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Exploring spatial and economic feasibility of olive mill wastewater disposal and reuse in sicily through GIS analysis

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Abstract
Olive mill wastewaters (OMWWs) present a substantial environmental challenge due to their high organic content. This study investigates sustainable OMWW management, focusing on field application, using a GIS-based approach to identify suitable areas in Sicily, Italy. Integrating regulatory, agronomic, hydropedological, and economic factors, the research offers a comprehensive evaluation of OMWW disposal strategies by explicitly linking spatial suitability to operational feasibility. The methodology included four phases: (I) identifying legally compliant areas; (II) agro-environmental suitability, assessing soil and environmental conditions; (III) economic suitability, based on a cost comparison between field application and transport to biogas plants; and (IV) final suitability mapping, locating olive oil mills with adequate land for OMWW disposal within defined service areas. Results showed 650,822.06 ha (25.19% of Sicily) were legally compliant, reduced to 216,368.98 ha (8.38%) after agronomic and hydropedological assessments. Economic analysis identified a break-even transport distance of 20 km, below which field application is more cost-effective than delivery to biogas plants. Mapping identified 553 mills (91.71%) with sufficient land for OMWW disposal within this threshold, while 50 mills (8.29%) lacked adequate areas and require alternative management solutions. By converting regulatory and environmental constraints into service-area polygons and introducing a quantified economic threshold, this study moves OMWW management from suitability screening to feasibility-oriented planning. These findings support targeted, cost-efficient, and environmentally sound strategies for OMWW reuse, providing practical guidance for policymakers and operators in Mediterranean olive-growing regions.

Keywords Land suitability analysis · Service areas · Olive oil mills · Wastewaters on-field spreading · Economic and environmental suitability · Location intelligent analysis

1 Introduction

Olive Mills' Wastewaters (OMWWs) are by-products generated by the olive milling process in three-phase extraction systems, which produce olive oil, pomace, and wastewater. OMWWs contain a high concentration of polyphenols and phytotoxic, bacteriostatic

Extended author information available on the last page of the article

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antioxidant compounds, posing a significant disposal challenge for agro-industries (Garcia-Castello et al., 2010; Rahmanian et al., 2014).

To date, virgin pomace retains economic value, serving as a raw material for pomace oil extraction and, subsequently, being processed into spent pomace, primarily used as a fuel source (Gullon et al., 2020). In contrast, the management of vegetation water remains a critical issue, in accordance with current regulations, and represents an economic burden for olive mills (Ncube et al., 2024).

Typically, OMWW exhibits an acidic pH ranging from 4.0 to 6.7 and consists of more than 80% water. The primary organic constituents of vegetation water include oils and fats (5–10 g L^{-1}), polyphenols (up to 12 g L^{-1}), and sugars (up to 20–30 g L^{-1}) (Asgharnejad et al., 2021).

OMWWs represent a major environmental concern within the olive oil industry due to their high content of potentially polluting organic compounds (Messina & Modica, 2022; Enaime et al., 2024). Consequently, a comprehensive preliminary assessment of disposal strategies, particularly land application, is essential to ensure environmental sustainability. This assessment considers multiple factors, including site environmental characteristics, production chain attributes, and machinery features for OMWW field application (Akar et al., 2023; Elkadri et al., 2023; Salomone & Ioppolo, 2012; Saouini et al., 2023).

Italy's first organic regulation regarding liquid effluents was Law No. 319/1976, which set strict limits that small olive oil mills often found difficult to achieve. These operations faced significant challenges due to the high costs and inefficiency of available purification systems. Law No. 574/1996 allowed OMWW application on agricultural land, recognizing its fertilizing properties (Barbera et al., 2013; Di Bene et al., 2013).

Following a complex and evolving regulatory framework, Legislative Decree No. 152/2006 now regulates OMWW disposal, consolidating previous regulations while providing clear guidelines for sustainable wastewater management. A key goal of Legislative Decree No. 152/2006 was to establish protocols for waste streams not covered by EU Directive 2008/98/EC, particularly wastewater, ensuring that OMWW nutrients can be safely used in agriculture. The soil spreading of OMWW has both immediate herbicidal effects and gradual fertilization effects due to its organic matter content (Ayoub et al., 2014; Di Serio et al., 2008; Strano et al., 2014). OMWW, especially from continuous-cycle processing plants, contains valuable nutrients that improve soil fertility. When applied according to regulations, OMWW supports olive grove nutrition by supplying potassium, nitrogen, and phosphorus in specific fertilizing units (FU).

This nutritional contribution supports the growth and health of olive trees, enhances their productivity, and leads to significant economic savings for farmers (Di Vita et al., 2015). By utilizing OMWW as a fertilizing agent, farmers can reduce their dependence on conventional fertilizers, thereby lowering input costs. These economic advantages, coupled with the environmental benefits of recycling agricultural by-products, underscore the importance of adopting sustainable practices in olive cultivation (Paredes et al., 1999).

This study uses a GIS-based approach to systematically identify and evaluate areas suitable for OMWW field spreading, linked to each active olive oil mill in Sicily. Improper disposal of OMWW treatment poses significant environmental issues, such as soil and water pollution. The main objective is to investigate environmentally sustainable ways to reuse OMWW, providing a foundation for an economic analysis and comparison with other disposal options. The core hypothesis is that by combining environmental, agronomic, and economic criteria through a GIS framework, we can effectively identify areas suitable for the sustainable and cost-effective application of OMWW in the field. The agronomic and hydropedological characteristics of potential land areas will be assessed to determine OMWW suitability, taking into account topography, soil properties, and crop compatibility.

