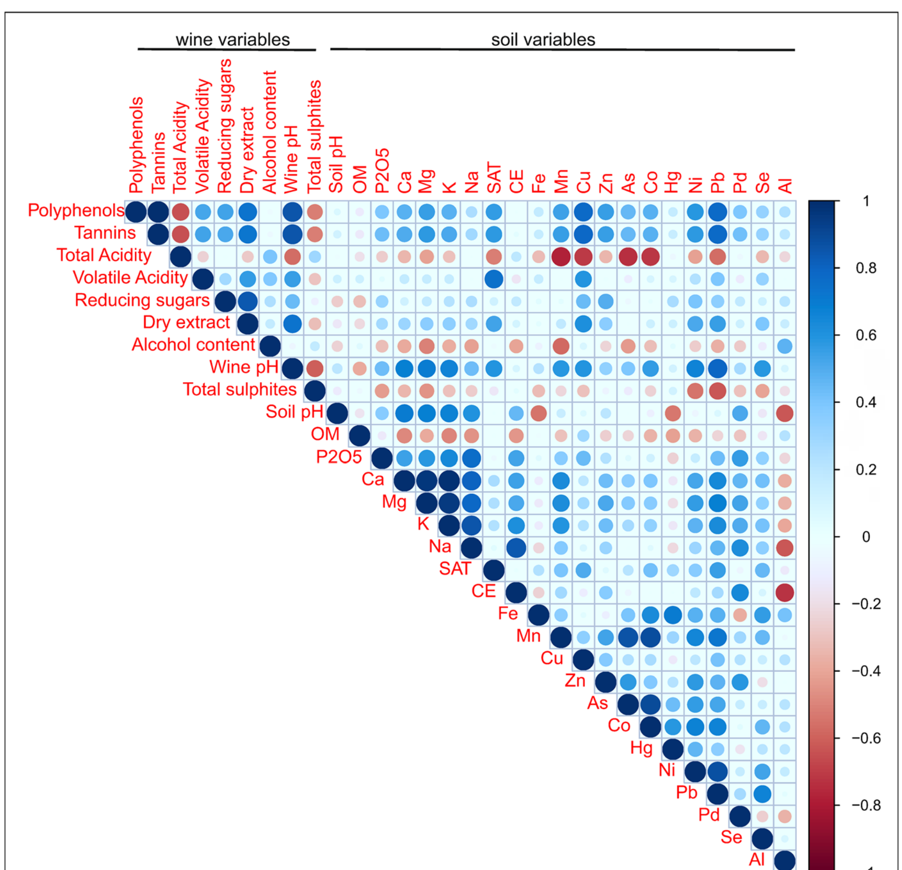

Figure 6. Correlation plot between all pairs of the wine variables (nine main variables) and soil variables (21) measured. Color scale according to Spearman correlation coefficient (*r*) and circle size absolute *r* values. See Supporting Information Table S1 for variable codes.

Finally, regarding the correlation between soil and wine variables (considering a subset of variables excluding metals and rare elements) of the studied vineyards, polyphenols and tannins in the wine samples were positively correlated ($r > 0.50$) with different soil parameters such as Mg, SAT, Mn, Cu, Zn, Ni and Pb (See Supporting Information Figure S1). This is in line with most reports highlighting a correlation between metals from anthropogenic origin such as Cu, Pb and Zn (Frink, 1996; Ma *et al*., 1997; Peris *et al*., 2007). The occurrence of Mn and Ni can be explained by their natural presence due to lithogenic components characteristic of the volcanic soils in the Canary Islands. In contrast, no significant associations were found between metals and the percentage of soil organic matter. Significant and strong positive correlations ($r > 0.65$) were also found between wine pH and the concentrations of Ca, Mg, K, Ni and Pb measured in the soil samples. The total acidity of the wine samples was negatively correlated ($r < -0.70$) with the concentrations of Mn, Cu, As and Co in soil samples. Increased K and Ca levels are generally described as an increase in pH and total acidity, but this relationship is only present here in the case of pH but not for total acidity (Retallack & Burns, 2016). Similarly, there is no correlation between Na, Pb and Ca content with alcohol levels commonly described in the literature (Laibarra, 2015). There is a significant negative correlation between pH and Al, which is remarkable given that high Al levels in acidic soils can cause phytotoxicity and impair nutrient absorption (Seguel *et al*., 2013).

4. Conclusion

In summary, the statistical analysis revealed that island type was the most significant factor contributing to wine differentiation over wine type and production method. This observation holds true for both soil and wine samples. Nonetheless, some distinctions exist between the management systems. As our comprehension of wine quality deepens, the role of soils and soil properties in the long-term preservation of the vineyard and the expression of terroir becomes increasingly apparent. Further research is necessary to broaden our understanding of soil-wine correlations, incorporating regional variability and site-specific requirements. Additionally, efforts should be made to minimize confounding factors such as oenological additives and processing aids to prevent the distortion of soil-wine correlations.

Despite the inclusion of many potentially confounding variables, this research found no consistent differences between the two production methods. Conversely, it indicates that island specificities and land-use history can play a crucial role in determining soil management. The Canary Islands require further investigation to ascertain soil characteristics and tailor agricultural recommendations to each specific island, encompassing not only wine but also other agricultural produce. Practical implications for vineyard farming involve recognizing the significant differences in agronomic conditions on each island, which are currently underestimated in official recommendations.

There is a need for additional research on soil elemental composition, as four soil samples exceeded the legal maximum limits for Ni and Hg contents, three of which were found on Lanzarote. Based on the toxicological profile of soils, regular monitoring of Ni and Hg in agricultural soils in volcanic environments is recommended. Furthermore, bioremediation strategies such as bioventing, biosparging, bioaugmentation and biostimulation, which are all ecologically safe and cost-effective, should be implemented.

Significant research gaps persist in the literature on organic wine and vineyard management, particularly in volcanic regions. Currently, determining the boundaries between polluted and nonpolluted soils is challenging, necessitating further investigation into anthropogenic and natural soils in the archipelago and other volcanic areas. More research is needed to comprehend the anthropogenic or natural origin of metals in wines produced on soils of volcanic origin. It seems plausible that As, Hg, Co, Ni, Al, Mn and Pd are associated with parent or source rocks, while Cu is clearly linked to agricultural activities, and Pb could have both anthropic and natural origins, deviating from patterns found in other areas such as the Mediterranean. Further research would clarify potential toxicological concerns associated with wines produced on soils of volcanic origin.

Authors' contributions

Conceptualization: E.P.D. and P.A.G. Methodology and Formal analysis: P.A.B., O.P.L., A.C.A.D. and M.M.H.G. Validation: Investigation: E.P.D and P.A.G. Funding acquisition: E.P.D. Drafting of manuscript by P.A.G. Review and comments by O.P.L., A.C.A.D and P.A.B. All authors read and approved the final manuscript.

Disclosure statement

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