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Evaluating the environmental impacts of smart vineyards through the Life Cycle Assessment

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HIGHLIGHTS

- Employing weather stations alone is insufficient to achieve environmental goals.
- LCA could allow the benefits accruing from smart technologies to be exploited.
- The LCA could avoid burden shifting from one life cycle step to another.
- Machine and electricity use was the major impact source in smart vineyards.

GRAPHICAL ABSTRACT

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ABSTRACT

This study aimed to assess the environmental effectiveness of vineyards utilising on-site weather stations integrated with a decision support system (DSS), and to identify the critical hotspots in smart farms that have already obtained integrated or organic certification. For this purpose, Life Cycle Assessment (LCA) methodology was applied. The research comprised three smart farms employing on-site weather stations and a traditional farm without advanced technologies, which served as a benchmark. The analysis revealed variations in environmental footprints driven by differences in farm management practices and soil characteristics. The results highlighted that smart farms, in compliance with integrated or organic certifications, focus on reducing inputs such as agrochemicals or water consumption. However, these reductions could shift the environmental burden to other impacts, such as those related to machinery use, which remained the most critical aspect across all vineyards considered. In some smart farms, critical issues involve other aspects, such as irrigation and fertilisation. The lack of awareness about the potential environmental impacts of the adopted technical options could make smart farms more impactful than traditional farms. Interestingly, this study found that solely implementing advanced technologies could fall short of achieving ecological objectives. This study emphasises the significance of utilising LCA as a valuable tool to support farmers in making informed decisions while adopting technological strategies to achieve environmentally sustainable goals.

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1. Introduction

The negative environmental impact of agriculture is an old issue that remains a serious concern because it is responsible for 29 % of the total greenhouse gas (GHG) emissions and utilises 70 % of all available freshwater (Rinaldi et al., 2016). Population growth and the consequent demand for food, as well as climate change, which puts the quality and amount of food available at risk (Alexandratos and Bruinsma, 2012; Maja and Ayano, 2021; Molotoks et al., 2021; Turi et al., 2014), could increase the environmental impacts of the agri-food sector. In this regard, the European Union, as part of "The European Green Deal" (EC, 2019), has introduced the "Farm to Fork Strategy", aimed at creating a fairer, healthier and more environmentally friendly agri-food sector (EC, European Commission, 2020). Therefore, ecological transitions have become a priority for agricultural systems. In addition, the wine sector has become aware of the significant environmental impact of its activities. The effects of conventional viticulture on soil degradation and surface water pollution due to the intensive use and production of synthetic fertilisers and pesticides (Rugani et al., 2013; Villanueva-Rey et al., 2014), air pollution resulting from greenhouse gases and other emissions generated by agricultural machinery (Balafoutis et al., 2017; Renaud-Gentié et al., 2020), and excessive land and water consumption (Christ and Burritt, 2013) have also been demonstrated. Therefore, the need to measure the environmental sustainability of wine chains has increased in recent years. In this regard, different indicators and methods have been proposed and implemented, such as carbon and/or water footprints (Bonamente et al., 2016; Bosco et al., 2011; D'Ammaro et al., 2021a; Marras et al., 2015; Miglietta et al., 2018; Rinaldi et al., 2016; Rugani et al., 2013; Vázquez-Rowe et al., 2013), a set of indicators defined in the program VIVA established by the Italian Ministry of the Environment to promote the sustainability of the Italian wine sector (Borsato et al., 2020; D'Ammaro et al., 2021b; Lamastra et al., 2016), and Life Cycle Assessment (LCA) (Casson et al., 2022; Fusi et al., 2014; Gazulla et al., 2010; Harb et al., 2021; Jourdaine et al., 2020; Masotti et al., 2022; Pattara et al., 2012; Roselli et al., 2020; Villanueva-Rey et al., 2014). The wine sector was the first to experience a significant ecologically oriented transformation, as the reputation of wine, more than that of other products, was closely tied to its origin and the climatic conditions of the relevant territories (terroir). Hence, operators consider climate change a deeply concerning issue, given its worldwide influence on wine production (Ollat et al., 2016; Santos et al., 2020). The environmentally sound turn is also dictated by increasing pressure from customers, whose purchasing choices tend to increasingly favour farms sensitive to environmental issues (Vecchio et al., 2023). Another reason that makes the ecological transition the right way for wine operators is the opportunity to expand their businesses by entering food and wine tourism. Garibaldi (2023) highlights that cellars and vineyards are the most interesting tourist places, as shown by numerous Italian vineyards being part of wine tourism itineraries. In addition, in the Sardinian region, which is considered a good destination for any wine enthusiasm, tourism is a profitable business for farms involved that generates 7–10 % of their turnover. As sustainability is a driver of choice for travellers attracted by these experiences, winegrowers interested in joining these tourist circuits must demonstrate their commitment to environmental protection by investing in ecological certifications and innovative technologies aimed at reducing the impact of their activities on the environment (Festa et al., 2023).

The transition from conventional to integrated, organic, or biodynamic farming is considered an appropriate approach to reduce the negative impacts of viticulture (Borsato et al., 2020; Masotti et al., 2022; Notarnicola et al., 2017; Renaud-Gentié et al., 2020; Rouault et al., 2016; Volanti et al., 2022). In this regard, the European standards for integrated and organic agriculture principally focus on reducing synthetic fertilisers and pesticides but do not consider other aspects, such as GHG emissions. Accordingly, organic farms may not necessarily have better environmental performance than conventional farms (Renaud-Gentié et al., 2020; Rouault et al., 2016; Rugani et al., 2013; Venkat, 2012). Thus, other strategies are needed to fully achieve environmental sustainability.

Smart technologies are considered a very promising solution for achieving environmental and economic efficiency in agricultural activities (Lieder and Schröter-Schlaack, 2021). As a result, a shift towards "smart farming" methods is taking place. The implementation of new technologies, such as global positioning systems (GPS) (Balafoutis et al., 2017), satellite and airborne remote sensing (Sassu et al., 2021), geographic information systems (GIS) (Ozdemir et al., 2017), robotics (Pradel et al., 2022), Internet of Things (IoT), cloud computing, drones, and artificial intelligence (Dantas et al., 2021; Drath and Horch, 2014), has enabled farmers to monitor field conditions and make strategic decisions for the whole farm or even a single plant (Khan et al., 2022; Martinho and Guine, 2021). Considering that successful farming depends on the monitoring of meteorological conditions, the application of wireless sensor networks (WSN), frameworks, and IoT platforms to detect various parameters such as soil temperature and moisture, air temperature and humidity, rainfall, and wind conditions has rapidly increased (Ebiesuwa et al., 2022; Nachankar et al., 2018; Prabu et al., 2021). These IoT-enabled networks can automate numerous farm activities through decision support systems (DSS) (Rinaldi and He, 2014). Therefore, in agriculture, it is becoming more common to use on-site weather stations integrated with a DSS, which allows growers to make well-informed decisions on several aspects of vineyard management, such as disease and pest control, irrigation scheduling, alerts on potential hazards such as freezing or hailstorms, control of the growth phase of grapevines, and grape ripening.

Some studies have shown that the introduction of innovative technologies benefits farms by maximising yields and reducing impacts (Balafoutis et al., 2017; Canaj et al., 2021; Casson et al., 2022; Del Borghi et al., 2022; Núñez-Cárdenas et al., 2022). However, there are certain exceptions. Pradel et al. (2022) highlighted an overall increase in the environmental impact of a vineyard when weeding was carried out with robots rather than in a conventional manner. In addition, the use of technologies to reduce a given impact may increase the occurrence of different environmental harms (trade-offs). For example, in Australian vineyards, the reduction in water use achieved through the conversion from flood to drip irrigation increased GHG emissions owing to the increased energy consumption for water pressurisation (Longbottom and Petrie, 2015). Therefore, a multi-criteria assessment from the perspective of the life cycle stages of a product should be appropriate for exploiting all the environmental benefits offered by innovation, especially when the operations responsible for negative impacts are diverse, as in viticulture. Indeed, Bosco et al. (2011) and Vázquez-Rowe et al. (2012), in Italian and Spanish vineyards, respectively, indicated that fertiliser and pesticide production were the primary processes involved in global warming, whereas Rouault et al. (2016) and Balafoutis et al. (2017) observed that field energy was the leading cause of GHG emissions for French and Greek vineyards, respectively. The implementation of LCA has the potential to address these challenges and aid in the decision-making process for adopting technological solutions that optimise resource utilisation and minimise the environmental impact of crop production (Balafoutis et al., 2017; Canaj et al., 2021; Del Borghi et al., 2022; Núñez-Cárdenas et al., 2022; Pradel et al., 2022). This methodology, based on international standards (ISO, 2006), is widely used to assess environmental impacts and improve the environmental performance of goods and services throughout their life cycles (Finnveden et al., 2009; Guinée, 2002; Tukker, 2000). It has also found various applications in the agricultural sector (Arzoumanidis et al., 2017; Notarnicola et al., 2017). In viticulture, LCA has primarily been employed to compare organic, biodynamic, and conventional farming methods (Masotti et al., 2022; Rouault et al., 2016; Rugani et al., 2013; Sinisterra-Solís et al., 2020; Villanueva-Rey et al., 2014; Volanti et al., 2022), and as an eco-design tool to evaluate the potential impact of precision agricultural strategies on vineyards (Rouault et al., 2020;

