



Waste-derived amendment design and its effectiveness in soil and grapevine sustainability

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Abstract

Propose Sustainable agriculture promotes the use of local resources for management and production without diminishing crop profitability. This represents a challenge in the search for new products with lower environmental impact and fertilizer alternatives that meet the nutritional needs of crops. The objective of this study was to develop a tailored amendment, formulated and produced from recovered waste, and to evaluate its effectiveness in meeting the specific needs of the soil and the *Vitis vinifera* var. Red Globe crop.

Methods The amendment was formulated from agro-industrial waste (asparagus residue, four different types of bagasse, cattle manure, and ash) sourced within a 150-km radius from the production facility. Its response in a vineyard —1 ha per treatment— was compared against a mix of cattle and sheep manure (conventional amendment). Quality assessment was performed based on the soil's physicochemical characteristics during the 615 days after application, and its response to the crop during the first year, using growth and productivity variables. Economic performance was assessed through a cost–benefit comparison of the two amendments transportation, production, application and product sells.

Results The soil fertilized with the designed amendment showed improved nutritional status, with increased organic matter, nitrogen, and cation exchange capacity compared to both the control and pre-fertilization conditions. Vine growth and productivity parameters showed a significant increase in branch length, yield, bunch count per plant, and bunch weight, resulting in an increase of more than 9 Mg of grapes/ha with the designed amendment compared to the conventional one. Economic evaluation revealed a net gain exceeding USD 18,500 per hectare when using the designed amendment instead of the conventional manure, therefore the financial analysis also showed the opportunity for scaling it up in the sector.

Conclusion The designed amendments based on the valorization of agro-industrial waste proved to be an appropriate solution for vineyard fertilization, contributing to improved its productivity and soil quality.

Keywords Sustainable agriculture · Waste recovery · *Vitis vinifera* · Composted amendment · Manure

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1 Introduction

In the 21st century, there has been an intensified concern about addressing the environmental impact generated by agricultural activities without affecting the economic performance of the crops (FAO 2018). Effective management of crop fields is essential to mitigating environmental damage such as the eutrophication of water bodies (Beeckman et al., 2018; MacDonald et al. 2011), being a proper fertilization a key factor (Chien et al. 2009). This implies not over-applying mineral fertilizers but just the necessary nutrients required by a crop in a specific soil at a specific time, being recently addressed by an Integrated Nutrient Management (INM) strategy (Jat et al. 2015; Wu and Ma 2015; Beeckman et al., 2018; MacDonald et al. 2011). This will be beneficial

both, the environment and it has also been demonstrated to enhance economic performance by reducing costs (Amanullah et al. 2023; Wu and Ma, 2015). Additionally, the optimization on fertilization management to only fulfill soil and crop demands is key for reaching sustainability in agriculture (Hebebrand and Glauber 2023; Medinets et al. 2025). In viticulture specifically, integrated organic fertilization strategies have been shown to improve not only soil physicochemical properties but also influence grape biochemical composition, including phenolic compounds, anthocyanins, and nutritional attributes.

Promoting circular economy in agriculture is one of the most promising strategies (Chojnacka et al. 2020; Comission 2020). The use of agro-industrial by-products and waste as fertilizers offers a promising alternative to complement inorganic fertilizer applications (Amanullah et al. 2023; Jat et al., 2015). This approach reduces costs while enhancing soil properties by adding organic matter, which indirectly improves key edaphic parameters such as cation exchange capacity, water retention, and the gradual release of nutrients (Agnew and Leonard 2003; Scotti et al. 2015). The valorization of waste in agriculture can be performed by directly applying these materials (crop residues) to the soil to prevent erosion, for example, but also through composting, instead of sending them to landfills (Lou and Nair 2009), which causes pollution besides clogging problems. Scientists support the development of organo-mineral amendments as a sustainable alternative for waste valorization (Ravindran et al. 2021). A substantial number of scientific articles and books discuss the benefits of these practices, such as reducing greenhouse gas emissions (Lou and Nair 2009; Walling and Vaneckhaute, 2020), improving soil structure, water retention, and obtain a hygienized —through fermentation processes— product, among others (Le and Price, 2024).

In vineyards, several studies have already demonstrated that waste-derived organic amendments can improve soil organic matter, nutrient availability and biological activity, while significantly raised grape yield and total acidity (Rubio et al. 2013). Similarly, the combined use of cover crops and amendments made from by-products has also been shown to increase grape yield and influence berry sugar concentration in cool-climate vineyards (Messiga et al. 2016). More recently, long-term trials in Mediterranean vineyards have shown that different organic amendments such as municipal solid-waste compost, cattle manure and sewage sludge can alter soil fertility and water availability, highlighting the need to better understand soil–plant feedback under organic fertilization strategies (Botelho et al. 2020). Last year, Kaya et al. (2024) showed that the right use of soil management and waste-derived fertilizers can reduce the concentration of biogenic amines and this year. However, it is needed to keep on studying the behavior of waste-derived organic

amendments as fertilizers, specifically for vineyard Biagi et al. (2025). They tested the vineyard soil health by modifying soil C and N pools, enzymatic activities and the structure of bacterial and fungal communities, highlighting the effect of the type of waste-derived amendment, which can behave as a regular amendment but also as mineral fertilizers.

Given the current issues previously mentioned regarding waste generation, the scarcity and rising costs of fertilizers (Hebebrand and Glauber 2023b), and the conservation of soil quality and groundwater, innovative alternatives that can address these problems in an environmentally and economically viable way are needed. These amendments cannot totally replace inorganic fertilizers to sustain the production levels necessary to feed the current and future global population due to, for example, their inability to target a specific soil nutrient because their application inevitably alters other soil elements. This limitation presents a significant challenge for the scientific community, many of whom have pushed the INM (Jat et al., 2015; Wu and Ma, 2015), where combining organic and inorganic fertilizers can enhance crop quality and yield through more precise and specific fertilization, thereby minimizing nutrient loss and respecting the environment. Comprehensive reviews also underline that organo-mineral products obtained from waste streams can simultaneously address soil degradation, nutrient imbalances and greenhouse gas emissions (Bouhia et al. 2022; Uddin et al. 2025).

Our approach is conceptually related to the organo-mineral fertilization framework, which combines organic matrices with mineral nutrients to enhance nutrient use efficiency and soil health. However, very few studies have explored the formulation of waste-based amendments specifically tailored to the nutrient demands of grapevine and to the constraints of a given vineyard soil, without relying on synthetic mineral fertilizers. Positioning our study within this emerging field helps bridge the gap between general organo-mineral fertilizer research and viticulture-focused applications. In addition, understanding the temporal evolution of soil properties following organic amendment application is crucial for optimizing fertilization strategies, as recent multi-year investigations have demonstrated significant time-dependent changes in nutrient availability and soil chemical characteristics (Kaya et al. 2024).

Thus, the objective of this study is to demonstrate in field conditions that formulating an amendment from many waste-derived materials to target specific crop and soil nutrients demands is a plausible sustainable strategy that has environmental, social and economic benefits. An innovative aspect of this approach is the exclusion of synthetic inorganic fertilizers within the fertilizer, replacing them with organic and inorganic waste as a potential alternative, differing from INM. A key challenge lies in ensuring that the

theoretical formulation (expected properties) aligns with the observed performance of the final product, while complying with the European Union (EU) Regulation 1009/2019 on fertilizers—which is one of the most developed and restricted regulations worldwide. This novel methodology for synthesizing sustainable fertilizers is highly relevant, as it facilitates the efficient management of large quantities of waste, yielding both economic and environmental benefits. Furthermore, it has the potential for global application, considering legislative constraints, which could be revised based on scientific evidence.

2 Materials and methods

2.1 Setting and experimental design

This study was conducted in the desert of Sechura, Piura (Peru), at the agro-industrial facility of Frutas de Piura S.A.C company, dedicated to the production, processing, and export of mango, grape and banana (Fig. 1). This area has an arid and warm climate with a maximum temperature range from 27.5 to 34 °C, while the minimum ranges from 17 to 23 °C (July and February, respectively). The mean annual precipitation is 235 mm, concentrated from January to April (Castro et al. 2021).

The soil of the study area belongs to Haplic Arenosols group (IUSS Working Group WRB 2022), characterized by a 90% of sand, low fertility, and cation exchange complex, no structure and no diagnostic horizon observed (MINAM 2010).

A representative 2.7 hectares of the vineyard was selected, which was managed uniformly and irrigated using the same well (Fig. 1). The experimental area contains 3200 plants of *Vitis vinifera* var. Red Globe, ~14 years old, were affected by *Cylindrocarpon* spp—black foot disease of grapevine—showing a yield decrease from ~27 Mg ha⁻¹ (2018) to ~18 Mg ha⁻¹ (2020).

