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REVIEW ARTICLE

Nature-based strategies to regenerate the functioning and biodiversity of vineyards

Raúl Ochoa-Hueso[1,2] | **Emma Cantos-Villar**[3] | **Belén Puertas**[3] | **Juan F. Aguiar del Rio**[1] | **Ignacio Belda**[4] | **Manuel Delgado-Baquerizo**[5] | **Victoria Fernández**[6] | **Antonio Gallardo**[7] | **José L. García-Morales**[8] | **Teresa Garde-Cerdán**[9] | **Luis Gonzaga-Santesteban**[10,11] | **Cristina Lazcano**[12] | **Isabel M. Liberal**[1] | **Lilia Serrano-Grijalva**[1,2] | **Germán Tortosa**[13] | **Ramón Casimiro-Soriguer**[1]

[1]Department of Biology, Botany Area, IVAGRO, University of Cádiz, Campus de Excelencia Internacional Agroalimentario (CeiA3), Campus del Rio San Pedro, Cádiz, Spain

[2]Department of Terrestrial Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands

[3]IFAPA Rancho de la Merced, Consejería de Agricultura, Pesca, Agua y Desarrollo Rural, Junta de Andalucía, Jerez de la Frontera, Spain

[4]Laboratorio de Biodiversidad y Funcionamiento Ecosistémico, Instituto de Recursos Naturales y Agrobiología (IRNAS), CSIC, Sevilla, Spain

[5]Laboratorio de Biodiversidad y Funcionamiento Ecosistémico, Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS), CSIC, Sevilla, Spain

[6]Departamento de Sistemas y Recursos Naturales, Universidad Politécnica de Madrid, Ciudad Universitaria, Madrid, Spain

[7]Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Sevilla, Spain

[8]Department of Environmental Technologies, Faculty of Marine and Environmental Sciences, IVAGRO-Wine and Agrifood Research Institute, University of Cadiz, Cádiz, Spain

[9]Grupo VIENAP, Instituto de Ciencias de la Vid y del Vino (CSIC, Universidad de La Rioja, Gobierno de La Rioja), Logroño, Spain

[10]Departamento de Agronomía, Biotecnología y Alimentación, Universidad Pública de Navarra, Campus Arrosadia, Pamplona-Iruña, Spain

[11]Institute for Multidisciplinary Research in Applied Biology (IMAB), Universidad Pública de Navarra, Edificio Jerónimo de Ayanz, Campus Arrosadia, Pamplona-Iruña, Spain

[12]Department of Land, Air and Water Resources, University of California, Davis, Davis, California, USA

[13]Department of Soil and Plant Microbiology, Estación Experimental del Zaidín, CSIC, Granada, Spain

Correspondence
Raúl Ochoa-Hueso, Department of Biology, Botany Area, IVAGRO, University of Cádiz, Campus de Excelencia Internacional Agroalimentario (CeiA3), Campus del Rio San Pedro, Puerto Real, 11510 Cádiz, Spain.
Email: rochoahueso@gmail.com

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Abstract

Grapevine is one of the most important perennial fruit crops worldwide. Historically, vineyards were compatible with soil conservation practices and multitrophic biodiversity, but vineyards are now generally eroded and biologically impoverished, making them more susceptible to pests and diseases. However, the idiosyncrasy of the wine sector places wine growers in a unique position to lead the adoption of a range of sustainable management strategies and, thus, to pioneer a wider transformation of the agricultural sector. In this article, we provide an overview of nature-based management strategies that may be used for the regeneration of the functioning and biodiversity of vineyards and that may also lead to improved plant nutrition, grape berry quality and the

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suppression of pathogens and pests. These strategies include the use of microbial and nonmicrobial biostimulants, fertilization with organic amendments as well as foliar fertilization with nature-based products, the use of cover crops and the reintegration of livestock in vineyards, especially sheep. We will also pay special attention to the implementation of circular economy in the vineyard in relation to the previously mentioned management strategies and will also discuss the importance of considering all these aspects from a holistic and integrative perspective, rather than taking them into account as single factors. Assuming the integral role of soils in the functioning of agroecosystems, soils will be considered transversally across all sections. Finally, we will argue that the time is now ripe for innovation from the public and private sectors to contribute to the sustainable management of vineyards while maintaining, or even improving, the profit margin for farmers and winemakers.

KEYWORDS

ecological transition of agriculture, nature-based solutions, plant health, soil health, sustainable viticulture

1 | INTRODUCTION

Vineyards, defined as areas of land where grapevines are grown, are one of the most important types of perennial cultivation systems worldwide and, in many regions, they represent an invaluable cultural heritage, are a strategic engine of local economies, and provide a source of income for many families (Miguel-Aristu et al., 2019; Rodríguez García et al., 2010). As historical sources demonstrate, vineyards traditionally harboured a great biodiversity of plants, insects, and birds (Paiola et al., 2020). However, the intensification and industrialization of viticulture and the excessive use of ploughing, fertilizers, and pesticides, among other husbandry techniques, have led to vineyards that are highly eroded, biologically impoverished and much more susceptible to pests and diseases (Altieri & Nicholls, 2002; Schütte et al., 2020).

In many resource-intensive conventional farming systems, including vineyards, yields are high, but biodiversity and ecosystem functioning are often reduced (Matson et al., 1997), and food webs are markedly simplified (Banerjee et al., 2019; Tsiafouli et al., 2015). Due to the often-unappreciated role of soil biodiversity for plant health and protection, this widespread biodiversity loss is partly to be blamed for the ever-growing demand for agrochemicals, with negative consequences for producers and the quality and safety of their products (e.g., grapes or wine in the case of vineyards). To adapt to sustainable agriculture, winegrowers will need to reduce the use of chemicals and avoid soil degradation, while minimizing potential yield losses (Kleijn et al., 2019). However, the economic pressure placed on producers and manufacturers due to competition from emerging markets and new wine-growing areas, which contribute to lower prices for raw and processed materials, poses an added challenge of how to simultaneously restore the biodiversity and functioning of vineyards while increasing the profit margin for producers and the rest of the market chain (Kleijn et al., 2019). An additional challenge to the sustainable intensification of agricultural production systems, including vineyards, is to reduce hunger and poverty by producing increasing amounts of food, feed and bioenergy for a growing world population, but with minimal loss of biodiversity and ecosystem functioning, in agreement with the Sustainable Development Goals of the United Nations (https://sdgs.un.org/goals). However, the idiosyncrasy of the wine sector, which is currently more associated with social interactions and luxury, places winegrowers in a unique position to lead the adoption of sustainable agriculture principles and, thus, to pave the way for other cropping systems that are more essential for human nutrition.