Tziolas et al., 2023). Few studies have focused on utilising LCA to evaluate the environmental impacts of vineyards using advanced technologies (Balafoutis et al., 2017; Casson et al., 2022; Pradel et al., 2022), highlighting that awareness of the impacts linked to the farm management techniques adopted is fundamental to leverage all the benefits derived from the implementation of smart technologies. Therefore, it may be difficult to assert that smart farms have better environmental performance than traditional farms without this knowledge. Further studies are needed to deepen the knowledge of the opportunities offered to smart farms using the LCA methodology to highlight the environmental criticalities due to farm management and to obtain data on which to make informed choices to improve their environmental performance. This approach allows the benefits accrued from smart technologies to be exploited. Considering the usefulness of on-site weather stations integrated with DSS in vineyards, this study involved three smart farms employing this technology and, as a benchmark, a farm that did not utilise advanced technologies, with the following main objectives:

1) Identifying critical hotspots from an environmental perspective that may persist in smart farms using remotely controlled on-site weather stations operating in the same geographical area under the same meteorological conditions that have already indicated their commitment to environmental protection through certification.
2) testing the hypothesis that employing smart technologies alone enables farms to achieve environmental sustainability objectives fully.

2. Materials and methods

2.1. Case studies

LCA studies on vineyards in Northern Sardinia (Italy) were conducted using data from the year 2021. Three smart farms (A_{sm}, B_{sm} and C_{sm}) equipped with on-site weather stations including multiple sensor devices which could monitor wind speed, wind direction, air temperature, relative humidity, rainfall, solar radiation, air pressure, light, soil moisture, and leaf wetness were selected. The data acquired through the WSN are automatically sent to the cloud and readable by a smartphone so that the operator can monitor the trends of the parameters of interest, make quick decisions, and act effectively. Agronomic technicians supervised the selected vineyards to obtain reliable information and data. As a benchmark for smart farms, a traditional farm (D_{tr}) was considered, which did not use any technological devices to acquire information on weather forecasts and soil conditions but relied entirely on the multi-year experience of an agronomist and the regional meteorological service. The farms involved, whose characteristics are detailed in Table 1, were located in a limited geographical area characterised by a Mediterranean climate, with mild winters and hot, sunny summers tempered by sea breezes. The average values of temperature, humidity, and rainfall registered by the on-site weather stations owned by the farms during the grape growth cycle are listed in Table 1. The farms involved follow the path of sustainability guaranteed by environmental certification. Specifically, three farms obtained the SQNPI (*Sistema di Qualità Nazionale di Produzione Integrata* - National Quality System of Integrated Production) certification, established in Italy by Decree Law No. 4 (2011). This certification is granted to agricultural and agro-industrial production methods which comply with the technical standard of

Table 1
Characteristics of the selected farms. Data from the reference year (2021).

Farm	A_{sm}	B_{sm}	C_{sm}	D_{tr}
Vineyard planting (year)	2017	2010	1970	1987
Rainfall (average in mm)	391.9	238	125.6	–
Temperature (°C) (average of the period April–August)	Mean 19.7 Min. 11.9 Max. 27	Mean 20.3 Min. 13.9 Max. 26	Mean 19.3 Min. 13.8 Max. 27	–
Humidity (average in %)	76	65	59.8	–
Type of certification	Integrated	Integrated	Organic	Integrated
Size (ha)	3.17	40	31	12
Plants per ha	4000	5680	3367	3800
Total grape production (kg)	19,000	176,825	107,700	120,000
Yield (kg/ha)	6000	4421	3474	10,000
Cultivar(s) (%)	Vermentino (100)	Vermentino (60) Cannonau (35) Cabernet (2.5) Sangiovese (2.5)	Vermentino (83) Cannonau (9) Carignano (3) Bovale (2) Merlot (2) Cabernet s. (1)	Vermentino (30) Cannonau (30) Monica (20) Cagnulari (15) Moscato (5)
Soil structure (%)	Loamy (45) Sandy (40) Clayish (10) Silty (5)	Sandy (83) Silty (9) Clayish (8)	Sandy (80) Silty (10) Loamy (10)	Clayish (80) Limestone (20)
Type of soil operations (times/year)	Shredding (1) Use of tiller (1) Milling (1)	Tillage (1) Pre-pruning (1) Shredding (1) Use of tiller (1)	Shredding (1) Mowing (1) Use of tiller (1) Mechanical weed control (5)	Tillage (1) Pre-pruning (1) Shredding (1) Use of tiller (1) Mechanical weed control (1)
Techniques to prevent soil erosion	Green manuring	Green manuring	Green manuring	None
Fertilisation (times/year)	1	1	1	1
Technique of fertilisation	Burying	Burying and foliar	Burying	Fertigation
Use of plant protection products (times/year)	6	6	12	6
Type of irrigation	Variable drip irrigation (precision irrigation) powered by electricity	Drip irrigation with gravity fall	None	Drip irrigation powered by a diesel generator
Amount of water for irrigation (m^3/ha)	300	2300	None	15
Water origin	Well	Reservoir	–	Municipal water network
Type of weather station employed	Netsens, Florence, Italy	Pessl Instruments, Weiz, Austria	Netsens, Florence, Italy	None

integrated production, an agri-food production system that uses production techniques aimed at minimising the use of synthetic chemicals and rationalising fertilisation in compliance with ecological, economic, and toxicological criteria. One of the farms (C_{sm}) obtained the organic certification in compliance with the EU Regulation 2018/848. The farms involved in this study had areas ranging from approximately 3 ha to 40 ha, yielding 3400–10,000 kg/ha of grapes. The production almost exclusively concerns grapes for certified Controlled and Guaranteed Denomination of Origin (DOCG), Controlled Denomination of Origin (DOC), and Typical Geographical Indication (IGT) wines. The production protocols for these certifications provide guidelines for grape cultivation techniques and yield limits. "Vermentino" is the predominantly grown grape cultivar in the farms involved; however, winegrowers manage all varieties cultivated under the same management schemes. The differences between farms were related to the soil texture, which ranged from predominantly sandy to mostly clayey, as well as the type of soil operations and the number of repetitions of each practice per year (Table 1). Fertilisation techniques range from fertigation and foliar fertilisation to buried fertilisation. Regarding irrigation, all farms adopted the drip irrigation system, with a variable (Farm A_{sm} and Farm B_{sm}) or uniform rate (Farm D_{tr}). Unlike the others, Farm C_{sm} did not include an irrigation phase. To identify the production steps that most influenced the environmental performance of each farm, the contributions to the various impact categories from soil operations (accounting for those linked to tillage, weed, and grass management), irrigation, fertilisation, and plant protection treatments were considered separately (Table 3). Regarding the phases related to fertilisation and plant protection treatments, the contributions to the considered impact categories of input products (manufacturing and use), diesel consumption for the use of machinery for spreading products, transport of products from the selling point to the farm, and product packaging were analysed in detail (Table 4).

2.2. LCA

2.2.1. Goal and scope definition

This study aimed to evaluate the environmental performance of grapes from vineyards operating under the same climatic conditions and employing on-site weather stations and identify the aspects related to the different farm management techniques that significantly influence their environmental footprint. The functional unit (FU) chosen for this study was 1 kg of grapes produced; an FU based on mass was considered more suitable when only upstream processes were considered (Pizzigallo et al., 2008; Zambelli et al., 2023). Modelling was performed using SimaPro software (ver. 9.1.1.1) (PRé-sustainability, 2023). A "from cradle to farm gate" approach was adopted (Fig. 1), i.e., from the production of raw materials to obtaining grapes. The vineyard planting stage and explantation stage were excluded from the analysis to avoid additional uncertainties from data with poor accuracy provided by the farms. Gazulla et al. (2010) excluded these stages by considering the long average lifespan (30–70 years) of vineyards. Replacement of dead or damaged vines was a usual activity carried out during the year. Therefore, the impacts of this activity were included in grape production. In general, these stages are included when analysing impacts related to transitioning from one agricultural technique to another (Falcone et al., 2016; Ferrara and De Feo, 2018). The soil operations considered for each farm are listed in Table 1. All inputs (water, fuel, energy, fertilisers, and pesticides) and output flows (emissions into the air, water, soil, and waste) were considered for each agricultural stage or activity within the defined boundaries (Fig. 1). These data refer to the year 2021. Given the seasonal variability of crops and microclimatic conditions, which could also imply variability in the characteristics of agricultural practices (Ferrara and De Feo, 2018), it is advisable to use average data over three or more years (Borsato et al., 2020; Harb et al., 2021). However, referring to a single year is typical (Gazulla et al., 2010; Harb et al., 2021; Laca et al., 2021; Russo et al., 2021) because of the difficulty of conducting data collection over multiple years.