The experiment consisted of two treatments: (1) a Control treatment, in which a conventional amendment composed of cattle and sheep manure was thoroughly incorporated into the soil; and (2) an inoculated amendment treatment (IA), where the formulated amendment—prepared from asparagus residue, four types of bagasse, cattle manure, and ash—was similarly mixed with the soil. The treatments were defined to compare the farmer's management against the innovative formulated alternative, which contain a microbial cocktail to combat *Cylindrocarpon* spp and to stimulate the growth of new young roots (see Sect. 2.2 for more details about inoculation). The treatments were applied in one hectare each (~20 rows of plants), which were separated by a lane of 0.75 hectares (~15 rows of plants). Both

Fig. 1 Location of the study area, experimental area and plot diagram with an area of 1 ha for each treatment (C: Control; IA: Inoculated Amendment)

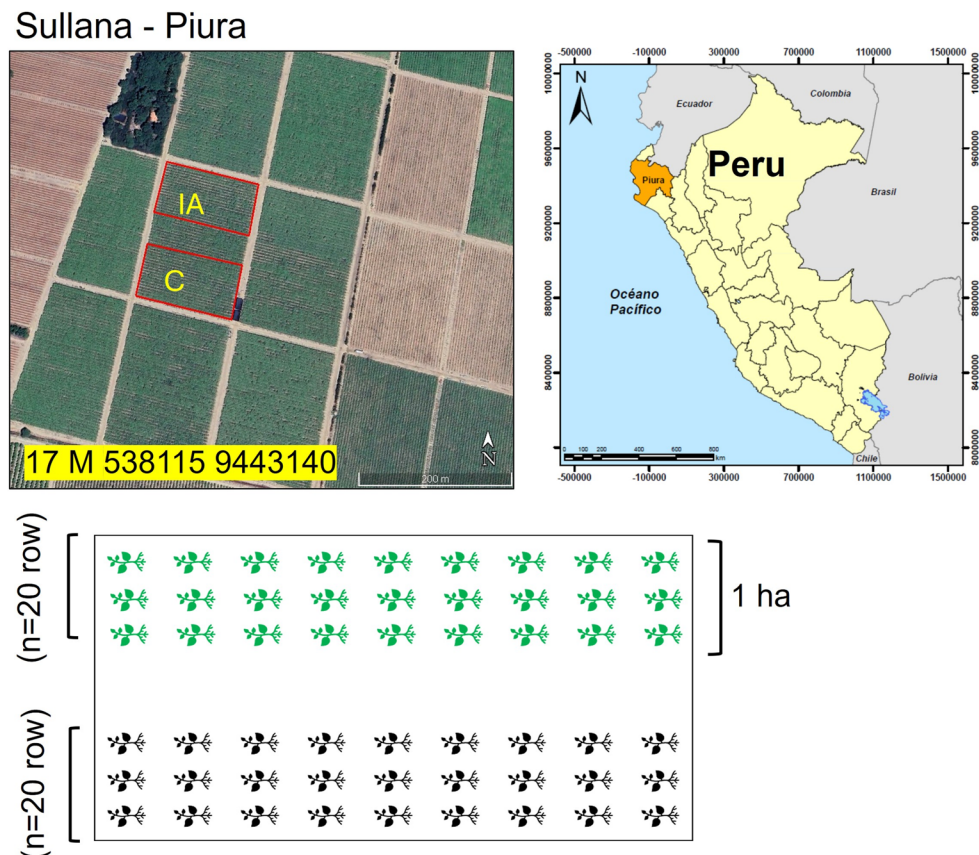


Table 1 Expected and observed soil properties in relation to grapevine requirements (Torres et al. 2017)

Parameters	Units	Soil Properties		Crop nutrients uptake kg ha ⁻¹
		Recommended	Observed	
OM ¹	g kg ⁻¹	> 15	17.7	-
pH	-	6.2–7.0	7.1	-
EC ² (1:1)	dS m ⁻¹	< 1.5	0.74	-
Total N	mg	300–600	200	90
Inorganic N	kg ⁻¹	15–30		-
Olsen P		> 15	37	7
Fe		4–6	28	-
Mn		2–4	7.9	-
Cu		0.5–1.0	3.1	-
Zn		0.8–1.5	8.6	-
B		0.8–1.5	0.4	-
CEC ³	cmol _c	8–15	5.9	-
Exchange Ca	kg ⁻¹	7–10	4.28	18
Exchange Mg		1.0–1.5	1.29	11
Exchange K		0.3–0.5	0.35	118
Exchange Na		0.03–0.3	0.01	-
SBases		> 8	5.93	-
Ca _{CEC}	%	60–65	72.2	-
Mg _{CEC}		12–15	21.8	-
K _{CEC}		2–3	5.9	-
Na _{CEC}		< 1	0.2	-
Ca/Mg	-	8	3.3	-

¹Organic matter; ²Electrical conductivity; ³Effective cation exchange capacity

amendments were applied at the same time and according to the farmer's methodology. A trench ~35 cm wide and ~30 cm deep was dug on one side of the plants row (125 m long), where the amendments (C and IA) were manually mixed with the soil (~400 Mg) and the mixture was then covered with 5 cm of soil. The corresponding doses were 55 and 35 kg of manure and design amendment per plant (65 and 42 Mg ha⁻¹, respectively). The crop was drip irrigated, sharing the treatments through the same system that was managed by the farmer. The irrigation water quality characteristics are presented in Table S1.

During the study, the main soil chemical properties, plant growth parameters (shoot length, shoot diameter, number of internodes and yield), and leaf and fruit quality were monitored, which are mentioned in the following sections.

2.2 Elaboration and formulation of the designed amendment

The formulation of the designed amendment was based on plant demands and soil conditions, complying with the levels established in the European Regulation 1009/2009 on Fertilizers, specifically CFP3 (b) inorganic amendments (IA). The objective was to increase yield from 18 to 25 Mg/

Table 2 Designed amendment formula showing the volume (V) and dry matter (DMW) percentage (%) of each waste

Waste	V (%)	DMW (%)
W1–Bagasse A	5	3
W2–Ashes	6	27
W3–Bagasse B	10	7
W4–Bagasse C	10	7
W5–Bagasse D	10	7
W6–Cow manure	9	17
W7–Asparagus brushwood	50	32

The letters of the bagasse materials refers to the different industrial origin and therefore they possess different physicochemical properties.

ha, so the total amount of nutrients absorbed by the grapevine in a season was determined according to the guidelines of Torres et al. (2017) and the current soil condition (Table 1). With the identification of nutritional needs, various agro-industrial residues or by-products were selected to allow their use in the formulation, based on the key requirements that were: (1) Supply ~118 kg of available K during the season, releasing more than 50% in the first ~3 months and gradual release during the rest of the crop cycle, that is, contributing with materials that have a high content of available K, (2) Contribute to the increase of the cation exchange capacity, with the goal of going from 6 to 10 cmol_c/kg; (3) provide high contents of C and N that allow obtaining a product with an adequate C/N ratio, (4) Provide materials with slightly alkaline pH or low buffer capacity, as well as moderate to low electrical conductivities to obtain a product with pH conditions in the ideal range of 6.5–7.5 and <4 dS·m⁻¹, and (5) Low or zero content of potentially toxic elements, according to with the restrictions of mentioned regulation.

It was also considered that composting processes result in the loss of around 30% of organic carbon and 40% of total nitrogen, as well as some nutritional content, through leaching (Sommer 2001). Taking all these factors into account, seven wastes materials located near Inproyen's production facilities in Peru, were selected to ensure the economic viability of the designed product.

The formulation obtained for the designed amendment is presented in Table 2. It is obtained by mixing the materials in the indicated proportional quantities and homogenizing them. The mixture was then placed in trapezoidal piles with a base of 4 m and a height of 1.8 m. The temperature of the mixture was measured daily during the maturation process with a thermal lance (Dial GT300R-42 Industrial Bimetallic Thermometer) to ensure the sanitation of the resulting product (Larney et al. 2006). After 39 days, the amendment was physiochemically analyzed.

The designed amendment was then inoculated with *Trichoderma harzianum*, *Trichoderma asperellum* and *Trichoderma viridae* contained in Bio-Trichod[®] product and with *>Pseudomonas fluorescens* Azotobacter, *>Azospirillum* and *>Bacillus subtilis* contained in Promobiol[®] product. To achieve this, 2 kg of Bio-Trichod[®] and 2 L of Promobiol[®] in 400 L of water with 0.01% soap (to facilitate conidium homogenization) and the mixture was spread over the surface of the pile using a hand-pumped compressed air sprayer backpack. The estimated total conidia concentration of 4.7×10^4 conidia g⁻¹ of IA. Inoculation and homogenization were carried out three days before the application of the amendment designed in the field.

2.3 Physicochemical characterization and test monitoring

For the characterization of the wastes used for the formulation of the IA, as well as the resulting product, samples were collected, dried at 40 °C, homogenized and sieved at 2 mm. The following physicochemical analyses were performed on the fraction smaller than 2 mm: electrical conductivity (EC) (SMEWW 2017a) and pH (SMEWW 2017b) at 1:2.5 (m: V); total C, N and S contents (Schumacher 2002); total organic carbon (Co) (Walkley and Black 1934); labile carbon, extractable with sodium pyrophosphate (Cp) (Bascomb 1968); available phosphorus (Olsen et al. 1954); nitrate and ammonium (NO₃⁻, NH₄⁺) extracted by KCl and measured by spectrophotometry on a Power-Wave-XS microplate reader according to the methods proposed by (Miranda et al. 2001; Mulvaney 1996); cation exchange capacity (CEC, extraction with 1 M NH₄OAc buffered to pH 7) with the contents of Ca, Mg, Na and K in the CEC; The elemental contents of the available fraction determined at equilibrium (1:20; m: V) were determined using the methodology of Buján et al. (2010); and the elemental contents of the pseudo-total fraction obtained by acid digestion (EPA 3050B 1996). The different elements (Ag; Al; As; Ba; Ca; Cd; Co; Cr; Cu; Fe; Hg; K; Mg; Mn; Mo; Na; Ni; P; Pb; S; Sb; Se; Si; Sn; Sr; Tl; Ti; V and Zn) in the available and pseudo-total fractions were quantified by inductively coupled plasma optical emission spectroscopy (ICP-OES). The organic matter (OM) content was determined according to the Van Bemmelen conversion factor to total organic carbon (Co) $\times$ 1.72. All results were prepared in ISO 17,025 certified laboratories.