Nature-based agriculture, which is based on taking advantage of natural processes within agroecosystems (Mrunalini et al., 2022), is expected to provide a more environmentally sustainable alternative to resource-intensive conventional agriculture, although it often leads to lower yields (Reganold & Wachter, 2016), particularly during the first few years after conversion from conventional to a more nature-based agriculture (Schrama et al., 2018) (Figure 1). The feasibility of this reconversion could, therefore, be limited by the time necessary to adapt the operation of the farmland to the new management regime; that is, the recycling of soil organic matter and minerals as a main source of plant nutrients, and the use of compost, green manure and microbial and faunal natural enemies instead of mineral fertilizers and synthetic agrochemicals, among other strategies.

Improving the sustainability of agriculture and the recovery of functionally integrated mosaic landscapes will require, among other things, a transformation of the way in which crops receive the nutrients necessary for their growth (Kleijn et al., 2019; Mrunalini et al., 2022). Specifically, it is essential to overcome the dependence of crops on synthetic chemical fertilizers that impair the living component of soils (e.g., by reducing their microbial biomass and species diversity across trophic levels) and contaminate groundwaters, while simultaneously embracing fertilization strategies that

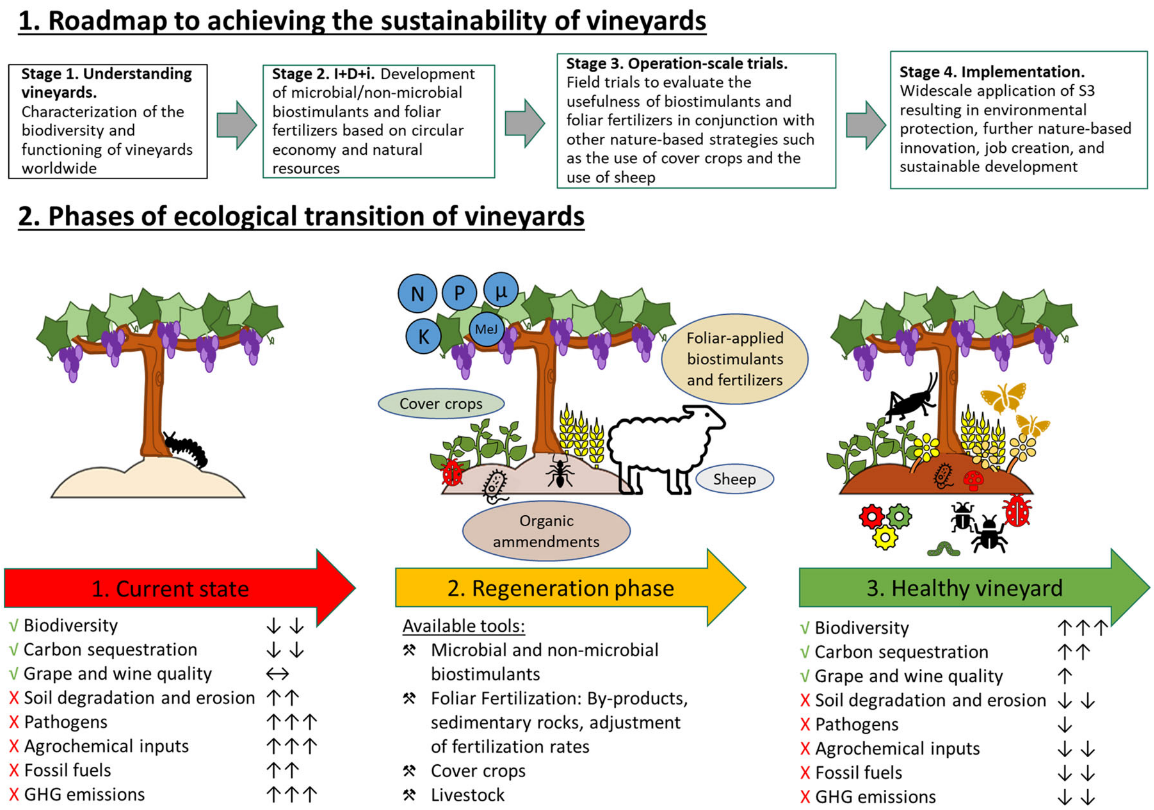

FIGURE 1 Roadmap to the successful implementation of nature-based solutions, and the main phases of the ecological transition of viticulture. GHG, greenhouse gases.

are more respectful of the environment and plant health (Kleijn et al., 2019; Mrunalini et al., 2022). In addition, high doses of mineral fertilizers have been related to an increase in the incidence of pests and diseases in crops, as well as the impoverishment of the microbiota associated with soils and the surface of plants (e.g., the phyllosphere) (Hartmann et al., 2015). In fact, the Food and Agriculture Organization of the United Nations recognizes that improving the sustainability of agriculture and the recovery of functionally integrated mosaic landscapes will require a transformation of the soil and its associated biota (Bender et al., 2016). The so-called crop soil microbiome, defined as the community of microorganisms (such as viruses, bacteria, fungi, protists and small invertebrates) inhabiting the soils where plants live, plays a key role in how essential nutrients contained in soil organic matter and minerals are transferred to plants through its control over nutrient cycling and suppression of pathogens and pests (Bender et al., 2016; Veen et al., 2019). These small invertebrates and microorganisms frequently live in close association with the plant roots, more specifically in the rhizosphere zone (e.g., the thin layer of soil around the roots), and can have a large impact on the sustainability and health of crops (Berendsen et al., 2012). Paradigmatic examples of the importance of coupled connections between key soil-borne organisms and the fine roots of crops through complex interaction networks include mycorrhizal fungi, phosphorus (P) and potassium (K) solubilizing bacteria and plant growth-promoting bacteria, which are essential for nutrition, defence against faunal pests (e.g., nematodes) and microbial diseases (e.g., fungi like *Fusarium*, *Verticillium* and *Alternaria*, or protists), and to tolerate environmental stress (e.g., drought and heat waves) by plants (Banerjee et al., 2019; Bender et al., 2016; Veen et al., 2019).