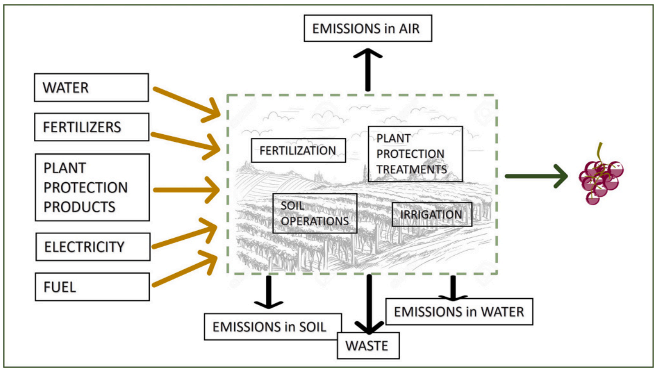

Fig. 1. System boundaries.

Facilities and equipment used to manufacture farm tools and machinery, as well as products and infrastructure related to employees' needs, were excluded (Pradel et al., 2022). Waste produced by employees during field operations, such as disposable masks, gloves, boots, and overalls, was not considered as their quantity, in terms of mass, did not exceed 1 % of the total. Vineyard stakes were excluded from the study because they were in the planting stage (Fusi et al., 2014). Finally, the wires for tying the shoots were not considered, as it was difficult to quantify all the manufacturing materials used, as they were made of mixed materials (e.g. rubber, plastic, iron, and natural twine).

Regarding the multifunctionality issue, the following choices were made: Farm D_{tr}-practiced fertigation integrates fertilisation into an irrigation system. The fertigation equipment was powered using a diesel generator. Thus, the allocation of diesel consumption between fertilisation and irrigation processes is required. The allocation could have been carried out considering the diesel needed to pump water for irrigation only and for fertilisation (Casson et al., 2022). Because such data were not available, we opted for an allocation criterion based on the mass (of water and fertiliser, respectively). In addition to being the most widespread allocation criterion, it also expresses a causal relationship between the flow to be allocated (amount of diesel consumed) and the functions provided (amount of water and fertiliser, respectively), as recommended by ISO 14044 (ISO, 2006). Therefore, based on the mass of water and fertiliser used in fertigation by Farm D_{tr} in the reference year, 1/6 of the diesel consumption for fertigation was allocated to the fertilisation phase, and the remaining 5/6 was allocated to irrigation.

2.2.2. Life cycle inventory

The input data collection (Table 2), initially conducted using a questionnaire to obtain the primary data, was subsequently completed and expanded through several direct interviews with the farms' reference technicians. Pesticide emissions in the three areas (air, water, and soil) were computed using the environmental distribution suggested by Mackay's model (level I) (Mackay and Paterson, 1981). Considering this distribution, substances for which data were not found were computed according to the Product Environmental Footprint (PEF) guidelines developed by the Joint Research Centre (JRC), which assume that 90 % of the substance is emitted into the agricultural soil compartment, 9 % into the air, and 1 % into the water (Zampori and Pant, 2019). The JRC guidelines, which propose specific emission factors for the main fertilising substances, were also considered for fertiliser emissions (Zampori and Pant, 2019). Secondary data were obtained from the Ecoinvent database (Ecoinvent database 3.5, 2018) and the Agri-Footprint database (Agri-Footprint 5.0, 2019); specifically, the collated data pertained to fuel, electricity, raw material production, transportation, and waste treatment.

Table 2

Data inventory related to the selected FU (1 kg of grapes).

Farm	Units	A_{sm}	B_{sm}	C_{sm}	D_{tr}	Farm	Units	A_{sm}	B_{sm}	C_{sm}	D_{tr}	Farm	Units	A_{sm}	B_{sm}	C_{sm}	D_{tr}
Main inputs						Main outputs						Main outputs					
Water	m3	5.00E−02	5.20E−01		1.50E−03	Grapes (FU)	kg	1.00E+00	1.00E+00	1.00E+00	1.00E+00	***to Soil***					
Diesel fuel	g	1.23E+01	4.05E+01	7.50E+01	5.22E+01	***to Air***						Fosetyl-aluminium	g	4.00E−01			1.40E−01
Lubrificating oil	g	4.80E−01		1.30E−01	7.60E−01	Dinitrogen monoxide	g	4.00E−02	1.10E−01	7.46E−05	7.00E−02	Myclobutanil	g	2.03E−04			
Electricity	KWh	4.30E−01				Nitrogen	g		1.00E−02			Quinoxyfen	g	2.37E−03			
Fertiliser						Ammonia	g	2.30E−01	6.00E−01	2.00E−02	3.60E−01	Magnesium	g	1.26E+00			
Fertiliser P_2O_5	g	8.86E−01	7.68E+00		3.75E+00	Ammonium nitrate	g		6.00E−02			Iron	g	1.26E+00			
Fertiliser N	g	1.19E+00	5.13E+00	1.40E−01	3.00E+00	Organic carbon	g	1.01E+01	1.33E+01	7.00E−01	1.88E+00	Calcium	g	1.01E+01			
Fertiliser K_2O	g	6.50E−01	9.90E+00		1.25E+00	Copper sulfate tri-basic	g	2.70E−03			1.00E−02	Potassium	g	6.30E−01	9.90E+00		1.25E+00
Magnesium oxide	g	1.26E+00	1.47E+00			Copper sulfate	g			7.00E−02		Copper sulfate tri-basic	g	3.00E−02			8.00E−02
Potassium carbonate	g		5.90E−01			Copper oxide	g	1.57E−03			4.68E−03	Copper sulfate	g				
Sulfur trioxide	g		7.35E+00		5.25E+00	Folpet	g	1.89E−03			7.00E−02	Folpet	g	1.00E−02			2.00E−02
Carbon	g	1.01E+01	1.35E+01	7.00E−01	1.88E+00	Copper oxychloride	g	8.53E−04				Copper oxychloride	g	2.00E−02		6.90E−01	
Calcium	g	5.05E+00			8.00E−01	Zoxamide	g	2.00E−02				Copper oxide	g			6.90E−01	
Zinc	g		6.79E−04		3.00E−02	Cymoxanil	g	3.00E−02	3.40E−01			Zoxamide	g	1.00E−02			
Iron	g	1.26E+00	1.36E−03			Mancozeb	g	1.16E−06				Mancozeb	g	3.30E−01	2.80E−01		
Manganese	g		2.71E−04			Penconazole	g	6.00E−02		7.90E−01		Metalaxyl-M	g	1.34E−04	1.11E−04		
Molybdenum	g		3.43E−03			Sulfur	g	4.00E−02			1.00E−02	Dimethomorph	g	4.84E−04			
Boron	g		2.88E−04			Fosetyl-aluminium	g	6.00E−06				Spiroxamine	g	5.00E−02	5.00E−02		
Copper	g		4.07E−04			Myclobutanil	g		5.00E−02			Penconazole	g	1.25E−03			
Pesticides						Potassium bicarbonate	g				6.00E−01	Sulfur	g	6.30E−01		7.77E+00	
Fosetyl-aluminium	g	4.30E−01			1.50E−01	Silicate	g			3.00E−01		Potassium bicarbonate	g		5.30E−01		
Sulfur	g	5.70E−01		8.74E+00	2.90E+00	Bentonite						Sulfur dioxide	g		7.35E+00		
Mancozeb	g	3.70E−01	3.10E−01			***to Water***						Bentonite	g			3.03E+00	
Copper sulfate	g	5.00E−02			9.00E−02	Fosetyl-aluminium	g	4.42E−03			1.50E−03	***Waste***					
Copper oxide	g			7.70E−01		Myclobutanil	g	1.96E−03				Paper waste	g	7.30E−01	6.00E−02	3.80E−01	
Disodium phosphate	g		3.00E−02			Nitrate	g	2.52E+00	8.80E−01	1.90E−01	3.99E+00	Plastics waste	g	3.00E−01	4.20E−01	9.00E−02	1.00E−01
Potassium carbonate	g		5.90E−01			Phosphorus pentoxide	g	5.68E+00	7.68E+00		3.75E+00	Alluminium waste	g	6.40E−01	6.00E−02		
Folpet	g	2.50E−02			8.00E−02	Copper sulfate tri-basic	g	9.50E−07			9.00E−04	Polylaminate waste	g	1.70E−01	2.15E−03		
Bentonite	g			3.36E+00		Folpet	g	1.00E−02			4.00E−02	Waste (tot)	g	1.86E+00	5.50E−01	4.70E−01	1.00E−01
Zeolite	g				3.90E−01	Copper oxychloride	g	6.00E−06		1.00E−02							
						Copper oxide	g			1.00E−02							
						Copper sulfate	g										
						Zoxamide	g	9.47E−05									
						Cymoxanil	g	1.42E−05									
						Mancozeb	g	3.71E−03	3.08E−03								
						Metalaxyl-M	g	2.00E−02	2.00E−02								
						Dimethomorph	g	1.00E−02									
						Penconazole	g	3.32E−03									
						Sulfur	g	1.00E−02		9.00E−02							
						Potassium bicarbonate	g		1.00E−02								
						Bentonite	g			3.00E−02							

2.2.3. Life cycle impact assessment

The CML-2001 baseline V3.06/EU25 LCIA method was used for the impact assessment phase as it is the most widely used assessment method in this context (Ferrara and De Feo, 2018). The impact categories considered were abiotic depletion (elements and ultimate reserves) (AD), abiotic depletion (fossil fuels) (AD_{ff}), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), photochemical oxidation (PO), acidification (AF), eutrophication (EP), freshwater aquatic ecotoxicity (FAE), marine aquatic ecotoxicity (MAE), and terrestrial ecotoxicity (TE).