Soil quality was monitored by sampling and analyzing the soil before application (PreT) and at 51, 163, 365 and 615 days after application (DAI), resulting in a total of five samplings. For each treatment (Control and IA), one composite sample of 12 subsamples was collected each time. These samples were obtained from the trench application

area at a depth of 30 cm, excluding the first 5 cm. The analyses performed correspond to the aforementioned methodology for pH, electrical conductivity, organic matter, total N, available P, cation exchange capacity, exchangeable cations, as well as micronutrient contents obtained by DTPA extraction (Lindsay and Norwell 1978).

At the plant level, aspects of development, productivity and nutrition in the leaves and fruit were evaluated. Growth parameters of the plants, such as shoot length and diameter and the number of internodes, were measured twice during the monitoring period (at 62 and 129 DAI), using the same 20 plants selected at random per treatment each time. Additionally, four days before harvest, the number and weight of bunches were measured to determine yield, as well as the size and Brix of the grapes. To achieve this, bunches were counted on 15 plants per treatment, and a total of 100 bunches were weighed. The size of the grapes was measured using a digital caliber on 90 grapes, and the Brix degrees were measured on 15 grapes using a refractometer.

Nutrient concentration in leaves was measured twice before and after implementation, choosing the veraison plant stage as the most stable period for foliar sampling (Torres et al. 2017). This stage is the phase in grape development when berries begin to change color and accumulate sugars, marking the transition from growth to ripening. During this stage, nutrient concentrations in leaves are more stable, providing a reliable representation of the vineyard's nutritional status. 50 leaves (one per plant, opposite to the first bunch of the charger branch) from each treatment were collected. The nutrient concentration in fruits was also measured one time before and after implementation, taking the samples 1 day before harvesting. Grapes (50) were randomly selected from the bunches weighed. Either leaves or fruits were dried out and then digested with nitric acid before elemental content was measured by ICP-OES.

Soil inoculum monitoring was not carried out because of the marked concentration decrease under field conditions, particularly in soils with sandy texture and low content of organic matter (Gonzalez-Guzman et al. 2021).

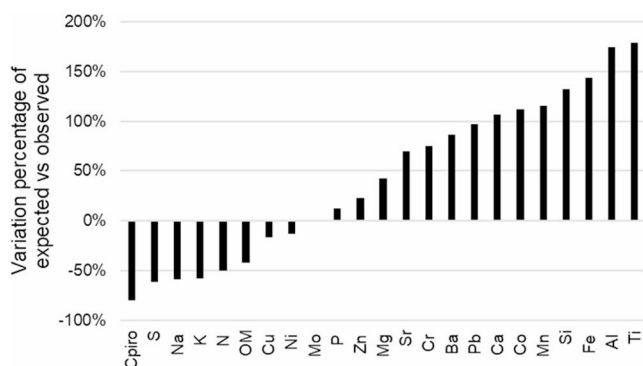
2.4 Statistical analysis

A Randomized Design ANOVA where variables were compared between Control and IA treatments was performed. A square root transformation was used when the data did not fulfill normal distribution and homoscedasticity. Due to the inherent variability of field experiments and the large-scale nature of this trial we denoted the term “significant” as the probability of less than 10% ($P < 0.1$) to refuse null hypothesis (Gomez and Gomez 1984; Crawley 2015; Gonzalez-Guzman et al. 2021). All statistical analyses were performed

Table 3 Chemical properties of the traditional manure (Control) and the designed amendment (IA)

Parameter	units	Control	IA	Parameter	units	Control	IA
pH	-	8.9	8.7	Mg	g kg ⁻¹	5.1	3.9
EC	dS m ⁻¹	5.6	4.0	Na	g kg ⁻¹	3.7	1.0
CEC	cmol _c kg ⁻¹	-	33.9	Fe	mg kg ⁻¹	1545	12,030
OM	g kg ⁻¹	800	240	Cu	mg kg ⁻¹	16	25
Cp	g kg ⁻¹	-	8.7	Mn	mg kg ⁻¹	82	215
S	g kg ⁻¹	8.3	1.2	Zn	mg kg ⁻¹	44	59
N	g kg ⁻¹	23.2	5.2	B	mg kg ⁻¹	128	120
P	g kg ⁻¹	3.5	4.2	Mo	mg kg ⁻¹	<2.5	5.0
K	g kg ⁻¹	24.4	8.4	Co	mg kg ⁻¹	-	4.0
Ca	g kg ⁻¹	20.8	16.0				

EC: Electrical conductivity; OM: Organic matter; CEC: Cation exchange capacity

**Fig. 2** Percentage variation of the concentration values formulated of chemical elements respect to final observed in the IA formulation

with the software STATISTIX v. 10.0 (Analytical Software, Tallahassee, FL, USA).

3 Results and discussion

3.1 Quality of the designed amendment

The amendment was designed to comply with European Union Fertilizer Regulation 1009/2019, under Functional Product Category (PFC) 3B. To address the correct dosage of the materials used in the formulation, the total and available content was considered (Table S2), without posing a risk to the environment, and the quality of the resulting product was evaluated (Table 3) and showing its analytical robustness with the coefficients of variation of each analysis (Table S3).

The formulation was one of the key steps, in which nutritional aspects, soil demands and loss in the production process were considered. The loss of elements to the atmosphere and through leaching must be considered due to different variables such as moisture (Richard et al., 2002), bulking agents (Zhang and Sun, 2016), redox potential (Khalil et al. 2008), aeration, particle size, time, organic matter content, C/N ratio (Bueno et al. 2008; Sadaka and El-Taweel

2003), temperature (Noble et al. 2011), and withdraw turnings (Ma et al. 2022; Wang et al. 2024). The amendment was sanitized, with the composting process exhibiting a thermophilic phase (45–70 °C) that persisted for 19 days, with a total of 8 days exceeding 60 °C. The day after exceeding this temperature, the pile was mixed to homogenize and prevent high water evaporation due to its scarcity. The total duration of the homogenization and fermentation processes was 39 days, reducing the composting process time and eliminating turning (mainly minimizing C and N losses). Despite this, the parameters Cp, N, S, and OM have decreased significantly in the final product (Fig. 2). This is due to the significant loss of C (CO₂ and CH₄), N (NH₃ and N₂O), and S gases during fermentation (Bao et al. 2010). The Cp experienced the greatest decrease since it represents the carbon fraction easily degradable by microorganisms (Hall et al. 1996). On the other hand, the expected results were obtained with respect to leaching, showing the greatest losses in Na and K (Fig. 2), elements more soluble in water, contrary to what was found by Gao et al. (2023), who found a decrease in the order Ca>K>Mg>Na. This may be due to the higher concentration of Ca and Mg in the cell wall of organic waste (Bagasses) and the higher soluble concentration of K and Na in the manure and ashes used. In agreement with what was seen in Gao et al. (2023), micronutrients (Fe, Cu, Mn and Zn) and potentially toxic elements such as Sr, Ba, Pb, and Co were increased due to organic decomposition and weight loss and because heavy metals are not biologically degraded (Fig. 2). In addition, Si, Fe, Al and Ti increased due to their high concentration in ashes and low leaching loss favored by the alkaline pH. The influence of processing methods on nutrient retention and availability in organic amendments has been extensively studied, with recent research demonstrating that pre-treatment strategies and processing conditions significantly affect the chemical composition and nutrient release characteristics of the final products (Incesu et al. 2022; Kaya et al. 2024, 2025).

On the other hand, regarding the suitability of the amendments, when comparing the Control and the IA, both showed

elevated reaction conditions, with a $\text{pH} > 8.5$, as well as high EC (Table 3). The IA presented lower EC because of the stabilization of the materials during the composting process, which leads to salt loss (Álvarez González et al., 2009), the elimination of potential pathogens, and favors the formation of humic substances (Noble and Roberts 2004). These substances are responsible for the high CEC observed in IA, of $\sim 34 \text{ cmolc/kg}$ (Table 3), and the resulting capacity to retain cationic nutrients (Ca, Mg, and especially K), which will improve the gradual release of nutrients at times of crop demand (Cayuela et al. 2004).

The OM contents were high in Control compared to the IA, with values of 800 and 240 g/kg, respectively (Table 3). While these values are high in Control, they also show a greater tendency toward mineralization, with very low C/N ratios. In IA, the C content in its labile fraction (C_p) is less than 1%, which could be related to greater stability (Table 3). This favors root development because it prevents rapid mineralization of organic matter within the soil, and consequently a possible abrupt change in soil pH (Lauchli and Grattan 2017; Tan et al. 2019).

For most macronutrient and micronutrient contents, the IA presented much lower contents, which is largely due to leaching losses during the composting process (Alvarez González et al. 2009). The greatest differences were observed for S and N, with approximately 8 and 5 times higher in Control than in IA (Table 3). The P contents were higher in IA, with values of 4.2 g/kg (Table 3), which is related to the contribution of ash as part of the constituents, which contributes a mineral fraction, such as apatite or oxides, that are not readily available, as also observed by other authors (Möller et al. 2007; Tan and Lagerkvist, 2011). Regarding the maintenance of P in the designed amendment, high Fe contents were observed (12030 mg/kg), which favors the binding with phosphate groups, which are stable and less vulnerable to leaching (Tan and Lagerkvist, 2011).