The increasing interest of consumers, policymakers and industry in nature-based solutions for a more sustainable food production system and for improving carbon (C) sequestration in agricultural soils means a greater need for science-based evidence to refine management approaches (Kleijn et al., 2019). Based on this premise, the main goal of this article is to provide an overview of the current knowledge regarding the implementation of nature-based sustainable management strategies for the regeneration of the functioning and biodiversity of vineyards, and ultimately, vineyard health (Figures 1 and 2; Box 1). Nature-based strategies that have been proposed to maximize plant nutrition while contributing to the suppression of pathogens and pests include: (i) the use of microbial and nonmicrobial biostimulants, which are not considered fertilizers in regulatory terms but generally involve beneficial effects on plant production and grape quality, and which are typically applied in small quantities (Jindo et al., 2022; Yakhin et al., 2017); (ii) fertilization with organic amendments as well as foliar fertilization with nature-based products, whose main advantages include the application of lower doses of fertilizer, and the possible co-addition of beneficial microorganisms, including microorganisms with biostimulant and protective effects

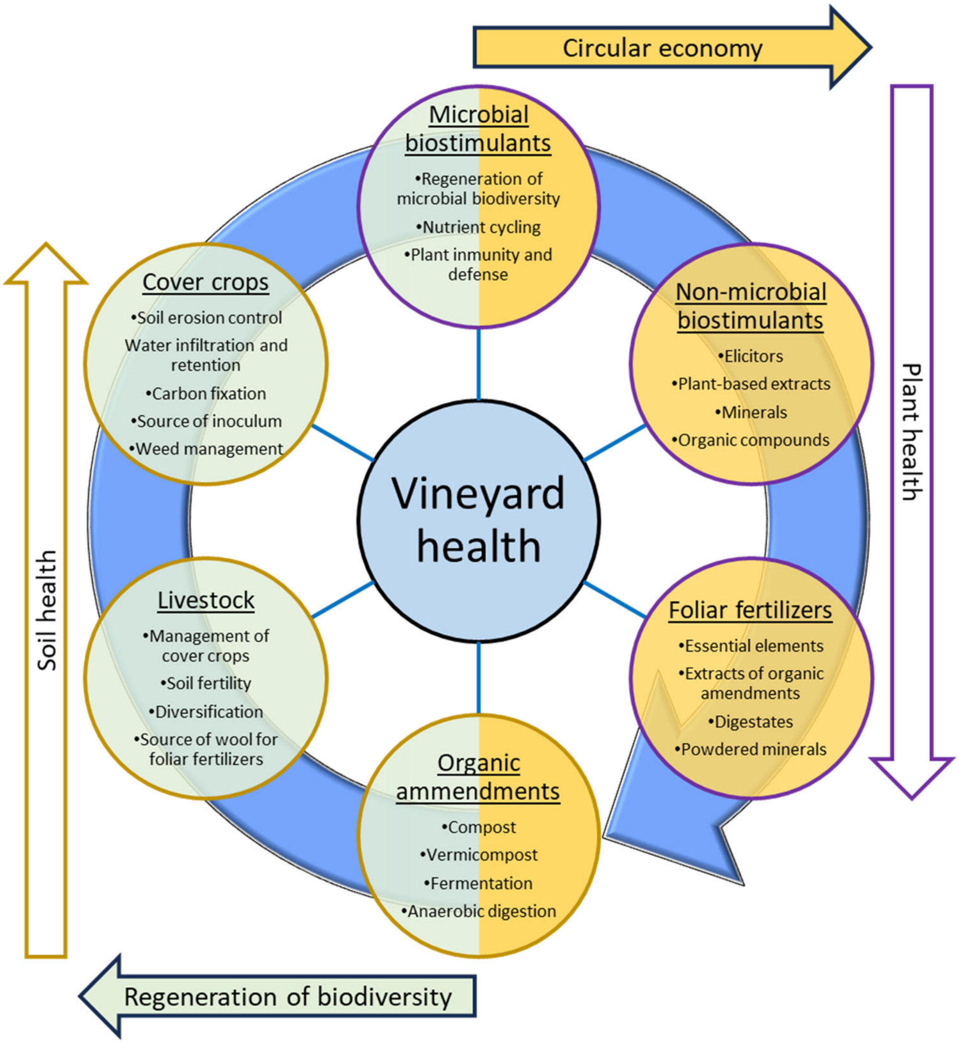

FIGURE 2 Conceptual links among nature-based strategies collectively aimed at improving the health of vineyards.

(Ishfaq et al., 2022); (iii) the use of cover crops (Winter et al., 2018) and (iv) the integration of the use of livestock, especially sheep, in vineyards (Lazcano et al., 2020). The recoupling of viticulture and livestock could contribute to regenerating soil fertility and its associated microbiota through deposition of dungs and urine, as well as by moderate trampling (e.g., by burying litter residues), especially when vines are missing their leaves. We will also pay special attention to the implementation of a circular economy in the vineyard in relation to the previously mentioned management strategies, as well as to the regeneration of soil fertility through the contribution of processed organic materials such as manure or compost, which were both common practices before the implementation of the massive use of agrochemicals for crop production and which currently represent a legislation challenge. The circular economy is defined by the European Parliament as a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. We will also discuss the importance of considering all these aspects from a holistic and integrative perspective, rather than treating them as isolated factors, to successfully address the challenge of regenerating the functioning and biodiversity of vineyards, a cropping system where the coexistence between man and nature is millenary. We are also defining the necessary steps that may need to be taken for achieving the widespread sustainability of viticulture (Box 1). These steps should involve both the public and private sectors and their results should be able to permeate to society. Finally, assuming the integral role of soils in the functioning of agroecosystems, soils will be considered transversally across all sections.

2 | BIOSTIMULANTS

2.1 | Microbial biostimulants

The use of biostimulants has recently emerged as a useful tool to regenerate the functioning of croplands. A biostimulant could be defined as a product that improves plant productivity or other

BOX 1. Achieving the sustainability of viticulture through the regeneration of soil- and plant-associated microbial biodiversity

Achieving the sustainability of viticulture will likely require understanding, among other things, the microbial biodiversity associated with the grapevine, particularly that in soils, and its role in the functioning of vineyards (Figure 1). This is important to establish science-based benchmark criteria that can then be used to set regeneration targets. This task will involve the characterization of soil- and plant-associated biodiversity (bacteria, archaea, fungi and micro- and macrofauna) across a wide of wine regions worldwide involving a representative range of soil and climatic conditions and varieties (both rootstock and scion), with emphasis on the rhizosphere. Steps are currently being undertaken in partnership with the Global Initiative of Sustainable Agriculture and Environment (https://www.globalsustainableagriculture.org/vine-microbiome/), while previous efforts include the work by Gobbi et al. (2022) for soils, and by Zarraonaindia et al. (2015) for soils and plant organs. In a benchmark study, Gobbi et al. (2022) showed that soil prokaryotic communities in vineyards are dominated by the bacterial phyla Proteobacteria, Actinobacteria and Acidobacteria, and the archaeal genus *Nitrososphaera*, while the soil fungal community is dominated by the genera *Solicoccozyma*, *Mortierella* and *Alternaria*. However, we still do not know the functional role that most of these microorganisms play in the vineyard.