Normalisation, which is an optional step in the LCAs, was also performed. For normalisation, the absolute impact indicators for the various impact categories are compared to reference scores – the so-called "normalisation factors" (NFs) – describing the impacts associated with a reference system, e.g. a region (Sala et al., 2017; D'Ammaro et al., 2021b), to obtain dimensionless indices. Therefore, normalisation allows comparisons between impact categories by expressing them on a common scale. In this study, the NFs were based on the total impacts for the EU 25 area, according to the CML2001 method.

3. Results and discussion

The characterisation results for the environmental footprint of each farm are shown in Table 3. The relative contribution of the vineyards to each impact category, presented in Fig. 2, highlighted that the smart organic farm (C_{sm}) contributed to eight impact categories out of 11 impact categories more than the other farms. These results are in agreement with those of previous studies (Renaud-Gentié et al., 2020; Rouault et al., 2016; Rugani et al., 2013; Venkat, 2012), highlighting that organic farms may have worse environmental effects than conventional farms. It should be noted that the impacts of the traditional Farm D_{tr} were similar or sometimes even lower than those of the smart farms, except for FAE, which had the greatest contribution by far. However, to identify the environmental criticalities and better understand which phases of production most affected the performance of each farm, an analysis of the contributions to the impact categories from soil operations (detailed for each farm in Table 1), irrigation, fertilisation, and plant protection treatments was conducted (Table 3). The analysis of the life cycle stages, presented in Fig. 3, shows that in Farms B_{sm}, C_{sm}, and D_{tr}, soil operations made the greatest contribution to most of the impact categories. In contrast, irrigation, particularly the related electricity consumption, has the greatest impact in Farm A_{sm}. Fertilisation in Farms A_{sm} and B_{sm} and the use of pesticides in Farms C_{sm} and D_{tr} had the second-greatest impact. Therefore, in line with Lamastra et al. (2016), pesticides and fertilisers did not have the most relevant effects at the vineyards considered. Criticalities persisting in the life cycle stages of smart farms are analysed and discussed in the following sections. Moreover, a comparison with the literature was made considering that grape production is heterogeneous, making comparisons with other studies difficult owing to different choices regarding FU, system boundaries, and other assumptions (Letamendi et al., 2022).

3.1. Fuel consumption and impact of soil operations

Considerable differences were observed among the smart farms with regard to fuel consumption (Table 2). Organic Farm C_{sm} had the highest diesel consumption (75 g/kg), which was approximately double that of Farm B_{sm} and approximately six times that of Farm A_{sm}. The fuel consumption of Farm C_{sm} was similar to that of Farm D_{tr}. Comparison of diesel consumption of the vineyards involved in this study with the other vineyards located in Sardinia. Indeed, the diesel consumption (105.6 g/kg) reported by Marras et al. (2015) was two to nine times higher than that of the farms considered in this study. On the contrary, in the Sardinian vineyard analysed by Benedetto (2013) and Fusi et al. (2014) (after converting into g/kg the data originally referring to 1 0.75-L bottle of wine as a FU, corresponding to 1.1 kg of grape), the consumption of diesel (around 11 g/kg) was similar to that of Farm A_{sm}, but lower than that of the other farms. The fuel consumption of these vineyards was also higher than that of the farms located outside Sardinia. The diesel consumption (after conversion of data from L/ha to g/kg of grapes) for 15 conventional wines from 8 farms located in various regions of central-northern Italy (D'Ammaro et al., 2021b) varied between approximately 8 g/kg and 60 g/kg (on average 35 ± 17.5 g/kg), thus placing the conventional vineyard D_{tr} of our study towards the higher end of this range. Compared with other organic farms, the diesel consumption of Farm C_{sm} was around four times higher than farms in the north of Italy (Masotti et al., 2022), and around five to eight times higher than the Spanish farms analysed by Villanueva-Rey et al. (2014) across two different years (15 g/kg and 9.2 g/kg, respectively). Notably, the farms considered in the aforementioned studies had higher yields than the

Table 3
Contribution of the various farm activities to the impact categories considered.

	Farm	Impact categories										
		AD (kg Sb eq)	ADff (MJ)	GW (kg CO2 eq)	OLD (kg CFC-11 eq)	HT (kg 1,4-dB eq)	FAE (kg 1,4-dB eq)	MAE (kg 1,4-dB eq)	TE (kg 1,4-dB eq)	PO (kg C2H4 eq)	AF (kg SO2 eq)	EP (kg PO4 eq)
Soil operations	A_{sm}	6,76E−07	8,53E−01	7,12E−02	8,10E−09	2,49E−02	6,87E−04	3,84E+01	2,22E−04	2,56E−05	4,20E−04	7,16E−05
	B_{sm}	1,84E−06	2,32E+00	1,94E−01	2,20E−08	6,77E−02	1,87E−03	1,04E+02	6,04E−04	6,96E−05	1,14E−03	1,95E−04
	C_{sm}	4,20E−06	5,31E+00	4,43E−01	5,04E−08	1,55E−01	4,27E−03	2,39E+02	1,38E−03	1,59E−04	2,61E−03	4,45E−04
	D_{tr}	1,74E−06	2,20E+00	1,83E−01	2,09E−08	6,42E−02	1,77E−03	9,90E+01	5,72E−04	6,60E−05	1,08E−03	1,84E−04
Irrigation	A_{sm}	3,52E−07	1,98E+00	1,58E−01	2,20E−08	2,43E−02	1,19E−03	7,33E+01	1,31E−03	3,52E−05	8,93E−04	1,05E−04
	B_{sm}	0	0	0	0	0	0	0	0	0	0	0
	C_{sm}	0	0	0	0	0	0	0	0	0	0	0
	D_{tr}	2,00E−09	1,60E−01	1,11E−02	2,05E−09	7,26E−04	4,97E−05	4,27E−01	4,86E−06	3,73E−06	1,14E−04	2,47E−05
Fertilisation	A_{sm}	2,32E−07	5,30E−01	4,49E−02	5,40E−09	1,12E−02	2,08E−03	1,52E+01	4,89E−04	1,91E−05	3,01E−04	7,95E−03
	B_{sm}	1,36E−06	1,70E+00	1,84E−01	1,23E−08	3,51E−02	1,70E−03	4,76E+01	2,90E−04	4,66E−05	9,29E−04	1,12E−02
	C_{sm}	4,51E−07	5,44E−01	4,60E−02	5,19E−09	1,65E−02	4,37E−04	2,41E+01	1,41E−04	1,61E−05	2,65E−04	6,47E−05
	D_{tr}	2,27E−07	2,64E−01	4,56E−02	1,00E−09	1,49E−03	3,45E−05	6,07E−01	6,22E−06	4,97E−06	1,66E−04	5,47E−03
Plant protection treatments	A_{sm}	5,66E−07	2,46E−01	1,93E−02	3,30E−09	1,88E−02	9,98E−01	1,21E+01	7,19E−04	1,00E−05	1,80E−04	3,28E−05
	B_{sm}	8,04E−07	6,69E−01	5,53E−02	6,54E−09	1,98E−02	1,00E−03	2,11E+01	1,76E−04	2,12E−05	3,67E−04	5,61E−05
	C_{sm}	4,10E−06	1,47E+00	1,23E−01	1,42E−08	5,13E−02	1,37E−03	6,68E+01	3,97E−04	4,56E−05	7,65E−04	1,58E−04
	D_{tr}	4,27E−07	5,48E−01	3,97E−02	4,57E−09	1,59E−02	2,96E+00	2,13E+01	2,04E−03	1,50E−05	2,47E−04	4,62E−05
Total impact	A_{sm}	1.82E−06	3.61E+00	2.93E−01	3.87E−08	7.92E−02	1.00E+00	1.39E+02	2.74E−03	8.99E−05	1.80E−03	8.16E−03
	B_{sm}	4.00E−06	4.69E+00	4.33E−01	4.09E−08	1.23E−01	4.58E−03	1.73E+02	1.07E−03	1.37E−04	2.44E−03	1.14E−02
	C_{sm}	8.75E−06	7.32E+00	6.12E−01	6.98E−08	2.23E−01	6.07E−03	3.30E+02	1.92E−03	2.21E−04	3.64E−03	6.68E−04
	D_{tr}	2.40E−06	3.17E+00	2.80E−01	2.85E−08	8.23E−02	2.96E+00	1.21E+02	2.62E−03	8.97E−05	1.61E−03	5.73E−03

sm = smart farm; tr = traditional farm.