The IA, being constituted from the mixture and interaction of different agro-industrial wastes, was evaluated for its content of potentially toxic elements, in accordance with EU legislation (Unión Europea, 2019), the results of which are presented in Table 4. The highest contents were evident for Al and Cr, the former being associated with mineral constituents and of neglected availability under the existing pH conditions (Dhal et al. 2013; EPA 2003). The Cr also originates from the ash, being found in unavailable forms and the values, of 148 mg/kg (Table 4), meet the contents for class B in fertilizers obtained from materials of plant or animal origin. The remaining metal and metalloid contents are low, some of them below the analytical detection limits and do not pose a risk, even meeting the metal values to be considered as class A fertilizers (Table 4). It is important to emphasize that the total contents, although they are

Table 4 Potentially toxic elements contained in designed amendment (IA)

	Ag	Al	As	Ba	Cd	Cr	Hg	Ni	Pb	Sb	Se	Sn	Sr
	mg kg ⁻¹												
IA	1.2	9240	<5	47	0.5	148	<2.5	8.8	5.5	<5	<10	<5	71

normally considered at the regulatory level, must consider the available fractions and the biogeochemical evolution that they may undergo in the soil.

3.2 Evolution of the amended soil

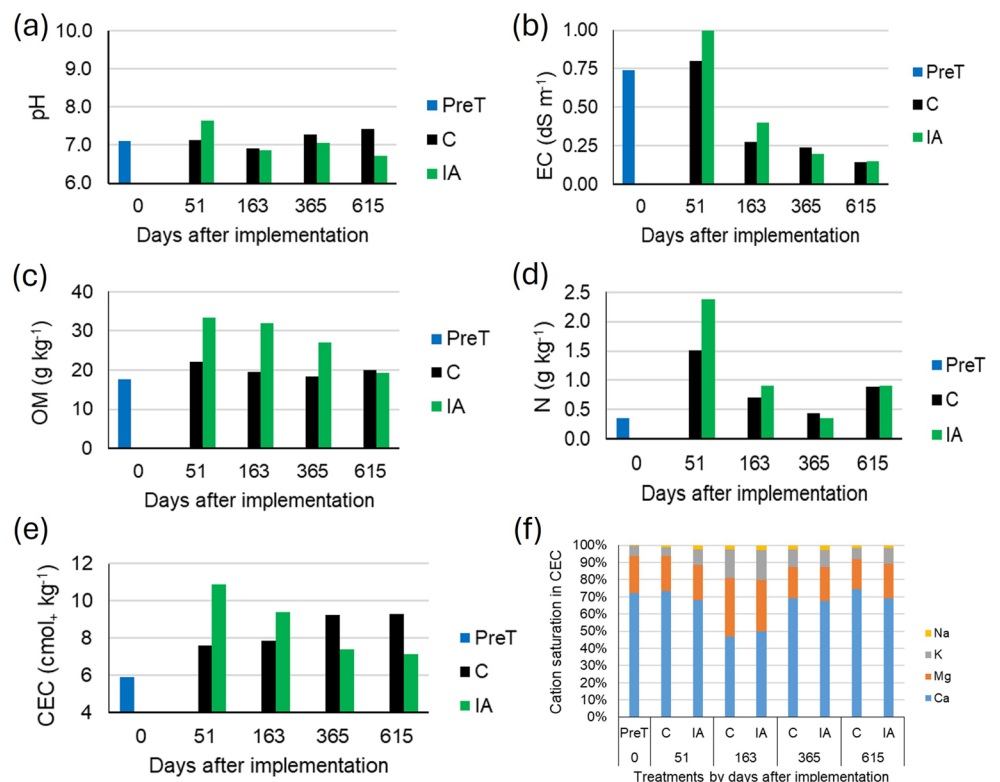
The application of both amendments, Control and IA, at doses of 65 and 42 Mg/ha respectively, led to changes in various physicochemical parameters at the soil level throughout the 615-day follow-up period (DAI). Soil pH remained close to neutral throughout the evaluation period (Fig. 3A), initially increasing in the IA treatment due to the liming effect of the ash (Ohno and Erich, 1990) and decreasing over time as a result of acidification and degradation of OM, reaching values of almost one pH unit lower than the control treatment after 615 DAI. Soil EC was the parameter that varied the most during the experiment, decreasing to 0.25 dS/m—from 0.75 dS/m—with both amendments in the first 365 DAI, and continuing to decrease to 0.14 dS/m at 615 DAI (Fig. 3b). Colloidal flocculation and adsorption of negatively charged ions from OM appear to be the dominant processes (Churchman et al. 1993), in addition to plant nutrient uptake.

Soil OM increased 10 g/kg more with AI than with Control at 51 DAI, contrary to what would be expected given the OM contribution of each amendment and the lower application rate at IA (Fig. 3c). However, as indicated above, the IA exhibited greater stability and lower losses

due to mineralization or leaching within the soil. The contents in the soil with IA remained higher than pre-treatment values for 615 DAI (Fig. 3c), while for the Control, values similar to the initial soils were maintained throughout the evaluation period, in the different periods of this first year of monitoring and maintenance of these contents for 615 DAI (Fig. 3c). The N content with the application of the amendments increased to 1500 and 2400 mg/kg of soil (Control and AI, respectively) at 51 DAI, and then gradually decreased over time, with final values of the first year (365 DAI) similar to those under pre-fertilization conditions, which increased slightly in the following year as a result of the continuous degradation of the OM (Fig. 3d). During the evaluation year, the N content obtained met the recommended amounts for this nutrient in soils according to Torres et al. (2017) (Table 1). It is worth noting that despite the difference in the application of each amendment, the IA treatment showed greater efficiency from the start, as it contained more stable N forms due to the amendment was stabilized, contrarily to manure application (Bernal et al. 2009). In the Control treatment, since the OM was fresh, most of the C and N content was lost after application either by leaching or to the atmosphere (Qi et al. 2023). This was evident in the first season at 51 DAI, which was already lower than for the IA (Fig. 3c-d).

The cation exchange capacity is low, both from the values prior to the different treatments and with the addition of both amendments at different times. The initial increase

Fig. 3 Temporal evolution of soil properties in the 615 days after the application of the amendments (C: Control; IA: designed amendment; PreT: soil values previous to application) for the following parameters: (A) pH; (B) EC: electrical conductivity; (C) OM: organic matter; (D) N: total nitrogen, (E) CEC: cation exchange capacity, and (F) cations in the exchange complex



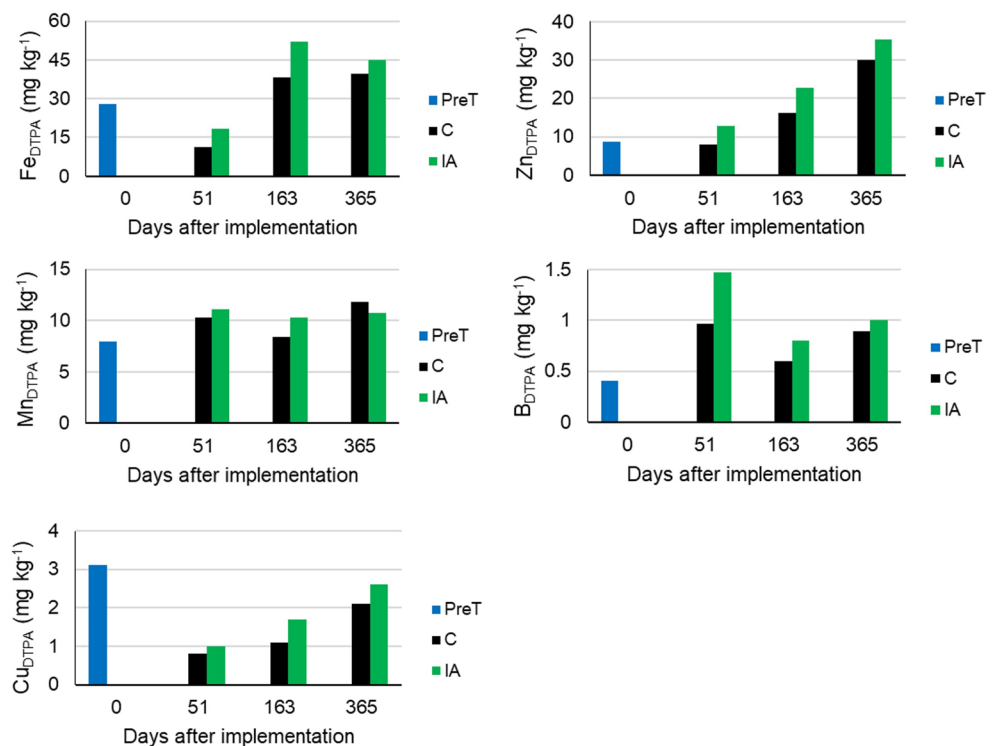
observed in IA also led to an initial increase in the CEC, from 6 to 11 $\text{cmol}_\text{c}/\text{kg}$ (Fig. 3e), conditions already suitable for soils of this crop (Torres et al. 2017). The decrease in the IA treatment was also associated with the loss of the OM, reaching values of around 7 $\text{cmol}_\text{c}/\text{kg}$ for 365 DAI, which were maintained for 615 DAI (Fig. 3e). The evaluation of the cations presents in the exchange complex showed that the proportion of exchangeable K in the IA treatment at 51 DAI was 3 times higher than in the C treatment, which was one of the objectives pursued in the formulation and whose increase was maintained until 163 DAI. After this time, the amount of K in the complex is not different between treatments, remaining similar in the 615 DAI evaluated. No significant differences were observed at different times or between treatments, with the complex saturated by Ca ranging between 45 and 70%, followed by Mg, K, and Na (Fig. 3f). These temporal patterns in soil organic matter and nutrient dynamics align with recent multi-year monitoring studies in vineyards, which have demonstrated sustained improvements in soil quality parameters extending beyond single growing seasons following organic amendment applications (Kaya et al. 2025).