A second critical step to drive the sustainable transition of viticulture may involve the development of microbial inoculants, nonmicrobial biostimulants and foliar fertilizers based on the circular economy of the vineyard to enhance the nutritional status and health of grapevines that should then be tested under controlled conditions for a wide range of locally relevant grape varieties. The development of microbial inoculants should be informed by a deep ecological knowledge of the role of microbial communities in driving soil and plant health and fruit quality. Furthermore, these inoculants, biostimulants and foliar fertilizers should be tested in combination with other soil regeneration strategies such as the use of organic amendments, plant covers, as well as the use of sheep to control plant covers. These first necessary steps should be taken simultaneously within both the private and public sectors with the aim of transferring the generated knowledge to winegrowers, thus resulting in environmental protection, further innovation, and job creation. Currently, publicly funded initiatives like the 'Living Soils' Project (https://suelosvivos.es/), a Regional Operational Group funded by the EIP-Agri, are starting to pave the way in this direction.

Allowing vineyards to quickly transition from their current degraded state to a healthy state by speeding up the regeneration phase will contribute to solving one of the most pressing needs of our global society over the next 10–15 years: the design and implementation of a sustainable transition to nature-based agriculture that can feed the 9.8 billion people expected to populate the planet by 2050 and at the same time safeguard biodiversity and the functioning of agroecosystems and the numerous services they provide to humanity.

agronomic characteristics such as tolerance to biotic or abiotic stresses, and whose said improvement is not due to its effect as a fertilizer (Gutiérrez-Gamboa et al., 2019; Jindo et al., 2022; Rouphael & Colla, 2020; Yakhin et al., 2017). Biostimulants can be mineral or biological substances. Treatment with complex mixtures of natural substances, including protein hydrolysates, natural extracts, humic acids and microorganisms, such as mycorrhizae and rhizobacteria, has also been shown to trigger biostimulant effects in plants (Gutiérrez-Gamboa et al., 2019; Jindo et al., 2022; Rouphael & Colla, 2020; Yakhin et al., 2017).

In the case of microbial biostimulants, most of the previous research has focused on single strains or formulations of a few strains (Jindo et al., 2022; Yakhin et al., 2017). Many of these biostimulants are made of bacteria belonging to the genera *Bacillus*, *Pseudomonas* or *Burkholderia*, or mycorrhizal fungi (see Jindo et al., 2022 for a comprehensive overview of bacterial and fungal biostimulants and their main reported effects). Recent studies suggest that locally derived microbial formulations can be particularly effective in promoting crop production in low-fertility soils, while commercially available synthetic communities (SynComs) may perform better in high-fertility soils (Jiang et al., 2023). Similarly, it has been suggested the importance of working with whole-soil complex communities that more realistically reflect the way in which these microorganisms function under natural conditions.

An alternative to the use of SynComs is the use of soil amendments enriched in microbial communities originating from healthy and productive soils. For example, it has been suggested that inoculation with whole-soil complex microbial communities could accelerate the regeneration of soils and direct the rapid transition to the desired sustainable state of farmlands (Toju et al., 2018). The efficacy of this approach has been clearly demonstrated during the natural succession of abandoned agricultural fields (Morriën et al., 2017). When restoring seminatural habitats, the introduction of small amounts of topsoil (i.e., inoculation with entire soil communities) from target sites can accelerate soil community development, which aids in the establishment of the desired natural vegetation (Harris, 2009). However, empirical evidence supporting the potential of whole-soil community inoculation in the transition from a conventional to a more nature-based agriculture, including perennial crops such as grapes, is surprisingly scant. Furthermore, a limitation of the whole-soil inoculation approach is the amount of soil required and the disturbance that would be created in the donor agroecosystem, which would necessarily limit the applicability of this approach to small-scale operations. One way to overcome this limitation is by preparing large volumes of inoculants under controlled conditions from small aliquots of soil, which can then be granulated together with compost and clay minerals (Chua et al., 2019). Sufficient amounts of inoculants could be produced by composting or fermenting sterilized plant by-products together with target rhizosphere soils particularly teeming with beneficial microbial and invertebrate life (Toju et al., 2018). This latter approach could also be used to provide added value to viticulture by-products, such as pruning waste, stems, sludge and lees, but it also poses several challenges in terms of reproducibility and control of the microbial content of the inoculum, particularly regarding the absence of pathogens.

2.2 | Nonmicrobial biostimulants

In recent years, we are witnessing a negative effect of climate change on grape composition, including the acceleration of the accumulation of sugars. This results in a mismatch between the technological maturity of grapes, and their phenolic maturity, which is still not achieved when the grapes are ready for harvest (Droulia & Charalampopoulos, 2022; Mira de Orduña, 2010). This has resulted in an increase in the use of nonmicrobial biostimulants aimed at improving grape quality. Most of these nonmicrobial biostimulants are foliar applied. Algal extracts have also commonly been used to improve the yield of vineyards, although other by-products of the agrifood industry, including pruning remains and vinification waste, as well as the by-products of vegetable production, are also an important source of bioactive ingredients (Jindo et al., 2022; Zarraonaindia et al., 2023).

The use of by-products of the wine industry for the production of biostimulants implies important changes towards sustainable viticulture. For example, vine shoots are traditionally left in the vineyard, and are sometimes used as organic fertilizer, but, recently, their use as a biostimulant has provided improvements to grape and wine quality (Sánchez-Gómez et al., 2016, 2017). Other higher plants have also been frequently used as raw material for the development of biostimulants, including plants belonging to families such as Amaryllidaceae, Brassicaceae, Ericaceae, Fabaceae, Fagaeae, Moringaceae, Plantaginaceae, Poaceae, Rosaceae, Solanaceae, Theaceae and Vitaceae. Agrifood by-products are sources of a wide variety of metabolites, including primary (e.g., amino acids, sugars, nucleotides and lipids) and secondary metabolites. Secondary metabolites are more specific and depend on the material used. Within this class of metabolites, phenolic compounds, furostanic saponins and sterols are considered beneficial substances that could contribute to improve the health status of plants, as well as the sustainability of vineyards (Yakhin et al., 2017). The use of biostimulants could also contribute to improve the health of the soil and its biodiversity by reducing the use of highly toxic agrochemicals. This aspect is key, given the importance of soil biodiversity for nutrient recycling, plant immunity, regulation of the hydrological cycle, and C sequestration in sustainable agricultural fields whose management is based on the functioning of nature.