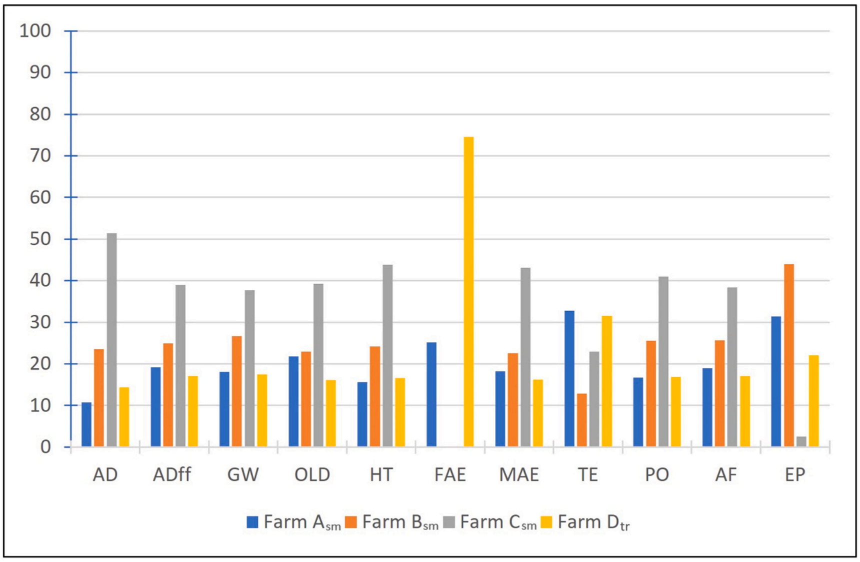

Fig. 2. Contribution (%) of the four farms to the impact catergories. *Method: CML-IA baseline V3.06/EU 25/Characterization/Excluding infrastructure processes/ Excluding long-term emissions.*

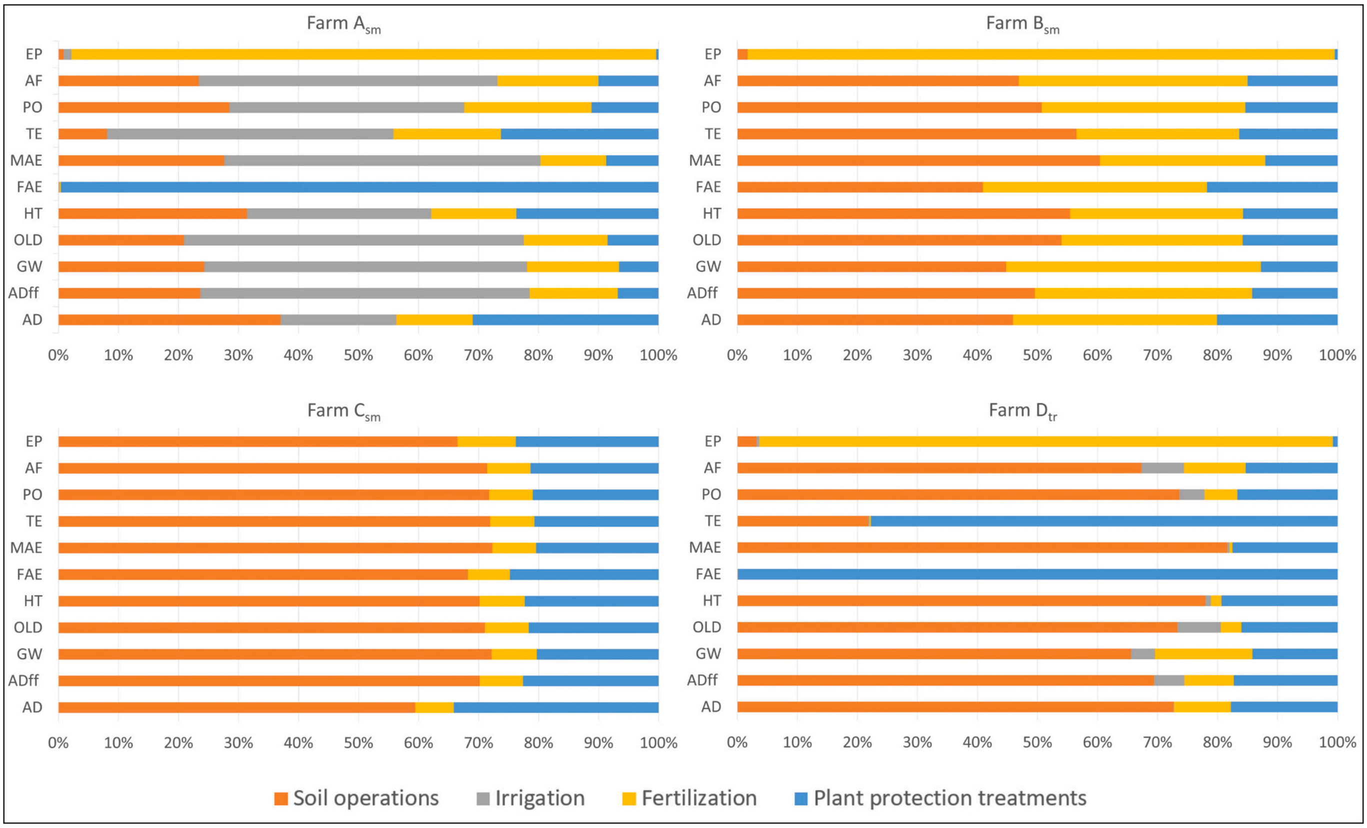

Fig. 3. Contribution (%) of the operations to the impact catergories related to the FU. *Method: CML-IA baseline V3.06/EU 25/Characterization/Excluding infrastructure processes/Excluding long-term emissions.*

smart farms considered in the present study. As the yield increases, the incidence of inputs and the related impacts per unit of harvested produce tends to decrease. Therefore, grape yield is a sensitive parameter that affects the environmental performance of vineyards (Bosco et al., 2011; Sinisterra-Solís et al., 2020).

Diesel consumption was allocated to soil operations, irrigation, fertilisation, and pesticide application (complementary Table S1) to evaluate its contribution to the different impact categories of the fuel used for various agricultural operations. Across the four farms examined, 70 % (approximately 60 % in Farm B$_{sm}$ and more than 80 % in D$_{tr}$), on average, of the fuel employed and the related impacts were attributable to soil operations. The remaining fuel was used to distribute fertilisers and pesticides, as discussed in Sections 3.3 and 3.4. More specifically, the incidence of the fuel-related impacts for fertiliser application ranged from approximately 7 % (C_{sm}) to almost 25 % (B_{sm}) (excluding D_{tr}, which carried out fertigation) of the overall fuel-related impacts. As regards the application of plant protection products, the percentage contributions ranged from approximately 14 % (A_{sm}) to almost 20 % (C_{sm}) of the overall fuel-related impacts.

Focusing on soil operations, it can be seen that Farm A_{sm} recorded the lowest impact for all categories (Fig. 3) since it carried out fewer operations than the other farms (Table 1). In contrast, organic Farm C_{sm}, despite not conducting certain agricultural operations (such as tillage and pre-pruning), had the highest impact. This farm had to repeat the practice of mechanical weed control five times a year, which the other farms either did not carry out (A_{sm} and B_{sm}) or carried out only once (D_{tr}). In the organic farm, this practice had to be repeated to prevent the grass from acting as a competitor for water and nutrients, since Farm C_{sm} chose to avoid irrigation and had mostly sandy soil that has very low water retention capacity. Therefore, the extent of the environmental impacts largely depends on farmers' management choices, as observed by Tuomisto et al. (2012). Owing to fuel consumption, soil operations generally had the highest impact on the categories AD, AD_{ff}, GW, OLD, HT, MAE, PO, and AF (Table 3), confirming the results obtained by Fusi et al. (2014) and Marras et al. (2015). Field energy was the input most related to GHG emissions, even in Greek farms (Balafoutis et al., 2017), regardless of whether conventional or precision viticulture techniques were used. Sinisterra-Solís et al. (2020) and Volanti et al. (2022) confirmed the primary role of machinery fuel on the negative environmental performances of both organic and conventional Spanish farms. In comparison with the literature, the GW impact category was mostly correlated with fuel consumption. Across the four farms analysed in this study, this category showed a value between 0.28 and 0.61 kg CO_2e (Table 3), within the range of about 0.1 to 1.42 kg CO_2e per kg of grapes observed in conventional (Balafoutis et al., 2017; Borsato et al., 2020; Bosco et al., 2011; D'Ammaro et al., 2021b; Harb et al., 2021; Laca et al., 2021; Sinisterra-Solís et al., 2020) and integrated (Rouault et al., 2016) vineyards. The organic vineyard has a value of 0.61 kg CO_2e, approximately 30 % higher than the average of the other vineyards. Therefore, as confirmed by other studies (Rouault et al., 2016; Rugani et al., 2013), the common opinion that organic agriculture has a lower carbon footprint than conventional agriculture is not universal. On the contrary, the behaviour of Farm C_{sm} differed from that observed in other organic farms whose value of GW was lower than that of conventional, and precisely 0.8–0.9 kg CO_2e/kg and 0.138 kg CO_2e/kg (average value over a 5-year period) of grapes in vineyards in the north of Italy found by Masotti et al. (2022) and Borsato et al. (2020), respectively. Finally, the GW of Farm C_{sm} is not even comparable with that obtained in Spanish organic vineyards, where the values range between about 0.05 and 0.13 kg CO_2e per kg of grapes (Sinisterra-Solís et al., 2020; Villanueva-Rey et al., 2014). In the farms analysed by Villanueva-Rey et al. (2014), however, most of the operations were carried out by hand, thus reducing the use of diesel by 80 %. As suggested by other authors (Vázquez-Rowe et al., 2012; Neto et al., 2013), reducing fuel consumption is the primary strategy for improving the environmental performance of vineyards. Several solutions have been proposed to mitigate emissions from fuel combustion, such as reducing the number and types of operations in vineyards in each season (Rugani et al., 2013) and introducing livestock to manage grass (Villanueva-Rey et al., 2014; Longbottom and Petrie, 2015). These activities imply efforts by agronomists to revise vineyard management techniques. Adopting eco-driving systems for tractors (Dettù et al., 2022), most-performing engines, and biofuel-powered (Hosseinzadeh-Bandbafha et al., 2021), green hydrogen-powered, or electric (Baker et al., 2022; Gao and Xue, 2020; Gorjian et al., 2021; Lagnelöv et al., 2021; Scolaro et al., 2021) tractors could contribute decisively to reducing impacts, a solution which, given the costs of high-tech machinery, is currently difficult to consider, especially in the case of small farms.