The micronutrient content, referring to the contents obtained through DTPA extraction for Fe, Zn, Mn, B, and Cu, was generally higher in IA than in Control, and was assessed in the first year of monitoring (Fig. 4). In general, the initial soil for the trial was not deficient in these elements, except for B, whose values were half of those recommended by Torres et al. (2017) (Table 1). The application of both

amendments for Fe did not lead to increases in the available fraction in the first 51 DAI, with increases observed starting at 163 DAI (Fig. 4). The Zn contents also showed similar behavior, although the availability of this element reached up to three times the contents previously present in the soil (Fig. 4). The Cu content remained below initial values in both treatments, and although it increased over time, at 365 DAI it reached values similar to those under previous conditions (Fig. 4). These results indicate that Cu availability is closely associated with OM, which acts as a complexing agent for this element and limits its availability, which is gradually released with the degradation or mineralization of OM. In any case, the available Cu contents also meet the recommended ranges for these elements in the soil for grape cultivation (Torres et al. 2017).

The concentration of available Mn remained stable with both Control and IA throughout the evaluation period, while B contents increased with the application of the amendments (Fig. 4). The application of IA showed higher levels than treatment Control for all evaluation periods, with values suitable for grapevine cultivation exceeding 0.85 mg B/Kg (Torres et al. 2017), which were maintained over time up to the 365 DAI evaluated (Fig. 4). The observed patterns in soil micronutrient availability are particularly important as they directly influence plant mineral nutrition and subsequently affect berry biochemical composition, including phenolic compounds, vitamins, and amino acid profiles (Kaya et al. 2025).

Fig. 4 Availability of soil micro-nutrients (Fe, Zn, Cu, Mn and B) before implementation (PreT) and throughout the first 365 days of monitoring in soils with application of conventional (C) and designed (IA) amendments



3.3 Grapevine growth and nutrition

The various improvements observed at the soil level with the application of IA, such as increased OM, N, and K availability in the CEC, as well as improved micronutrient content, led to improved growth and nutritional status in the vine compared to Control. Grapevines in the IA showed an increase in shoot length and diameter compared to Control, in the mid-growth period (62 DAI) and at the end of the branches (129 DAI), with statistically significant increases in shoot length for both periods (Fig. 5). In contrast, the number of internodes was slightly lower with the IA, implying an absence of water stress (Bavestrello-Riquelme et al. 2012) because adequate soil amendments enhance water availability (Hudson 1994). These physiological responses align with evidence showing that waste-derived amendments improve vine vigor, nutrient uptake efficiency, nutrient dynamics, root system architecture but also soil structure, microbial activation and gradual nutrient release (Messiga et al. 2016), which directly influencing shoot growth, leaf nutrient balance and berry formation (Botelho et al. 2020).

At the nutritional level, the status of the grapevine in both treatments was evaluated by the nutrient compositional diagnosis, which is discussed according to the range of normal values for vine leaves established by Torres et al. (2017). The nutrient analysis of the leaves (180 and 330 DAI) showed an enrichment in P, Fe and Zn in the plants

under both treatments (Table 5). Although the soils with both amendments presented neutral to slightly alkaline pH values, the availability of P remained high, facilitating its absorption by the plant. This is explained because organic amendments have demonstrated strong effects on P and K dynamics in vineyards, increasing their mobility and plant availability even under neutral or slightly alkaline soils (Sitzmann et al. 2024). Simultaneously, the contents in the leaves for Fe and Zn exceeded the recommended thresholds (specified for the ripening period) in both amendments, consistent with the high concentration of these elements in the fertilized soil (Fig. 4). Additionally, Fe and Zn concentrations agree with findings showing that amendments enhance micronutrient bioavailability and influence berry secondary metabolism, including phenolic and antioxidant profiles (Biagi et al. 2025). However, it should be noted that this also means that, although the addition of OM tends to form organo-mineral compounds, the levels in the soil for these elements were too high as indicated in previous sections, with the exception of Cu, which presents a greater affinity and greater complexation (Clemente et al. 2006), conditioning its availability and absorption by plants. In contrast, foliar concentrations of Ca, Mg, K, Cu and B were within acceptable ranges for both amendments (Table 5). It should be noted that the improvement in the availability of potassium (K) in the soil, favored in the AI treatment, was also reflected in the K contents at the level of leaves and fruits

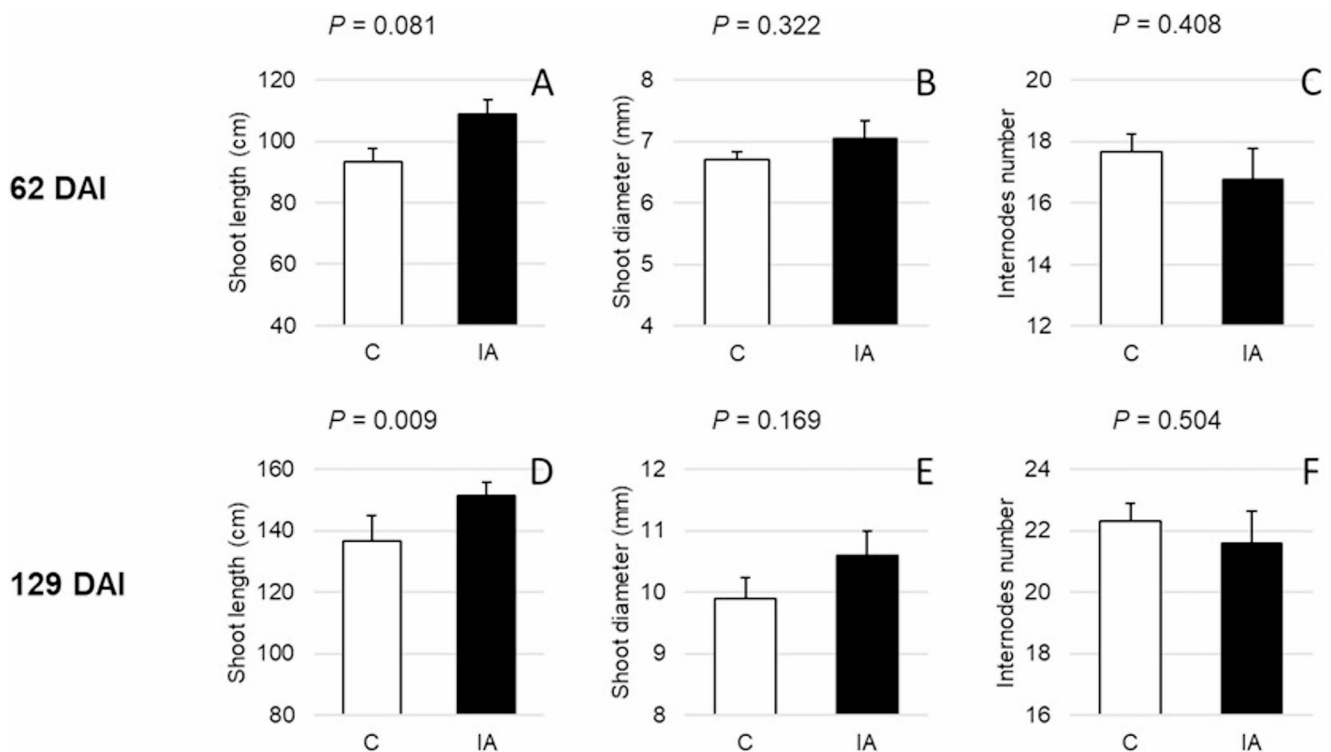
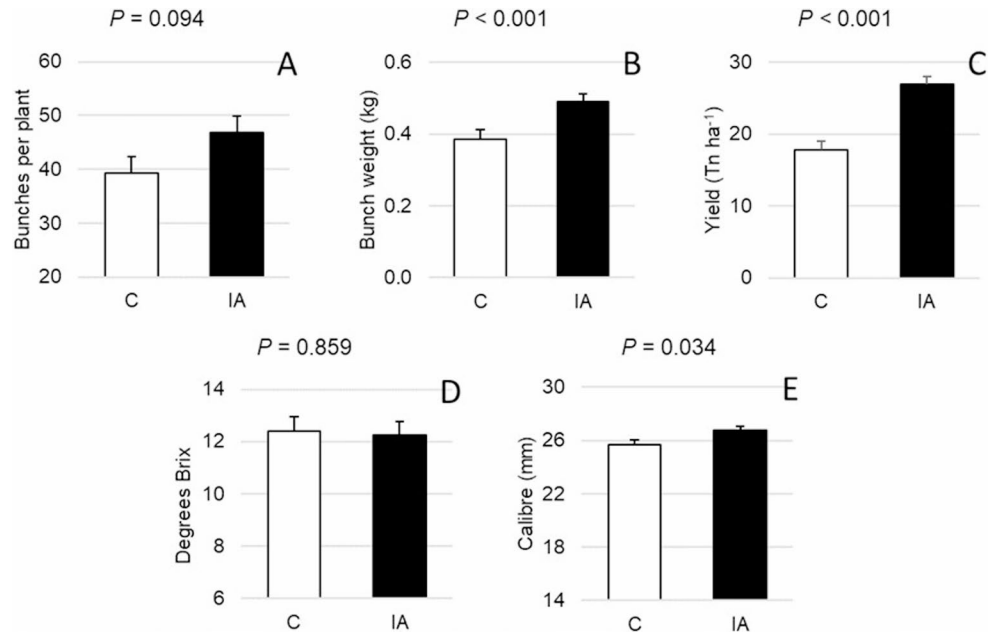