Among the nonmicrobial biostimulants most commonly used to increase phenolic maturity are nitrogen (N)-based compounds, by-products of the wine industry, and especially elicitors. The foliar application of urea and phenylalanine, as N compounds, can positively affect the content of N, phenolic and aromatic compounds in the grapes (Garde-Cerdán et al., 2014, 2015; Hannam et al., 2016; Hattori et al., 2019; Murillo-Peña et al., 2023; Portu, López-Alfaro, et al., 2015), which are determinants for the quality of grapes and wines. Elicitors, in turn, are defined as compounds that, when applied to a plant, induce the activation of the enzymatic metabolism needed to synthesize secondary metabolites in their plant tissues (Bavaresco et al., 2012; Gil-Muñoz et al., 2018; Gómez-Plaza et al., 2017; Portu, Santamaría, et al., 2015). Of all of them, methyl jasmonate (MeJ) has been the most studied one. The main effect of MeJ is the improvement of the phenolic composition in several grape varieties (Moro et al., 2020; Portu et al., 2018; Ranjbaran et al., 2022; Sáenz de Urturi et al., 2023). In spite of the good results obtained when MeJ is applied to grapevines, the high cost, low water solubility, low thermal stability and phytotoxicity of MeJ limit its efficient applicability, particularly at high concentrations (Chronopoulou et al., 2019; Hartmond et al., 2000). For this reason, currently, there are efforts to introduce the use of nanotechnology in viticulture, thus allowing to reduce the dosage of the elicitor (Garde-Cerdán et al., 2023; Gil-Muñoz et al., 2023). Because of their small sizes, nanoparticles have high surface area, sorption capacity and controlled-release kinetics, which can lead to an increase in nutrient use efficiency (Solanki et al., 2015). The development of nanoformulations for the controlled delivery of nonmicrobial biostimulants into plants and fields is, therefore, a promising tool to preserve and regenerate the functioning of vineyards while improving the quality of berries in an efficient and sustainable way.

3 | FERTILIZATION

All living organisms on Earth, including cultivated plants like grapevines, need a constant supply/source of energy and a set of chemical elements (17 in the case of plants) in adequate proportions to carry out their metabolic functions (Kaspari & Powers, 2016). Essential elements for plants include macronutrients such as C, hydrogen (H), oxygen (O), N, P, sulphur (S), K, calcium (Ca) and magnesium (Mg), and micronutrients like boron (B), chlorine (Cl), copper (Cu), iron (Fe), nickel (Ni), molybdenum (Mo), manganese (Mn) and zinc (Zn). Other elements that may also be needed for plants, despite not being essential, include iodine (I), silicon (Si), sodium (Na), selenium (Se) and cobalt (Co). With the exception of C and O, whose supply comes mainly from the air (CO_2 and O_2), the supply of the rest of the essential elements comes mainly from the soil, where they are present forming part of water, organic matter and minerals. Therefore, soil nutrient bioavailability determines the productivity and functioning of terrestrial ecosystems worldwide, regulating ecosystem services from food production to C sequestration (Ochoa-Hueso et al., 2023; Schlesinger et al., 2011).

Although the uptake of essential elements from soil occurs via root uptake, leaves can also absorb mineral elements and different kinds of substances, including biostimulants (Fernández & Eichert, 2009; Tanou et al., 2017). Actually, the latest scientific research suggests that foliar sprays may be a key strategy to accelerate the regeneration of the health of crops and the soils where they are grown (Ishfaq et al., 2022). The potential of this approach is demonstrated in the exponential development of foliar-applied products by companies in the agricultural and biotech sectors. Actually, almost any commercial product can be supplied as foliar sprays (e.g., urea, or phenylalanine) (Portu et al., 2015). Foliar sprays can also be based on the use of locally available natural resources. For example, kaolin or pulverized diatomaceous earth have been widely used as a foliar fertilizer due to their high content of essential nutrients, including macro- and micronutrients such as Si, Fe and Mg, as well as to their high fungicidal and insecticidal power (Constantinescu-Aruxandei et al., 2020; Korunic, 1998). In addition, sufficient amounts of foliar sprays could be produced by composting, vermicomposting, or digesting plant raw materials to subsequently produce an extract that can be applied to the foliage (e.g., compost tea). This latter approach could also be used to provide added value to viticulture by-products, such as pruning waste, stems, sludge and lees. This is linked to the concept of the circular economy, which is also being highly promoted by various national and international institutions, as well as by supranational organizations.

3.1 | Valorisation of by-products as fertilizers

The development of biostimulants and fertilizers based on the circular economy of the vineyards needs to be done in parallel with the development of new legislation. Although the current European legislative framework for the management of waste and by-products generated in the agricultural field establishes a current scenario focused on the circular economy and the recycling of organic matter and the nutrients contained in it, several aspects should also be considered to ensure the viability of the actions. This legislative framework establishes the regulatory aspects to ensure the sustainable contribution of nutrients to the soil, reducing emissions of greenhouse gases and other polluting gases, especially ammonia, avoiding contamination of both surface and groundwater, and preserving and improving the biological properties and biodiversity of agricultural soils, thus promoting their management as living soils, and avoiding the accumulation of heavy metals and other contaminants in agricultural soils.

The modern wine industry produces thousands of tons of organic waste annually, including grape pomace (62%), lees (14%), stalk (12%) and dewatered sludge (12%) (Ruggieri et al., 2009). These raw materials can be used as sources of organic matter and plant nutrients after biological treatment (Perra et al., 2022). One of the main ways for the proper management of these organic materials is composting, which allows the return of properly stabilized organic matter to soils of croplands. Compost is a fertilizer of organic origin that comes from the decomposition of the remains of plant and/or animal origin carried out by microorganisms, mainly fungi and bacteria. Its usefulness in regenerating soil fertility has been established since ancient times. The direct addition of compost to soils has a positive influence on the abundance and biodiversity of soil organisms (Heisey et al., 2022). Many examples of successful composting and co-composting of waste and organic by-products from the agrifood sector attest to its potential use in agricultural fertilization. For example, Pinto et al. (2023) studied the composting of grape pomace with grape stalks using static and turned piles. They found that the process could be developed with minimal intervention and produced compost with high organic matter content and plant nutrients. In addition, grape pomace can be efficiently co-composted with other organic wastes, such as manure, being safe in terms of pathogens and phytotoxicity (Martínez Salgado et al., 2019). Composts can be applied directly to the soil, through a foliar application of compost tea, or by fertigation (Evans & Percy, 2014). It is well documented that the application of compost improves vineyard sustainability, soil properties and wine characteristics, including fruit quality or aroma composition, among others (Palenzuela et al., 2023; Sharifi & Hajiaghaei-Kamrani, 2023).