3.2. Water consumption and irrigation

Water conservation is one of the primary reasons why smart farms use on-site weather stations. Irrigation was not carried out at the organic Farm C_{sm}, whereas significant differences in water consumption were recorded among the other farms (Table 2). The consumption of Farm A_{sm} was 10 times lower (0.05 m^3/kg) than Farm B_{sm}. Farm D_{tr} performed best in terms of water consumption (0.0015 m^3/kg) despite not using IoT devices to detect soil moisture. This difference did not seem to be attributable to the irrigation technique, as smart farms were using variable drip irrigation, whereas Farm D_{tr} adopted a drip-irrigation system with a uniform rate, which was found to have a consumption of approximately 9 % higher than the variable rate drip-irrigation system (Casson et al., 2022) implemented by smart farms. In this regard, the considerable effect was due to the different soil texture, which in Farm A_{sm} was loamy (i.e., "medium-textured", with a balanced presence of sand, silt and clay), in Farm B_{sm} was sandy and, therefore, had a poor water-holding capacity and a tendency to remain dry during the summer season, while the soil in Farm D_{tr} was mainly clayey and was thus able to retain a great deal of water. The latter also utilises zeolite, which helps to keep the soil aerated and moist for a long time (Yasuda et al., 1998) by reducing the need for irrigation. Farm B_{sm}'s agronomist claimed that by using the on-site weather station with moisture-sensing sensors in the field, irrigation became more rational, preventing the over- or under-watering of different areas of the field; however, this did not result in less overall water consumption. This technician justified the high water consumption by stating that water stress shortens the life cycle of the vines, resulting in high economic losses for the farm. The techno-managerial approach of Farm C_{sm} (no irrigation) does not seem appropriate for oenologists because high water stress can influence the organoleptic characteristics of grapes and, consequently, wine. Indeed, irrigation gives the red wine higher acidity and a better "*bouchet*" of polyphenols (Borsato et al., 2020; Cavaliere et al., 2010) and the white one a higher aromatic expression with a lower bitter taste (Zufferey et al., 2020). However, the example of Farm C_{sm} demonstrated that even when operating in Mediterranean climatic conditions and with a soil texture which is predominantly sandy, water saving could be possible. Thus, in Farm B_{sm}, water management seems inefficient, and all the opportunities offered by on-site weather stations should be exploited. Another aspect that might affect water use is the grapevine cultivar, as identified by Balafoutis et al. (2017) in the northern Greek vineyards, where water consumption was different in the case of the Sauvignon and Syrah cultivars (0.23 m^3/kg and 0.11 m^3/kg, respectively). Sinisterra-Solís et al. (2020) observed that in Spanish vineyards where different varieties were cultivated, the differences in water consumption and other inputs were ascribed to the yield more than the varieties. In this research, the grapevine variety was excluded as a factor influencing the considerable differences in water consumption observed since Vermentino was the exclusive or predominant grape variety cultivated, and, in any case, all the varieties were managed the same way across the farms. Therefore, soil characteristics and vineyard management choices may be more important than other factors in determining water use. Considering that water scarcity and the excessive exploitation of aquifers are factors linked to ongoing climate change and that forecasts indicate a growing demand for water in the Mediterranean area in the near future (Mancuso et al., 2020), the reduction of water consumption is an important challenge for Sardinian viticulture. Therefore, various management options should be considered in vineyards, such as adopting effective cultivation methods that leave the soil settled to prevent the surface runoff of rainwater or avoiding trampling that reduces the macropores, which are considered true soil reservoirs (Giordano, 1999).

As shown in Table 3, the irrigation phase generated impacts only in Farms A_{sm} and D_{tr} because of the energy consumption required to power the irrigation system. Farm A_{sm} drew water from a well that used electricity to run a pump to pressurise the irrigation system, and Farm D_{tr}

used a diesel-powered generator to distribute water from the municipal supply network. In Farm B_{sm}, the impact of irrigation was zero because it did not consume energy, as it applied gravity-fed surface irrigation by drawing water from a reservoir. Irrigation, the most impactful phase in Farm A_{sm}, was responsible for approximately 50 % of its total impact on the categories linked to air emissions (Table 3), which may be attributable to the Italian power mix that is largely dependent on fossil fuels. Apart from the drip irrigation already practised by farms, Russo et al. (2021) recommended using deficit irrigation and the implementation of photovoltaic-powered irrigation to mitigate GHG emissions and make vineyards more resilient to drought phenomena. Deficit irrigation is possible in the Mediterranean regions, as demonstrated by Farm C_{sm}. However, as stated previously, the effects of high water stress on the quantity and quality of production must be considered. The employment of renewable energy sources could be an appropriate choice from an environmental perspective and could even be integrated into vineyards through innovative specific agrivoltaic solutions (enovoltaics) (Padilla et al., 2022). The impacts of irrigation were greater in Farm A_{sm} than in the D_{tr} (Table 3) because the latter applied fertigation. Indeed, as explained in Subsection 2.2.1, the diesel consumption to power the fertigation equipment was partly allocated to the fertilisation phase and the remainder to irrigation. Considering the experiences of the traditional Farm D_{tr}, fertigation could be another solution for mitigating the impact of irrigation. However, this technique is difficult to apply to land with a high slope, and only fertilisers with high water solubility can be distributed. However, the trade-off between water and energy consumption must be considered to meet the vine cultivation and grape quality requirements (Roselli et al., 2020).

3.3. Fertilisation

In the fertilisation phase, different fertilisers purchased from the market were used in the vineyards. In addition, unlike the traditional Farm D_{tr}, smart farms utilise green manure to enrich the soil with nutrients. Farm A_{sm} estimated the input of nutrients from pruning residues of a sample of vines for a more rational use of fertiliser. Generally, eutrophication is the category in which fertilisation has the greatest impact. EP impact was generated almost exclusively by fertilisation, which contributed more than 95 % of the total EP impact, except for the Farm C_{sm}, where the contribution of fertilisation to EP was only 10 % of the total. The contribution of fertilisation to the total impact was by far the weakest in Farm C_{sm} because, for the various categories, its contribution to the total ranged between 5 % and 10 % (on average 7 %), decidedly lower than the impact levels, ranging between 27 % and 42 % (on average 34 % excluding EP), found in Farm B_{sm}. Although the traditional Farm D_{tr} used only chemical fertilisers and did not use green manure, the contribution of this phase to the various impact categories, excluding EP, ranged between 0 % and 17 % (on average, 7 %) of the total, an impact similar to or sometimes lower than that of smart farms. To explain the different behaviours and better understand which factors related to the fertilisation phase had the greatest impact, the contributions to the different categories given by the use of machinery for distributing the fertilisers, the production of the fertilisers and their fate in the environment, the transport of fertilisers to the farm from the sale point, and their packaging were considered. Across all the farms considered, the contribution of transporting fertilisers to the farm and their packaging's production and end-of-life was generally negligible (Table 4). In contrast, the major impact on most categories was due to the fuel for the machinery used for fertiliser application. Farm D_{tr} had a lower impact owing to machinery use than smart farms (Table 4) because it practised fertigation. The change in fertiliser management from conventional to fertigated led to a reduction in emissions derived from the application of products, thus, confirming the findings of Casson et al. (2022).