Fig. 5 Grapevine growth parameters (shoot length and diameter and number of internodes) for both treatments (C and IA) 62 (A, B, and C) and 129 (D, E, F) days after implementation (DAI). $N=20$ (by treatment)

Table 5 Concentration of macro and micronutrients in leaves at Pre-Treatment time, and 180 (end of vegetative growing) and 330 (ripening) days after implementation (DAI). Red color means concentration level above the maximum (Max) limit established by the INIA Manual (Torres et al. 2017), whilst pink colors means that concentration is below the recommended minimum (Min) concentration

Leaf nutrients	Units	Reference values		Sampling time & treatments				
		Min	Max	PreT	180 DAI	330 DAI		
				-	C	IA	C	IA
P	g kg ⁻¹	0.8	4	6.6	15.8	14.1	8.5	9.5
Ca		12	30	11.4	23.8	22.9	22.2	21.3
Mg		1.4	8	3.2	6.6	6.3	4.8	4.2
K		8	18	17.3	17.9	19.8	15.8	16.6
Fe	mg kg ⁻¹	40	200	367	364	464	1119	929
Cu		4	25	37	8	11	22	20
Mn		20	250	194	337	380	182	168
Zn		20	100	259	275	282	124	116
B		25	300	99	180	202	85	72

Fig. 6 Comparison of the mean number of bunches produced per plant (A), bunch mean weight (B), yield (C, number of plants per hectare × mean number of bunches per plant × mean weight of each bunch), degree Brix (D) and caliber (E) for both treatments. $N_{\text{bunches}} = 100$; $N_{\text{Calibre}} = 90$; $N_{\text{Brix}} = 15$ 

compared to treatment Control (Table 5). The enhanced foliar nutrient status observed with the designed amendment reflects complex soil-plant interactions that extend throughout the growing season, as recent research has demonstrated significant phenological stage-dependent variations in mineral, hormonal, and vitamin contents in grapevines (Kaya et al. 2025).

The results obtained are due not only to nutritionally appropriate formulation but also to the combined application of fungal and bacterial inoculants intended to combat the *Cylindrocarpon* spp and promote plant growth. pathogen. Trichoderma species applied can act as antagonists of other pathogens in soil, succeeding even against *Cylindrocarpon* spp (Fourie et al. 2001). In addition, plant growth promoters agents as the bacterial cocktail applied stimulate the formation of young roots (Vacheron et al. 2013). These effects were only assessed visually during field inspections, showing an improvement in root development in treated plants

with IA but there are no quantitative measurements of the improvement and effect of the biological factors considered. However, recent vineyard studies confirm that microbial inoculants synergize with organic amendments by promoting root proliferation, increasing nutrient-use efficiency and enhancing plant tolerance to soilborne pathogens, suggesting this represents an important area for future investigation in organic amendment systems (Biagi et al. 2025).

3.4 Fruit yield and quality

Vines in the AI treatment showed a significant increase in the number of bunches per plant and weight per bunch compared to the Control, which also resulted in a significant increase in crop yield, reaching 26.9 Mg/ha compared to 17.8 Mg/ha obtained in the control (Fig. 6). The concentration of Fe, Cu and Zn un fruits was between 24 and 12% higher with IA than with Control treatment (data not shown). This

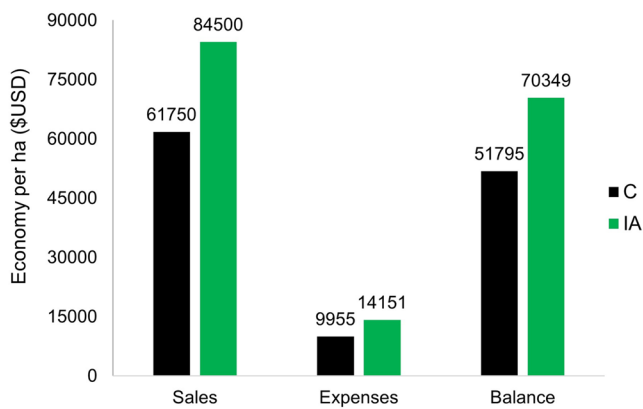


Fig. 7 Comparative economic analysis of conventional (C) and engineered amendment (IA) treatment systems in terms of sales, operating expenses, and balance sheet. Values expressed in US dollars (USD)

is supported by the increase in Fe and Zn observed in leave concentration. Thus, nutritional improvements at the foliar level have important implications for berry quality development, as recent studies have shown that organic fertilization influences phytochemical transformations throughout multiple berry development stages, affecting not only mineral content but also sugar accumulation, organic acid profiles, and secondary metabolite synthesis (Incesu et al. 2022; Kaya et al. 2025).

Fruit quality parameters for both treatments showed no significant differences in Brix degrees, with average values around 12°, while significant differences were observed in grape size, with those obtained in the IA being larger (Fig. 6). The increase in yield obtained in the IA is consistent with the increase observed in vegetative tissue growth. This increase is greater particularly when amendments enhance soil water retention, N availability and K supply, three factors strongly associated with bunch number, berry size and sugar accumulation (Botelho et al. 2020; Messiga et al. 2016), parameters that we have focused on at formulation step process.

Furthermore, grape size and Brix degrees are quality parameters (Poni et al. 2018), with the former significantly improving with the use of the designed amendment. Brix levels experienced a marginal decrease attributable to the dilution of soluble solids (predominantly sucrose), a common yield-related phenomenon. Contemporary research has revealed that organic fertilization impacts extend beyond basic nutrition to influence secondary metabolite profiles and even biogenic amine levels in grape berries, demonstrating the complexity of soil-plant biochemical interactions (Incesu et al. 2022; Kaya et al. 2025). Therefore, besides of waste valorization through composting the amendment also enhance the productivity and quality of grapes.

The cost-effectiveness analysis was conducted by comparing the unit price costs of implementing both treatments

(product and transportation costs) with the sales value of the product obtained under both treatments. The balance showed the benefits obtained from using the designed amendment versus the traditional amendment of more than USD 18,500 per hectare (Fig. 7). The costs associated with product acquisition were higher for the designed amendment, at \$270.27/Mg, compared to \$86.49/Mg for the conventional amendment. The elaboration cost of the IA is higher than that of manure, as these additional costs arise from material processing and the operational requirements of the composting process. Regarding transportation, the unit price was the same for both treatments, around \$67/Mg, given the similar distance traveled between source and final destination. At this stage, optimization resulted from using a smaller quantity of the IA compared to Control, resulting in a 35% reduction in transportation costs. Despite this, total costs per hectare were USD 9,955 for Control and USD 14,151 for IA, generating a higher cost of USD 4,196 with the use of the AI (Fig. 7).

This evaluation, although superficial and ignoring the overhead costs and other costs that affect companies equally with one type of amendment or another, demonstrated that although initial acquisition costs may entail a higher investment, investing in formulated amendment solutions with more stabilized materials allows for greater crop response, improving crop health and contributing to greater economic recovery. This also demonstrates the viability of these types of solutions (Bouhria et al. 2022, 2023; Uddin et al. 2025), which can be applied to different regional and crop contexts, and the additional benefit of once again allowing agro-industrial waste to integrate into biogeochemical cycles through the creation of amendments formulated according to the needs of the soil and crop. This contributes to circularity and a lower environmental footprint of the final products.

4 Conclusions

The formulation and production of fertilizers obtained from the valorization of agro-industrial waste is a sustainable strategy, not only environmentally but economically, for improving nutritional status in vineyards and enhancing soil quality. The results of this study showed how the designed amendment, despite being used in smaller quantities than conventional amendment, contributed to a greater increase in soil organic matter, increased CEC, and increased nutritional intake, without contributing to the risk of potentially toxic elements. Furthermore, waste stabilization through composting proved effective in maintaining C in the soil, slowing the rate of mineralization and providing a more stable fertilizer with gradual nutrient release. With the use of the designed amendment, vines showed greater branch

length and diameter, as well as a greater number and size of bunches per plant, increasing production by 9.1 Mg/ha more than the conventional amendment. This improvement led to a recovery in crop yields in just one year, following a three-year period of consecutive decline, and to meeting the nutritional needs and deficiencies identified at the soil level. These results contribute to the growing evidence base supporting organic amendment integration in viticulture systems, demonstrating that properly formulated products from waste valorization can simultaneously address multiple sustainability objectives, soil fertility enhancement, crop productivity improvement, environmental impact reduction, and economic viability while maintaining or improving fruit quality attributes.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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5. References