Anaerobic digestion technology represents another opportunity for the sustainable management of organic waste in the wine industry, alone or with other organic wastes (co-digestion) (Bolzonella et al., 2019). Anaerobic digestion is a well-established biological process used to convert organic waste into biogas, and it may be particularly useful for handling the wastewater generated in food processing, including winemaking, due to its high organic matter content and imbalanced dissolved organic C:N:P ratio. Full-scale anaerobic digestion plants are currently treating winery wastewater, and ongoing research is focused on improving process efficiency through innovative reactor configurations and operational conditions (Bolzonella et al., 2019). Furthermore, anaerobic digestion is widely used worldwide for digesting wine vinasses generated during the distillation process (Moletta, 2005). However, most studies are concerned with the digestion of grape pomace, but few refer to wine lees or grape stalks (Chiappero et al., 2023; El Achkar et al., 2017; Da Ros et al., 2016). Anaerobic digestates could be applied to agricultural soils and might be used in both their solid and liquid phases, depending on their characteristics (Slepetiene et al., 2023). Vermicomposting (organic matter transformation by earthworms) is another viable biotechnology for the treatment of wine organic wastes, as demonstrated by several studies (Gómez-Brandón et al., 2021, 2023; Karapantzou et al., 2023; Paradelo et al., 2011). Thus, the potential valorisation of by-products generated during wine production enables the recycling of organic matter and nutrients, fostering sustainable viticulture within a circular economy framework.

3.2 | Use of sedimentary rocks

In recent agricultural history, there have been several attempts to introduce the use of pulverized sedimentary rock applications to improve soil and crop health. For example, thanks to the research of Edmund Ruffin, considered by many as the father of soil science in the United States, the use of marly rocks with the presence of shells of marine organisms resulted in a true revolution in American agriculture during the 19th century, contributing to rejuvenate exhausted soils and increase the productivity of farmlands (Korunic, 1998). In the case of viticulture, in several traditional wine-growing areas in Europe such as the Jerez-Xérès-Sherry Protected Designation of Origin (PDO) in southern Spain or the Chianti PDO in Tuscany, one of the most widely available and usable natural resources as foliar fertilizer and natural fungicide and insecticide is diatomaceous earth. In the region of the Jerez-Xérès-Sherry PDO, this type of rock is known locally by the name of *Albariza*, while in the Chianti PDO, this is known as *Alberese*. In addition, diatomaceous earth has other known uses in agriculture such as a cereal grain preservative and animal dewormer (Constantinescu-Aruxandei et al., 2020; Korunic, 1998). Diatomaceous earth is formed by the sedimentation over millions of years of shells of marine organisms on the seabed, mainly diatoms, whose siliceous shells (frustules) are rich in Si and other minerals. Despite the historical uses of marl and diatomaceous earth, their application has generally fallen into disuse due to (i) the mechanization of the field, (ii) the incorporation into the market of synthetic agrochemicals offered by large companies in the sector whose agents of sales and agronomists discourage the application of low-cost natural products, as well as (iii) the standardization of the properties of the crops to establish their market cost (e.g., colour, absence of dust in cereal grains, etc.) (Constantinescu-Aruxandei et al., 2020; Korunic, 1998). However, due to its absence of harmful effects on plants, animals and humans, the use of rocks of sedimentary origin such as diatomaceous earth, marl or kaolin represents an opportunity to regenerate the health of farmlands and, therefore, to contribute to the ecological transition of viticulture. Just like it occurred in the 19th century in the United States. Nevertheless, despite their previous use by farmers and the agrifood industry, more scientific studies are needed to document its benefits for grapevines and soil health.

3.3 | Adjustment of fertilization rates

Another key aspect that must be considered for the proper fertilization of vineyards, both via foliar and/or soil application, is the adjustment of product doses, which must be adapted to the nutritional demands and growing conditions of plants. In grapevines, while a sufficient amount of nutrients is needed to achieve the desired crop yield, excessive nutrients (mostly N) can increase vigour, negatively impacting sink-source relationships in the vine and the canopy microclimate, potentially leading to changes in grape composition and wine quality (Lazcano et al., 2020). Thus, a delicate balance of bioavailable nutrients for plants is needed for the production of quality grapes and wines (Lazcano et al., 2020).

Normally, in crops, the optimal ranges of nutrients both in the soil and in the leaves are established based on agronomic tables. However, the low availability and, therefore, low uptake rates of specific chemical elements that are essential nutrients for plant growth can be difficult to assess based on soil and plant tissue chemical analyses, but it can be reflected in a poor stoichiometric adjustment of plant tissues (Ochoa-Hueso et al., 2021). In fact, plants require specific proportions of the 17 essential elements mentioned above to maintain their stoichiometry (Elser et al., 2010; Schlesinger et al., 2011) and to function properly, thus contributing to the coupling of many elemental cycles (Finzi et al., 2011; Rumpel & Chabbi, 2019). In this sense, we know that the cycles of all chemical elements within and between ecosystems are strongly interrelated or, in other words, they are coupled. Indeed, elemental coupling is a characteristic of healthy ecosystems, where the cycles of the different elements are strongly coupled to C, for example, through contributions of plant organic matter, decomposition and assimilation of essential nutrients by plants for their growth (Finzi et al., 2011; Rumpel & Chabbi, 2019). The dynamic coupling or decoupling of elemental cycles is often represented as changes in stoichiometric nutrient ratios, but these nutrient ratios do not usually consider the complexity of dealing with many essential nutrients simultaneously. Therefore, changes in the coupling of soil and plant nutrients are likely to have effects on the productivity and functioning of entire ecosystems (Elser et al., 2010; Ochoa-Hueso et al., 2021; Schlesinger et al., 2011). This suggests that indicators based on elemental coupling are potentially useful for understanding relative nutrient limitation and, thus, for designing fertilization strategies more in line with needs, thus reducing the risk of overfertilization and, therefore, of contamination and degradation of ecosystems and groundwaters. This is also linked to the concept of adaptive management of agroecosystems.

3.4 | Foliar fertilization to improve the sustainability of vineyards

The supply of foliar nutrient sprays has been implemented in agriculture and viticulture since at least more than one century ago (Fernández & Eichert, 2009), compared to more recent practices involving the supply of biostimulants to the foliage of crop plants (Garde-Cerdán et al., 2021; Saa et al., 2015; Tanou et al., 2017). Plant responses to foliar treatments may be variable due to the many variables affecting the process of absorption and bio-assimilation of the supplied compound/s (Fernandez & Brown, 2013; Fernández & Eichert, 2009). The factors affecting the efficacy of foliar sprays may be grossly associated with the environment (e.g., light, relative humidity, or temperature), plant-related characteristics (e.g., leaf-surface nature, or plant physiology and metabolism) and the physicochemical nature of the spray formulation and application method, which means that this practice should be carefully planned and managed (Fernández & Eichert, 2009; Fernández et al., 2021).