When considering only the impacts of the products, the data reported in Table 4 provide evidence that the products utilised by Farm C_{sm} (algae) had the lowest impact. In this vineyard, the fertilisers' contribution to the total impact of the various categories did not exceed 3 %. At the same time, in the other farms, excluding EP, it ranged between 1 % and 20 % of the total. Fertilisers contributed, on average, for 5 % of Farm A_{sm} and D_{tr} and 10 % of B_{sm} to the total. In Farm B_{sm}, the greatest contribution was from NPK-based fertilisers. These products were also used by Farm D_{tr}; however, the amounts employed were one-third of those employed by Farm B_{sm} (Table 2). Farm D_{tr} had a nutrient-rich, clayey soil with less need for fertilisers (Table 1). Furthermore, it uses zeolite, one of its properties being the prolonged action of the fertiliser, which prevents the leaching of nutrients into the soil (Soltys et al., 2020). NPK-based products affect different product categories. The contribution of these fertilisers to GW, PO, and AF is principally related to their production processes, particularly the consumption of fossil fuels and the extraction of phosphorus or potassium from rock materials (Bosco et al., 2011; Casson et al., 2022). Furthermore, urea production contributed to the HT category, especially with regard to the emission of metals (in particular, Ba, Ni, Cr VI, and Hg). P- and N-based compounds were responsible for the eutrophication caused by Farms B_{sm} and D_{tr} (Fig. 2). These products are translocated through runoff and leach into water, which significantly affects the EP category (Jourdaine et al., 2020; Ngatia and Taylor, 2018). Farm A_{sm}, which used pelleted manure, contributed the most to the ecotoxicity categories (Table 4). Manure is considered a product with a high environmental burden, principally regarding CH_4 emissions when spread on the soil (Volanti et al., 2022). Nevertheless, it was proved that pelletising-drying could lower the nitrogen and CH_4 emissions from agro-biowaste compost (Ball et al., 2004) and mitigate the farm's environmental impact by more than 63 % (Sarlaki et al., 2021). In addition, the pelleted manure used in Farm A_{sm} was inoculated with the selected microbial strains. Compared to those not inoculated, this fertiliser allows a 40–60 % reduction in N_2O emissions (Nishizawa et al., 2014). Therefore, the impact of Farm A_{sm} may have been overestimated. Pelleted manure principally affected the EP category, like the NPK compounds. Therefore, approximately 97 % of the eutrophication caused by Farm A_{sm} was due to this natural fertiliser. Other natural products, such as algae employed by Farm C_{sm}, had little effect on all environmental categories, including EP. Thus, vineyards employing natural fertilisers did not necessarily have a lower level of impact than those utilising synthetic fertilisers, as highlighted by the comparison between Farms A_{sm} and D_{tr}. Therefore, farmers should consciously choose the type and quantity of these products while considering their environmental burden.

3.4. Plant protection treatments

In smart vineyards, on-site weather stations integrated with DSS were used for irrigation and pest management. Indeed, microclimatic conditions, such as local temperature, sun exposure, and average annual rainfall, influence vine diseases, and the quantity of pesticides to be applied in the vineyard (Ferrara and De Feo, 2018). As shown in Table 2, differences were observed in the types and quantities of pesticides used in the vineyards. Similar to other certified organic farms (Borsato et al., 2020; Masotti et al., 2022; Volanti et al., 2022), Farm C_{sm} exclusively utilises mineral products, and this type of plant protection product is among the few pesticides allowed in organic farming. However, considering that Cu accumulation may alter soil life, using Cu compounds in viticulture remains controversial. Karimi et al. (2021) reported that an amount of up to 4 kg/ha/year of Cu should not substantially modify soil biological quality and function. Based on this consideration, the amount of copper used by Farm C_{sm} (2.7 kg/ha/year) was lower than the proposed limit (Karimi et al., 2021). The same considerations are valid for Farm A_{sm} and D_{tr} utilising an amount of Cu compounds equal to 0.05 kg/ha/year and 0.9 kg/ha/year, respectively.

Smart Farms A_{sm} and B_{sm}, as well as the traditional D_{tr}, utilised mineral and synthetic products, particularly mancozeb, folpet, and fosetyl-aluminium, as a single pesticide or a combination thereof

Table 4
Contribution of the fertilisation and plant protection treatments to the impact categories.

Operation	Farm		Impact categories										
			AD (kg Sb eq)	ADff (MJ)	GW (kg CO2 eq)	OLD (kg CFC-11 eq)	(HT (kg 1,4-dB eq)	FAE (kg 1,4-dB eq)	MAE (kg 1,4-dB eq)	TE (kg 1,4-dB eq)	PO (kg C2H4 eq)	AF (kg SO2 eq)	EP (kg PO4 eq)
Fertilisation	A_{sm}	Machine use	1,35E−07	1,71E−01	1,42E−02	1,62E−09	4,98E−03	1,37E−04	7,68E+00	4,44E−05	5,12E−06	8,40E−05	1,43E−05
		Products	2,14E−08	8,77E−02	1,21E−02	4,82E−10	1,98E−03	1,80E−03	4,70E+00	4,13E−04	6,42E−06	1,36E−04	7,92E−03
		Transport	7,51E−08	2,71E−01	1,86E−02	3,30E−09	4,27E−03	1,46E−04	2,81E+00	3,19E−05	7,51E−06	8,11E−05	1,50E−05
		Packaging	3,80E−13	−2,28E−05	−4,57E−07	2,57E−14	4,11E−08	1,91E−09	1,64E−04	1,11E−09	−1,81E−10	−1,02E−09	2,28E−11
	B_{sm}	Machine use	7,51E−07	9,49E−01	7,92E−02	9,01E−09	2,77E−02	7,64E−04	4,27E+01	2,47E−04	2,85E−05	4,67E−04	7,96E−05
		Products	5,55E−07	5,74E−01	9,19E−02	1,00E−09	4,44E−03	8,37E−04	2,82E+00	2,01E−05	1,30E−05	4,06E−04	1,11E−02
		Transport	5,21E−08	1,88E−01	1,29E−02	2,29E−09	2,96E−03	1,01E−04	1,95E+00	2,21E−05	5,21E−06	5,62E−05	1,04E−05
		Packaging	5,35E−12	−3,20E−04	−6,42E−06	3,61E−13	5,77E−07	2,68E−08	2,31E−03	1,56E−08	−2,54E−09	−1,43E−08	3,20E−10
	C_{sm}	Machine use	4,17E−07	5,27E−01	4,40E−02	5,00E−09	1,54E−02	4,24E−04	2,37E+01	1,37E−04	1,58E−05	2,59E−04	4,42E−05
		Products	3,27E−08	1,37E−02	1,80E−03	1,36E−10	1,10E−03	1,06E−05	3,45E−01	3,82E−06	2,21E−07	4,18E−06	2,03E−05
		Transport	1,10E−09	3,96E−03	2,72E−04	4,82E−11	6,24E−05	2,13E−06	4,11E−02	4,66E−07	1,10E−07	1,18E−06	2,19E−07
		Packaging	1,97E−12	−1,18E−04	−2,36E−06	1,33E−13	2,12E−07	9,86E−09	8,49E−04	5,76E−09	−9,36E−10	−5,27E−09	1,18E−10
	D_{tr}	Machine use	4,00E−10	3,20E−02	2,23E−03	4,10E−10	1,45E−04	9,93E−06	8,53E−02	9,72E−07	7,46E−07	2,28E−05	4,94E−06
		Products	2,25E−07	2,29E−01	4,32E−02	5,54E−10	1,29E−03	2,28E−05	4,86E−01	4,85E−06	4,13E−06	1,42E−04	5,47E−03
		Transport	9,29E−10	3,36E−03	2,30E−04	4,08E−11	5,28E−05	1,80E−06	3,48E−02	3,94E−07	9,29E−08	1,00E−06	1,86E−07
		Packaging	1,97E−12	−1,18E−04	−2,36E−06	1,33E−13	2,12E−07	9,86E−09	8,49E−04	5,76E−09	−9,36E−10	−5,27E−09	1,18E−10
Plant protection treatments	A_{sm}	Machine use	1,35E−07	1,71E−01	1,42E−02	1,62E−09	4,98E−03	1,37E−04	7,68E+00	4,44E−05	5,12E−06	8,40E−05	1,43E−05
		Products	3,77E−07	7,67E−02	4,14E−03	8,63E−10	3,44E−03	1,00E+00	2,59E+00	6,68E−04	3,84E−06	7,92E−05	1,82E−05
		Transport	5,30E−09	5,58E−03	4,00E−04	6,39E−11	2,79E−04	4,55E−06	8,67E−02	6,96E−07	7,66E−08	1,48E−06	2,63E−07
		Packaging	−2,31E−09	−1,23E−02	2,33E−04	6,91E−10	9,95E−03	2,25E−04	1,63E+00	6,31E−06	6,37E−07	6,52E−06	−2,48E−07
	B_{sm}	Machine use	5,01E−07	6,33E−01	5,28E−02	6,01E−09	1,85E−02	5,09E−04	2,85E+01	1,65E−04	1,90E−05	3,11E−04	5,30E−05
		Products	3,02E−07	4,94E−02	3,35E−03	4,44E−10	1,46E−03	4,87E−04	1,92E+00	1,23E−05	2,49E−06	6,02E−05	3,21E−06
		Transport	1,38E−09	5,11E−03	3,54E−04	6,01E−11	8,10E−05	2,74E−06	6,19E−02	5,90E−07	1,41E−07	1,53E−06	2,79E−07
		Packaging	−7,21E−10	−1,84E−02	−1,14E−03	3,39E−11	−1,80E−04	5,23E−06	−9,35E+00	−1,22E−06	−4,39E−07	−6,29E−06	−4,34E−07
	C_{sm}	Machine use	1,14E−06	1,45E+00	1,21E−01	1,37E−08	4,22E−02	1,16E−03	6,51E+01	3,76E−04	4,34E−05	7,12E−04	1,21E−04
		Products	2,95E−06	1,76E−02	1,51E−03	1,65E−10	5,95E−03	1,29E−04	1,21E+00	1,79E−05	1,76E−06	4,86E−05	3,65E−05
		Transport	2,44E−09	8,81E−03	6,04E−04	1,07E−10	1,39E−04	4,74E−06	9,13E−02	1,03E−06	2,44E−07	2,63E−06	4,87E−07
		Packaging	−2,54E−11	4,63E−05	5,61E−06	6,57E−12	9,70E−05	2,19E−06	1,48E−02	5,36E−08	7,54E−09	7,11E−08	−2,59E−09
	D_{tr}	Machine use	3,45E−07	4,35E−01	3,63E−02	4,13E−09	1,27E−02	3,51E−04	1,96E+01	1,13E−04	1,31E−05	2,14E−04	3,65E−05
		Products	8,00E−08	1,11E−01	3,05E−03	3,48E−10	3,12E−03	2,96E+00	1,55E+00	1,92E−03	1,76E−06	3,05E−05	9,30E−06
		Transport	1,83E−09	6,60E−03	4,53E−04	8,02E−11	1,04E−04	3,55E−06	6,85E−02	7,76E−07	1,83E−07	1,97E−06	3,65E−07
		Packaging	7,03E−12	−4,21E−04	−8,43E−06	4,74E−13	7,59E−07	3,52E−08	3,03E−03	2,05E−08	−3,34E−09	−1,88E−08	4,20E−10

sm = smart farm; tr = traditional farm.