- Agnew JM, Leonard JJ (2003) The physical properties of compost. *Compost Sci Util* 11(3):238–264. <https://doi.org/10.1080/1065657X.2003.10702132>
- Alvarez González Carlos Enrique, Gil E, Fernández-Falcón M, Hernández MM (2009) Water leachates of nitrate nitrogen and cations from poultry manure added to an Alfisol Udalf soil. *Water Air Soil Pollut* 202(1–4):273–88. <https://doi.org/10.1007/s11270-008-9975-6>
- Amanullah G, Ondrasek AR, Al-Tawaha (2023) Editorial: integrated nutrients management: an approach for sustainable crop production and food security in changing climates. *Front Plant Sci* 14:1–4. <https://doi.org/10.3389/fpls.2023.1288030>
- Bao Y, Guan L, Zhou Q, Wang H, Li Y (2010) Various sulphur fractions changes during different manure composting. *Bioresour Technol* 101(20):7841–7848. <https://doi.org/10.1016/j.biortech.2010.05.037>
- Bascomb CL (1968) Distribution of pyrophosphate-extractable iron and organic carbon in soils of various groups. *Eur J Soil Sci* 19(2):251–268. <https://doi.org/10.1111/j.1365-2389.1968.tb01538.x>
- Bavestrello-Riquelme C, Cavieres L, Gallardo J, Ibacache A, Nicolás, Franck, Andrés Zurita-Silva (2012) Evaluación de La Tolerancia a Estrés Por Sequía En Cuatro Genotipos de Vid (*Vitis Vinifera*) Provenientes Del Norte de Chile. 30pp
- Beeckman Fabian, Motte Hans, Beeckman Tom (2018) Nitrification in agricultural soils: impact, actors and mitigation. *Curr Opin Biotechnol* 50:166–73. <https://doi.org/10.1016/j.copbio.2018.01.014>
- Bernal MP, Alburquerque JA, Moral R (2009) Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresour Technol* 100(22):5444–53. <https://doi.org/10.1016/j.biortech.2008.11.027>
- Biagi Elena, Mazzon Martina, Musmeci Eliana, Gioacchini Paola, Paesano Anna, Fava Fabio, Ciavatta Claudio, Zanolli Giulio, Marzadori Claudio (2025) Waste-derived organic soil amendments for a sustainable vineyard management: linking microbiome responses to soil biochemistry. *Appl Soil Ecol*. <https://doi.org/10.1016/j.apsoil.2025.106406>
- Botelho Manuel, Cruz Amândio, Ricardo-Da-Silva Jorge, De Castro Rogério, Ribeiro Henrique (2020) Mechanical pruning and soil fertilization with distinct organic amendments in vineyards of Syrah: effects on vegetative and reproductive growth. *Agronomy*. <https://doi.org/10.3390/agronomy10081090>
- Bouhria Y, Hafidi M, Ouhdouch Y, Boukhari MEME, Mphatso C, Zeroual Y, Lyamlouli K (2022) Conversion of waste into organo-mineral fertilizers: current technological trends and prospects. *Rev Environ Sci Biotechnol* 21(2):425–446. <https://doi.org/10.1007/s11157-022-09619-y>
- Bouhria Youness, Hafidi Mohamed, Ouhdouch Yedir, Zeroual Youssef, Lyamlouli Karim (2023) Organo-mineral fertilization based on olive waste sludge compost and various phosphate sources improves phosphorus agronomic efficiency, *Zea mays*. agro-physiological traits, and water. *Agron* 13(1):249. <https://doi.org/10.3390/agronomy13010249>
- Bueno P, Tapias R, López F, Díaz MJ (2008) Optimizing composting parameters for nitrogen conservation in composting. *Bioresour Technol* 99(11):5069–5077. <https://doi.org/10.1016/j.biortech.2007.08.087>
- Buján E, García-Arrese A, Velasco-Molina M, Macías F (2010) La Disolución Del Suelo En comunidades de Erica andevalensis

- Del Entorno de Las Minas de Riotinto (Huelva, SO España). *Rev Cienc Agrar* 33:111–118
- Castro A, Davila C, Wil L (2021) Félix Cubas, Grinia Avalos, Carlos López Ocaña. In: Villena D et al (eds) Servicio Nacional de Meteorología e Hidrología Del Perú. SENAMHI) Climas Del Perú Mapa de Clasificación Climática Nacional
- Cayuela ML, Bernal MP, Roig A (2004) Composting olive mill waste and sheep manure for orchard use. *Compost Sci Util* 12(2):130–136. <https://doi.org/10.1080/1065657X.2004.10702171>
- Chien SH, Prochnow LI, Cantarella H (2009) 102 advances in agronomy Chap. 8 recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts, 1st edn. Elsevier Inc. [https://doi.org/10.1016/S0065-2113\(09\)01008-6](https://doi.org/10.1016/S0065-2113(09)01008-6)
- Chojnacka Katarzyna, Moustakas Konstantinos, Witek-Krowiak Anna (2020) Bio-based fertilizers: a practical approach towards circular economy. *Bioresour Technol* 295:122223. <https://doi.org/10.1016/j.biortech.2019.122223>
- Churchman GJ, Skjemstad JO, Oades JM (1993) Influence of clay minerals and organic matter on effects of sodicity on soils. *Aust J Soil Res* 31:779–800
- Clemente R, Escolar Ángeles, Pilar Bernal M (2006) Heavy metals fractionation and organic matter mineralisation in contaminated calcareous soil amended with organic materials. *Bioresour Technol* 97(15):1894–1901. <https://doi.org/10.1016/j.biortech.2005.08.018>
- Comission E (2020) Comisión Europea Circular Economy Action Plan (CEAP)
- Crawley MJ (2015) *Statistics: An Introduction Using R*, Second edition. John Wiley & Sons, Ltd
- Dhal B, Thatoi HN, Das NN, Pandey BD (2013) Chemical and microbial remediation of hexavalent chromium from contaminated soil and Mining/Metallurgical solid waste: a review. *J Hazard Mater* 250–251:272–291. <https://doi.org/10.1016/j.jhazmat.2013.01.048>
- EPA (1996) Method 3050B: acid digestion of Sediments, Sludges, and soils. In: *Selected Analytical Methods for Environmental Remediation and Recovery (SAM)*, p 723
- EPA (2003) *Ecological Soil Screening Level for Aluminum Interim Final*. Washington DC
- FAO (2018) Transforming food and agriculture to achieve the SDGs. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001328](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001328)
- Fourie PH, Francois H, Van der Vyver J, Wouter Schereuder (2001) Effect of trichoderma treatments on the occurrence of decline pathogens in the roots and rootstocks of nursery grapevines. https://doi.org/10.14601/Phytopathol_Mediterr-1619. *Phytopathology Mediranea*
- Gao Y, Wang S, Tan W, Beidou Xi (2023) Dynamics of nutrient elements and potentially toxic elements during composting with different organic wastes. *Front Sustain Food Syst* 1–10. <https://doi.org/10.3389/fsufs.2023.1181392>
- Gomez KA, Gomez AA (1984) *Statistical Procedures for Agricultural Research*, Second. John Wiley & Sons, Inc
- Gonzalez-Guzman A, Raya-Diaz S, Sacristán D, Yousef M, Sánchez-Rodríguez AR, Barrón V, del Campillo MC, Torrent J (2021) Effects of entomopathogenic fungi on durum wheat nutrition and growth in the field. *Eur J Agron*. <https://doi.org/10.1016/j.eja.2021.126282>
- Hall GEM, Vaive JE, MacLaurin AI (1996) Analytical aspects of the application of sodium pyrophosphate reagent in the specific extraction of the labile organic component of humus and soils. *J Geochem Explor* 56(1):23–36. [https://doi.org/10.1016/0375-6742\(95\)00046-1](https://doi.org/10.1016/0375-6742(95)00046-1)
- Hebebrand C, Glauber J (2023) The Russia-Ukraine War after a Year: Impacts on Fertilizer Production, Prices, and Trade Flows. *Global Consequences*. International Food Policy Research Institute (IFPRI), Washington D.C., pp 43–47. https://doi.org/10.2499/9780809629439_08
- Hudson BD (1994) Soil organic matter and available water capacity. *J Soils Water Conserv* 49(2):189–194
- Incesu Melek, Karakus Sinem, Seyed Hajizadeh Hanifeh, Ates Fadime, Turan Metin, Skalicky Milan, Kaya Ozkan (2022) Changes in biogenic amines of two table grapes (Cv. bronx seedless and Italia) during berry development and ripening. *Plants*. <https://doi.org/10.3390/plants11212845>
- IUSS Working Group WRB (2022) World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria, p. 234
- Jat Lokesh Kumar, Singh YV, Meena Santosh Kumar, Meena Sunita Kumari, Parihar Manoj, Jatav HS, Meena Raj Kumar, Meena Vijay Singh (2015) Does integrated nutrient management, enhance agricultural productivity? *J Pure Appl Microbiol* 9(2):1211–21
- Kaya Ozkan, Yilmaz Turhan, Ates Fadime, Kustutan Fulya, Hatterman-Valenti Harlene, Seyed Hajizadeh Hanifeh, Turan Metin (2024) Improving organic grape production: the effects of soil management and organic fertilizers on biogenic amine levels in *Vitis vinifera* Cv., ‘Royal’ grapes. *Chem Biol Technol Agric*. <https://doi.org/10.1186/s40538-024-00564-2>
- Kaya Ozkan, Karakus Sinem, Ates Fadime, Daler Selda, Hatterman-Valenti Harlene (2025) Enhancing royal grape quality through a three-year investigation of soil management practices and organic amendments on berry biochemistry. *Chem Biol Technol Agric*. <https://doi.org/10.1186/s40538-025-00733-x>
- Khalil A, Domeizel M, Prudent P (2008) Monitoring of green waste composting process based on redox potential. *Bioresour Technol* 99(14):6037–6045. <https://doi.org/10.1016/J.BIORTECH.2007.11.043>
- Larney Francis J., Buckley Katherine E., Hao Xiyang, McCaughey W. Paul (2006) Fresh, stockpiled, and composted beef cattle feedlot manure. *J Environ Qual* 35(5):1844–54. <https://doi.org/10.2134/jeq2005.0440>
- Lauchli Andre, Grattan Stephen R (2017) Plant Stress under Non-Optimal Soil PH. In: Shabala S (ed) *PLant Stress Physiology*. CABI Publishing, Wallingford, pp 201–16
- Le Qianhan, Price GW (2024) A review of the influence of heat drying, alkaline treatment, and composting on biosolids characteristics and their impacts on nitrogen dynamics in biosolids-amended soils. *Waste Manag* 176:85–104. <https://doi.org/10.1016/j.wasman.2024.01.019>
- LECO Corporation (1999) Carbon/Nitrogen/Sulfur Determination by Combustion: CNS-2000 Instruction Manual
- Lindsay WL, Norwell WA (1978) Development of DTPA soil test for zinc, iron, manganese and copper. *Soil Sci Soc Am J* 42:421–423
- Lou XF, Nair J (2009) The impact of landfilling and composting on greenhouse gas emissions - a review. *Bioresour Technol* 100(16):3792–3798. <https://doi.org/10.1016/j.biortech.2008.12.006>
- Ma Q, Li Y, Xue J, Cheng D, Li Z (2022) Effects of turning frequency on ammonia emission during the composting of chicken manure and soybean straw. *Molecules* 27(2):1–21. <https://doi.org/10.3390/molecules27020472>
- MacDonald Graham K., Bennett Elena M., Potter Philip A., Ramanakutty Navin (2011) Agronomic phosphorus imbalances across the world’s croplands. *Proc Natl Acad Sci U S A* 108(7):3086–91. <https://doi.org/10.1073/pnas.1010808108>
- Medinets Sergiy, Oenema Oene, Spears Bryan M., Buyanovskiy Andriy, Medinets Volodymyr, Brownlie William J., Nemitz Eiko, Vieno Massimo, Sutton Mark A. (2025) Nutrient asymmetry challenges the sustainability of Ukrainian agriculture. *Commun Earth Environ* 6(1):845. <https://doi.org/10.1038/s43247-025-02826-9>