Some foliar-applied biostimulants such as kaolin (Monteiro et al., 2022) may have a direct effect on the leaf surface, but mineral elements and many other nonmicrobial biostimulants have to be absorbed by the foliage to be effective (Fernandez & Brown, 2013; Fernández et al., 2021). Foliar absorption has been shown to occur in the liquid phase; hence, factors affecting drop drying such as the supply of reduced spray volumes, low relative humidity or high temperature at the time of treatment may limit the chance for foliar absorption to occur (Fernández & Eichert, 2009; Fernández et al., 2021). Leaf surface physicochemical features may also greatly vary among plant species, varieties or growing conditions, and they can affect wettability and the effectiveness of foliar sprays (Fernández et al., 2021).

Hence, for optimising the efficacy of foliar sprays of nutrients and agrochemical treatments, it will be necessary to characterise the leaf surface traits and wettability of crop species/varieties, evaluating potential changes due to plant ontogeny. In addition to foliar formulation, physicochemical properties and spraying technology also play a key role (Fernández & Eichert, 2009; Fernández et al., 2021). An additional challenge is to determine the optimal concentration range of foliar treatments, which for various nutrients has been found higher than expected because of low foliar absorption rates (Fernández & Eichert, 2009). The permeability of plant organs may also vary with age, and the main foliar uptake mechanisms may also change during plant development (Fernández et al., 2021). Therefore, future studies should focus on identifying the best timing for supplying foliar treatments in which crop organs may be more permeable and plants are more responsive to foliar nutrient and biostimulant sprays. Moreover, foliar fertilization is a quick and target-oriented strategy to supplement crop plants, but it should not be considered a substitute or sole practice to follow (Niu et al., 2021). Actually, it has been shown that the nutrient elements and other constituents of foliar fertilizer formulations may stimulate the uptake of soil-applied fertilizers, suggesting that an integrated approach that considers both soil-based and foliar fertilization strategies is often the most effective way to ensure optimal plant nutrition as well as crop and soil health (Niu et al., 2021).

4 | COVER CROPS

Another highly applicable method that can contribute to the regeneration of soil functioning and biodiversity in the vineyards is the use of cover crops. Plant covers have been employed as green manure in vineyards since Roman times, where white lupin, clovers or other legumes were sown and, when a sufficient height had been attained, were dug in (Pieters, 1927). However, the specialisation of cropping systems that started in the 19th century (Darricau & Darricau, 2019), and the later intensification of grape growing in the 20th century, decreased its importance in favour of the use of mineral fertilisers and mechanical tillage (Haider et al., 2019; Winter et al., 2018).

Today, the species used as plant covers in vineyards are mainly legumes or grasses, although a diversity of plants can be used, including complex communities made up of native species belonging to different functional groups (Guzmán et al., 2019; Haider et al., 2019). When properly managed, plant covers offer a wide variety of ecosystem services and may improve vineyard performance (Abad et al., 2021a, 2021b; Winter et al., 2018). The use of cover crops is directly associated with a significant reduction in soil erosion (Bagagiolo et al., 2018; Gontier et al., 2014; Ruiz-Colmenero et al., 2011) due to a slower run-off of precipitation, leading to higher infiltration rates than can contribute to alleviate drought in vineyards with Mediterranean-type climate (Abad et al., 2023; García-Díaz et al., 2018). Cover crops also contribute to increasing soil organic matter (Celette et al., 2009; García-Díaz et al., 2018; Peregrina, 2016; Virto et al., 2012) and, although this increase is relatively slow, contribute to C sequestration. Greater soil organic matter can also increase soil water holding capacity (Hudson, 1994).

Cover crops also frequently result in an increased population of arthropods, small mammals and birds (Abad et al., 2021a), and may enhance the presence of species that act as natural enemies against vineyard pests (Begum et al., 2006; Burgio et al., 2016; Nicholls et al., 2000), thus contributing to decreasing pest pressure (Daane et al., 2018; Sanguankeo & León, 2011). Cover crops can also result in greater microbial biomass because of increased soil C and rhizodeposition (Steenwerth & Belina, 2008). This increase in microbial biomass is likely associated with a greater abundance of decomposers, thus enhancing the ability of soil to recycle nutrients (Vukicevich et al., 2016). Moreover, cover crops may also act as a reservoir of beneficial mycorrhizal inoculum sources (Nogales et al., 2021; Vukicevich et al., 2016).

The impact of cover crops on grape production is diverse, although competition for soil resources such as water and nutrients frequently results in a decrease in yield, particularly during the cover crop establishment period (Abad et al., 2021a). However, the intensity of this effect depends largely on the resources available, in turn, affected by soil depth and fertility, rainfall regime and use of irrigation and fertilisation. The intensity of this effect also depends on the competing ability potential of the rootstock (Abad et al., 2021a) and on the species forming part of the cover crop, whose main traits affecting competitive outcomes include rooting depth, phenology, nutritional demands and water use (Mercenaro et al., 2014; Susaj et al., 2013; Tomaz et al., 2017). Therefore, the implantation of cover crops in vineyards cannot be done without a thoughtful evaluation of these aspects to choose the best strategy in terms of species, cover crop width, and seasonal management. This will allow growers to harness the clearly positive effects of cover crops on the rest of the ecosystem services (Chapela-Oliva et al., 2022; Winter et al., 2018).

5 | REINTEGRATION OF ANIMAL HUSBANDRY

Integration of livestock and crop production is a core practice of traditional agrosilvopastoral systems, that has been practiced since ancient times (Garrett et al., 2020; Kassam et al., 2012). Nonetheless, the intensification of agricultural production has led to the decoupling of animal husbandry from crop production (Garrett et al., 2020). These highly specialized production systems are extremely inefficient in the management of nutrient fluxes and, therefore, highly polluting (Garrett et al., 2020; Naylor et al., 2005; Tilman et al., 2002). Formerly, it was common in many vineyards to use sheep to keep plant covers and weeds at bay during the winter season in which the vine is in the dormancy stage (Decker, 2001; Wilson & Daane, 2017). This also allowed the recycling of nutrients in vineyards (Wilson & Daane, 2017). Integration of sheep can entail savings in labour and machinery, reduction of herbicide use and also results in the return of preprocessed organic remains to the soil, with the consequent positive effects for C sequestration and soil biota (Brewer & Gaudin, 2020; Brewer et al., 2023; Kassam et al., 2012; Niles et al., 2017). It has been suggested that benefits to soil health and C sequestration are maximized in rotational or holistic sheep grazing systems, which consist of high-density and short-duration grazing events (Byrnes et al., 2018). In addition, sheep could be integrated into viticulture as a way of diversifying production and income sources through wool and meat sales (Ryschawy et al., 2021). Furthermore, wool, which is mostly composed of proteins, could be used as a raw material to produce foliar fertilizers (Gillespie et al., 2022). The hydrolysis of keratin, the main protein in sheep wool, results in amino acids such as cysteine that forms disulphide bridges, making it an unbeatable source of N and S, two essential elements in the operation of the vineyard (Gillespie et al., 2022; Kelly et al., 2017).