(Table 2). These chemicals are often used in conventional viticulture, as observed in Italian (Borsato et al., 2020; Ferrara and De Feo, 2018; Fusi et al., 2014), French (Rouault et al., 2016), and Spanish (Vázquez-Rowe et al., 2012; Villanueva-Rey et al., 2014) vineyards. Generally, the categories in which the pest control phase had the greatest impact were abiotic depletion and ecotoxicity. The contribution of these categories to the total burden was higher than the levels registered for the others, accounting for 1 % to 15 % on all the farms, except for the organic vineyard C_{sm}, where the levels ranged between 20 % to 24 %. Notably, in this phase, traditional farms that did not use advanced technologies had similar or lower impacts than smart farms across all categories except for FAE and TE (Table 3).

To identify the factors related to pest control that contributed the most to the different categories, the impacts of using machinery, products, and the transport and packaging of pesticides were considered (Table 4). As previously observed for fertilisation, these latter factors made a negligible contribution to the impact categories, whereas the greatest impact was attributable to the use of machinery to spread pesticides. This factor had the highest incidence in the organic Farm C_{sm}, which was carried out twice as many times (12/year) with low doses of pesticides compared to the other farms, as it used highly leachable sulfur and copper-based products. Similar results have been observed in Italian (Volanti et al., 2022), French (Rouault et al., 2016), and Cypriot (Litskas et al., 2020) organic vineyards. Litskas et al. (2020) attributed the substitution of synthetic pesticides to an increase in fuel consumption. In the case of Farm C_{sm}, the replacement of chemicals increased treatment frequency and, consequently, aggravated the impacts associated with the pest control phase.

By considering only the plant protection products, generally, for all the categories, excluding abiotic depletion and those linked to ecotoxicity, the contribution of pesticides to the total burden ranged between 1 and 5 %. To summarise, the contribution of pesticides to the total impact caused by the vineyards was, on average, 15 %, 3 %, 4 %, and 17 % for Farm A_{sm}, B_{sm}, C_{sm}, and D_{tr}, respectively. Farm A_{sm} had the greatest impact in five of the 11 categories (Table 4), principally due to the pesticides mancozeb and fosetyl-aluminium. Mancozeb, also used by Farm B_{sm} in quantities similar to A_{sm}, mainly affects AD due to the extraction of sulfur and metals employed for its production, as this pesticide is a manganese/zinc ethylene-bis-dithiocarbamate, and PO and AF for sulfur dioxide emissions during its production. Mancozeb's contribution to MAE due to the toxic effect of this pesticide on aquatic organisms (Vieira et al., 2020) was negligible (1 % of the total burden), confirming the findings of Russo et al. (2021). Considering that mancozeb exposure has been linked to a wide range of environmental and health hazards, the European Commission issued Regulation No. 2020/2087 (2020), which banned mancozeb use from 2022. Despite this, in 2021 (the year of data collection), two smart farms were using this pesticide, contrary to the traditional Farm D_{tr}, which did not utilise this product.

Folpet and fosetyl-aluminium were used in Farms A_{sm} and D_{tr}. In particular, these pesticides affected the impact categories connected to ecotoxicity due to their emissions into the air, water, and soil (Table 4). The effect of these two vineyards on FAE depended entirely (99 %) on the use of Folpet, and the impact of Farm D_{tr} on TE was, for about 70 % of the total, depending on the use of fosetyl-aluminium; A_{sm} and D_{tr} use these two products in different quantities. In particular, Farm A_{sm} used approximately one-third of the folpet (0.025 g/kg) used by the other farm and tripled the quantity of fosetyl-aluminium (0.43 g/kg). The various quantities of these two pesticides used indicated that Farm A_{sm} contributed the most to MAE, and D_{tr} contributed the most to FAE and TE (Table 4). Other viticulture studies (Renaud-Gentié et al., 2015; Vázquez-Rowe et al., 2012; Villanueva-Rey et al., 2014) have highlighted the effects of folpet on MAE. Organic Farm C_{sm}, which exclusively used mineral products based on copper, sulfur, and bentonite, had the least impact on all categories except for AD, HT, and EP, which made the most significant contributions. AD is related to sulfur and copper extraction, whereas the production of copper (Beylot and Villeneuve, 2017) and bentonite, to a minor extent (Zhou et al., 2021), contributes to HT and EP. The effect of Cu compounds on these categories is mainly linked to the emission of toxic metals during production and storage (Beylot and Villeneuve, 2017). Cu-related impacts may be overestimated because they are not adequately characterised by existing LCIA methods (Rouault et al., 2020).

3.5. Normalisation

The normalized results (complementary Fig. S1) showed that the categories that, in general, presented the greatest relative impacts were FAE (especially for Farms B_{sm} and A_{sm}) and MAE, followed by EP (except for Farm C_{sm}). Plant protection treatments are responsible for virtually all contributions to FAE. MAE was mainly affected by soil operations (diesel), except for Farm A_{sm}, which was irrigation because of related power generation. However, as highlighted in the literature, toxicity categories have a particularly high degree of uncertainty owing to incomplete inventory data for the reference system and lack of characterisation factors (Benini and Sala, 2016; Crenna et al., 2019; Scalbi et al., 2015; Van Hoof et al., 2013).

Therefore, excluding the toxicity categories, the most affected impact category in Farms A_{sm}, B_{sm}, and D_{tr} was EP due to the fertilisation phase. Fertilisation affected EP in both Farm A_{sm} and B_{sm} through the phosphorus pentoxide included in the fertilisation product. In Farm C_{sm} normalisation, the highest contribution was made by soil operations in all impact categories, confirming what was found with the characterisation. Excluding MAE, the most affected impact category was AD_{ff}, due to the use of fossil fuels.

4. Conclusion

Considering the limited studies related to the effect of smart farming on environmental impacts, research was conducted to evaluate the ecological effectiveness of vineyards employing on-site weather stations integrated with a DSS and to identify the critical hotspots that may persist in smart farms which have already started on the path towards sustainability. The results obtained through the LCA methodology showed that soil characteristics can exert both positive and negative influences on various aspects of environmental performance, irrespective of the use of decision-supporting technological devices. Agricultural machinery or electricity use were the major sources of impact; therefore, the main strategy for vineyard sustainability involves adopting measures to reduce the use of field energy. In addition, the results of this study highlight that replacing agrochemicals with natural products would not be the most appropriate choice from an environmental perspective. The contribution of organic fertilisers to certain impact categories could be higher than that of synthetic products, as in the case of an integrated smart farm which utilised pelleted manure, which had the greatest effect on the categories linked to ecotoxicity. Moreover, the objective of reducing herbicide, fertiliser, pesticide use, and water consumption in compliance with integrated or biological certification requirements shifted some of the environmental burdens to other life cycle steps, as in the case of the organic farm, whereby the water footprint improved, but the carbon footprint worsened.

Employing on-site weather stations to monitor climatic and soil conditions is insufficient for improving environmental performance. This study could enhance management and staff awareness of the importance of an integrated assessment throughout the life cycle stages of products to ensure a robust methodology to effectively leverage the advantage of technological innovation. Moreover, this study could be significant in assisting relevant stakeholders with decision-making to ensure a balanced trade-off between environmentally friendly and economically feasible options. A limitation of this study is that it was not possible to analyse the environmental performance of grape production before and after the installation of on-site weather stations to better understand how much these technologies could influence it. Further studies are required to deepen our knowledge of the environmental effects of smart farming to allow farmers to profit from the prime opportunities offered by smart technologies. Moreover, to achieve this objective, the economic aspects of grape production can effectively contribute to a comparative analysis of the sustainability of adopting technical management.

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CRediT authorship contribution statement

Valentino Tascione: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Andrea Raggi:** Writing – review & editing, Software, Methodology. **Luigia Petti:** Writing – review & editing, Software. **Gavina Manca:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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