- Messiga Aime J., Gallant Kyle S., Sharifi Mehdi, Hammermeister Andrew, Fuller Keith, Tango Martin, Fillmore Sherry (2016) Grape yield and quality response to cover crops and amendments in a vineyard in Nova Scotia, Canada. *Am J Enol Vitic* 67(1):77–85. <https://doi.org/10.5344/ajev.2015.15013>
- MINAM (2010) Mapa de Suelos Del Perú. Ministerio de Ambiente: 1. <https://www.geogpsperu.com/2015/10/mapa-de-suelos-onern.html> (March 7, 2023)
- Miranda Katrina M., Espey Michael G., Wink David A. (2001) A rapid, simple spectrophotometric method for simultaneous detection of nitrate and nitrite. *Nitric Oxide* 5(1):62–71. <https://doi.org/10.1006/niox.2000.0319>
- Möller HB, Jensen HS, Tobiasen L, Hansen MN (2007) Heavy metal and phosphorus content of fractions from manure treatment and incineration. *Environ Technol* 28(12):1403–1418. <https://doi.org/10.1080/0959332808618900>
- Mulvaney RL (1996) Nitrogen – Inorganic Forms. In: Sparks DL (ed) *Methods of Soil Analysis. Part 3. Chemical Methods*. American Society of Agronomy, SSAA, Madison, pp 1123–84. <https://doi.org/10.2136/sssabookser5.3.c38>
- Noble R, Roberts SJ (2004) Eradication of plant pathogens and nematodes during composting: a review. *Plant Pathol* 53(5):548–568. <https://doi.org/10.1111/j.0032-0862.2004.01059.x>
- Noble R, Dobrovin-Pennington A, Pietravalle S, Weekes R, Henry CM (2011) Indicator organisms for assessing sanitization during composting of plant wastes. *J Waste Manag* 31(8):1711–1719. <https://doi.org/10.1016/j.wasman.2011.04.007>
- Ohno Tsutomu, Erich M. Susan (1990) Effect of wood ash application on soil PH and soil test nutrient levels. *Agric Ecosyst Environ* 32(3–4):223–39. [https://doi.org/10.1016/0167-8809\(90\)90162-7](https://doi.org/10.1016/0167-8809(90)90162-7)
- Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No 939:18
- Poni Stefano, Gatti Matteo, Palliotti Alberto, Dai Zhanwu, Duchêne Eric, Truong Thuy Thanh, Ferrara Giuseppe et al (2018) Grapevine quality: a multiple choice issue. *Sci Hortic* 234:445–62. <https://doi.org/10.1016/j.scienta.2017.12.035>
- Qi Jiamin, Yang Hua, Wang Xingyuan, Zhu Hengxi, Wang Zixuan, Zhao Chenzhu, Li Bin, Liu Zewei (2023) State-of-the-art on animal manure pollution control and resource utilization. *J Environ Chem Eng*. <https://doi.org/10.1016/j.jece.2023.110462>
- Ravindran Balasubramani, Karmegam Natchimuthu, Yuvaraj Ananthanarayanan (2021) Cleaner production of agriculturally valuable benignant materials from industry generated bio-wastes: a review. *Bioresour Technol* 320:124281. <https://doi.org/10.1016/j.biortech.2020.124281>
- Richard Tom L., Hamelers H. V.M. (Bert), Veeken Adrie, Silva Tiago (2002) Moisture relationships in composting processes. *Compost Sci Util* 10(4):286–302. <https://doi.org/10.1080/1065657X.2002.10702093>
- Rubio R, Pérez-Murcia MD, Agulló E, Bustamante MA, Sánchez C, Paredes C, Moral R (2013) Recycling of agro-food wastes into vineyards by composting: agronomic validation in field conditions. *Commun Soil Sci Plant Anal* 44(1–4):502–516. <https://doi.org/10.1080/00103624.2013.744152>
- Sadaka S, El-Taweel A (2003) Effects of aeration and C:N ratio on household waste composting in Egypt. *Compost Sci Util* 11(1):36–40. <https://doi.org/10.1080/1065657X.2003.10702107>
- Schumacher BA (2002) Methods for the determination of total organic carbon in soils and sediments. *Carbon* 32(April):25
- Scotti R, Bonanomi G, Scelza R, Zoina A, Rao MA (2015) Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. *J Soil Sci Plant Nutr* 15(2):333–352. <https://doi.org/10.4067/s0718-95162015005000031>
- Sitzmann Tomas Javier, Sica Pietro, Grignani Carlo, Magid Jakob (2024) Testing biowaste materials as peat replacement in organo-mineral fertilizers. *Front Sustain Food Syst*. <https://doi.org/10.3389/fsufs.2024.1330843>
- SMEWW (2017b) 4500-H + PH. In standard methods for the examination of water and wastewater, standard methods for the examination of water and wastewater. Am Public Health Association. <https://doi.org/10.2105/SMWW.2882.082>
- SMEWW (2017a) 2510B CONDUCTIVITY. In Standard Methods For the Examination of Water and Wastewater, Standard Methods for the Examination of Water and Wastewater, Washington D.C.: American Public Health Association. <https://doi.org/10.2105/SMWW.2882.027>
- Sommer SG (2001) Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. *Eur J Agron* 14(2):123–133. [https://doi.org/10.1016/S1161-0301\(00\)00087-3](https://doi.org/10.1016/S1161-0301(00)00087-3)
- Tan Zhongxin, Lagerkvist Anders (2011) Phosphorus recovery from the biomass ash: a review. *Renew Sustain Energy Rev* 15(8):3588–3602. <https://doi.org/10.1016/j.rser.2011.05.016>
- Tan Hequn, Li Meng, Jie Dengfei, Zhou Yafang, Li Xin'an (2019) Effects of different litters on ammonia emissions from chicken manure. *Int J Agric Biol Eng* 12(4):27–33. <https://doi.org/10.2516/5.ijabe.20191204.5011>
- Torres E, Rivera Sebastián, Muena V, Corradini F, Sepúlveda P, Abarca P, Defilippi B et al (2017) Boletín INIA / No 18 Manual Del Cultivo de Uva de Mesa. ed. Torres P. Andrea. Providencia, Santiago de Chile: INIA and INDAP
- Uddin Md Kafil, Saha Biplob K., Wong Vanessa N.L., Patti Antonio F. (2025) Organo-mineral fertilizer to sustain soil health and crop yield for reducing environmental impact: a comprehensive review. *Eur J Agron*. <https://doi.org/10.1016/j.eja.2024.127433>
- Unión E (2019) Reglamento (UE) 2019/1009 del Parlamento Europeo y del Consejo de 5 de junio de 2019, por el que se establecen disposiciones relativas a la puesta a disposición en el mercado de los productos fertilizantes UE
- Vacheron J, Desbrosses G, Bouffaud ML, Touraine B, Claire Prigent-Combaret (2013) Yvan Moëgne-Loccoz, Daniel Muller, Laurent Legendre, Florence Wisniewski-Dyé, Plant Growth-Promoting Rhizobacteria and Root System Functioning. *Front. Plant Sci.* 4. <https://doi.org/10.3389/fpls.2013.00356>
- Walkley A, Black IA (1934) An examination of the degtjareff method for determining organic carbon in soils: effect of variation in digestion conditions and of inorganic soil constituents. *Soil Sci* 63:251–263
- Walling Eric, Vaneeckhaute Céline (2020) Greenhouse gas emissions from inorganic and organic fertilizer production and use: a review of emission factors and their variability. *J Environ Manage*. <https://doi.org/10.1016/j.jenvman.2020.111211>
- Wang Nanyi, He Yong, Zhao Keqi, Lin Xu, He Xi, Chen Anwei, Wu Genyi et al (2024) Greenhouse gas emission characteristics and influencing factors of agricultural waste composting process: a review. *J Environ Manage*. <https://doi.org/10.1016/j.jenvman.2024.120337>
- Wu Wei, Ma Baoluo (2015) Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. *Sci Total Environ* 512:415–27. <https://doi.org/10.1016/j.scitotenv.2014.12.101>
- Zhang Lu, Sun Xiangyang (2016) Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste. *Waste Manag* 48:115–26. <https://doi.org/10.1016/j.wasman.2015.11.032>