Despite the longevity of this practice, research into the ecological processes that underpin the benefits of livestock integration into vineyards is still scarce. Nonetheless, recent interest among winegrape producers throughout the world in nature-based production systems has spurred new research (Niles et al., 2017; Ryschawy et al., 2021). For example, in a controlled field experiment, rotational grazing resulted in sporadic increases in N_2O emissions, although this did not contribute to increasing the global warming potential of sheep grazing in this vineyard (Lazcano et al., 2022). This experiment also showed that sheep grazing had no negative effects on fruit quality (°Brix, phenolic compounds such as anthocyanins, and total acidity) or crop yields in the short term (Lazcano et al., 2022). In another field study involving eight commercial vineyards, Brewer et al. (2023) found that high-density, short-duration rotational grazing for more than 10 years resulted in higher soil microbial biomass, higher microbial activity and C use efficiency, than nearby vineyards without grazing. These increased rates and efficiency of microbial C accrual resulted in higher rates of C storage in the vineyard subsoil (30–40 cm depth), thus showing that sheep grazing could contribute to sequester more C and, therefore, mitigate climate change.

Despite the abovementioned benefits, there are still important limitations to the integration of livestock into vineyards, the most important being the timing of this practice. For most vineyards, sheep grazing is restricted to winter during vine dormancy (Schoof et al., 2021). Summer grazing requires structural modification of the vineyard to raise the trellis system and avoid leaf and grape consumption by sheep or, alternatively, the use of short-size sheep breeds (Conrad et al., 2022). Moreover, the transfer of copper-based fungicides to the cover crops can result in copper poisoning of the sheep (Trouillard et al., 2021). Another aspect that should be considered when implementing the use of sheep in vineyards is that this practice may need to be accommodated to soil type, particularly regarding texture, as this can affect the sensitivity of soils to trampling. Considering the size of the herd within the context of soil type is, thus, a critical aspect that should be carefully managed. Thus, despite that farmer experimentation and scientific studies performed in commercial vineyards show that sheep grazing decreases environmental footprint, improves soil health and sequesters C in vineyard soils, future research should also address existing barriers for the adoption of year-round grazing as well as aspects related to the sensitivity of soils to excessive trampling.

6 | ADVANTAGES OF A NATURE-BASED VITICULTURE

The main advantages of the nature-based approaches presented in this article include their low cost for the farmer, the low environmental impact, as well as the possibility of transferring protocols that can be implemented simply but effectively in small and medium-sized vineyards, thus promoting a more competitive economy. For large-scale operations, the cost/benefit analysis of incorporating nature-based management strategies should be carefully evaluated and transition may require additional expenses. In addition, this approach is linked to international directives, regulations and recommendations, including Focus 4C and B and Focus 5A, D and E of the European Innovation Partnership for Agricultural productivity and Sustainability (EIP-Agri; https://ec.europa.eu/eip/agriculture/en/node.html), whose priority objectives are to 'prevent soil erosion and improve soil management', 'improve soil management including the management of fertilizers and pesticides', achieving 'greater efficiency in the use of water in agriculture', 'reducing greenhouse gas emissions and emissions from agriculture', as well as 'promoting the conservation and C sequestration in the agricultural and forestry sectors'. By promoting the conservation and good management of soils, the largest reservoir of C globally, through the least inputs applied directly to its surface, a holistic and nature-based management approach will also contribute to Goal 13 of the international agenda (Sustainable Development Goals of the United Nations), whose mission is 'to take urgent measures to combat climate change and its impacts'. In addition, this framework is directly linked to Focus 5B of the EIP-Agri, which seeks 'greater efficiency in the use of energy in agriculture and in food processing'. In fact, it has been suggested that if one-third of all the world's grasslands, including cover crops in the inter-rows of vineyards and surrounding areas, were managed correctly through the use of livestock, we could significantly reduce atmospheric CO_2 concentrations (O'Mara, 2012), which is also linked to the '4 per 1000' initiative (https://www.4p1000.org/) of the United Nations Organization, and with the previously mentioned Focus 5D and E. In addition, the integration of sheep in wine-growing farms would favour the diversification of the sector.

7 | CONCLUSIONS

In summary, nature-based solutions for agriculture are expected to provide a more environmentally sustainable alternative to support food quality and safety while maintaining biodiversity and soil fertility in the context of global environmental change. Here, we reviewed some of the multiple sustainable management strategies available to the winegrower. These tools include: (i) the regeneration of microbial biodiversity, for example, through the application of microbial biostimulants, which can play a key role in nutrient recycling and plant immunity, and as biopesticides; (ii) the use of organic amendments based on the circular economy and foliar fertilization; (iii) the use of plant covers, which keep the soil protected against erosion and contribute to C sequestration and regulation of nutrient and water cycling; as well as (iv) the use of animals for the holistic management of vineyard agroecosystems. Specifically, the use of sheep in vineyards has been proposed as a key tool to improve soil health, as well as to control vegetation cover and adventitious plants, especially before bud break. Many studies have evaluated the potential of each of these strategies separately, but none have considered the combined use of complex community-based microbial biostimulant applications, elicitors, foliar fertilizers, cover crops and sheep for the regeneration of vineyards (Figures 1 and 2). Similarly, there are still many knowledge gaps on how foliar fertilization based on the application of compost extracts, earthworm humus, diatomaceous earth and hydrolysate sheep wool could serve to enhance the functioning and health of vineyards, both in isolation and in the context of the other previously mentioned sustainable management strategies. However, we argue that the time is now ripe for fostering innovation from both the public and private sectors to contribute to the sustainable management of vineyards while maintaining and even improving the profit margin for farmers.

AUTHOR CONTRIBUTIONS

Raúl Ochoa-Hueso conceived the idea and developed it with the rest of coauthors in a dedicated workshop. Raúl Ochoa-Hueso wrote the first version of the manuscript with input from all coauthors. All authors read and commented on subsequent versions. Figures were developed by Raúl Ochoa-Hueso and Ramón Casimiro-Soriguer, with feedback from all coauthors.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

This review article does not contain data.

ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.

ORCID

Raúl Ochoa-Hueso http://orcid.org/0000-0002-1839-6926
Manuel Delgado-Baquerizo http://orcid.org/0000-0002-6499-576X

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