The data generated will help identify environmentally and economically viable options, compared to the current alternative: transporting to biogas plants, considering costs and overall economic impact. Ultimately, the study aims to provide insights for better OMWW management, promoting sustainability and reducing environmental risks.

2 Materials and methods

2.1 Study area description

According to data from the International Olive Council (IOC), the European Union accounts for just over half of global olive oil production. Together with non-EU Mediterranean countries, the region contributes nearly 92% of the world's total production (Table 1). In terms of consumption, the EU utilizes more than 40% of the global oil produced. Meanwhile, there has been a steady increase in consumption in non-Mediterranean countries, which now account for 34.2% of the total, led by the United States of America. In the USA, olive oil consumption has reached 13% of the global total, reflecting a growing preference for olive oil over traditional seed oils.

Spain is the leading olive oil producer in the EU, accounting for the largest share of production (Table 1). In 2024, Spain produced approximately 1.29 Mt, contributing more than 38.22% of the world's olive oil production. Greece follows with an output of 0.25 Mt (7.41%), followed by Italy with 0.22 Mt, accounting for approximately 6.6% of the global total. In Italy, the primary olive-growing regions are Apulia, Calabria and Sicily. Together,

Table 1 Worldwide olive oil production and consumption in 2024. (source: our calculations based on the International Olive Council Production and Consumption prevision 2024-25) data, IOC, www.internationaloliveoil.org, last accessed August 11, 2025)

	Olive oil production		Olive oil consumption	
	000 (t)	%	000 (t)	%
Greece	250,00	7,41	110,00	3,59
Italy	224,00	6,64	395,00	12,89
Portugal	195,00	5,78	72,40	2,36
Spain	1.289,88	38,22	460,00	15,01
European Union (UE)	***1.973,08***	***58,46***	***1.326,40***	***43,28***
Algeria	85,00	2,52	90,50	2,95
Morocco	90,00	2,67	140,00	4,57
Syria	105,00	3,11	58,50	1,91
Tunisia	340,00	10,07	30,00	0,98
Turkey	450,00	13,33	200,00	6,53
Mediterranean Third Countries	***1.135,00***	***33,63***	***689,50***	***22,50***
USA	10,00	0,30	398,00	12,99
Australia	20,50	0,61	51,50	1,68
Extramediterranean Countries	***267,00***	***7,91***	***1.048,50***	***34,22***
Worldwide total	**3.375,08**	**100,00**	**3.064,40**	**100,00**

these three regions account for approximately 72% of the national olive production, from which over 76% of Italy's total olive oil output is derived.

The study area encompasses the region of Sicily (Southern Italy). Sicily is the largest island in the Mediterranean, covering an area of 25,420 km² (Fig. 1), and it is the third-largest olive-growing region in Italy in terms of cultivated area, olive production, and olive oil output, contributing 13.4%, 14.32%, and 15.2% of the national total, respectively (Italian National Institute of Statistics, ISTAT, https://www.istat.it/en/statistical-themes/censuses/agriculture, last access December 20, 2024).

Sicily has a Mediterranean climate with hot, dry summers and mild, wet winters. Most rain falls from October to March, with a clear summer drought. Temperature and rainfall patterns change along the coast, inland, and at higher elevations, with cooler conditions on Mt. Etna's slopes. Typical weather features include sirocco and mistral winds, along with high solar radiation. Olive farming mainly uses native varieties—Nocellara del Belice, Biancolilla, Cerasuola, Tonda Iblea, Nocellara Etnea, and Moresca—while Nocellara del Belice (and Giarraffa) are also used for table olives production. Olive groves grow from sea level up to low mountains, often on terraced hillsides with dry-stone walls. Soils vary from volcanic (Mount Etna) to calcareous (Hyblaean Mountains) and clayey (Trapani), creating a long-established agroecological mosaic with adjacent vineyards, citrus orchards, and Mediterranean maquis.

In Sicily, olive trees grow below 1,200 m a.s.l., extending uniformly from east to west. The only flat area with limited olive cultivation is the Catania plain, where citrus orchards dominate, except for the northern mountain ridge and the slopes of Mount Etna. According to a 2015 survey conducted by ISMEA (Italian Agricultural Food Market Services Institute, www.ismea.it, last accessed October 20, 2025), olive oil production in Sicily is predominantly managed by medium and small mills, most of which operate a continuous three-phase extraction process. Notably, 85% of these facilities process fewer than 500 tons of olives per year, while only approximately 3% of mills have the capacity to process more than 1,000 tons per season.

2.2 Census and mapping of olive oil mills (OOM)

To determine the number of active olive oil mills in Sicily, a comprehensive census was carried out by combining publicly available online databases with those provided by the Sicilian Region and other public and private research institutions (Tab. S3, Supplemental Material). The final database identified a total of 603 mills (Fig. 1) and includes, in addition to their names and spatial coordinates (latitude, longitude, and altitude), relevant contact details such as telephone numbers, e-mail addresses, and website links. The compiled database was subsequently converted into a point shapefile format to facilitate its use in a GIS environment. For this study, spatial analysis was performed using ArcGIS Pro (vers. 3.3, www.esri.com) in combination with the open-source software QGIS (vers. 3.34, https://qgis.org,).

2.3 Criteria for estimating olive oil mill wastewater (OMWW) production

Based on literature data (Hassen et al., 2023; IOOC, 2004), the average size of olive oil mills and the predominant processing methods used in Sicily indicate an estimated OMWW production of approximately 0.8 m^3 t^{-1} of crushed olives. This value represents the esti-

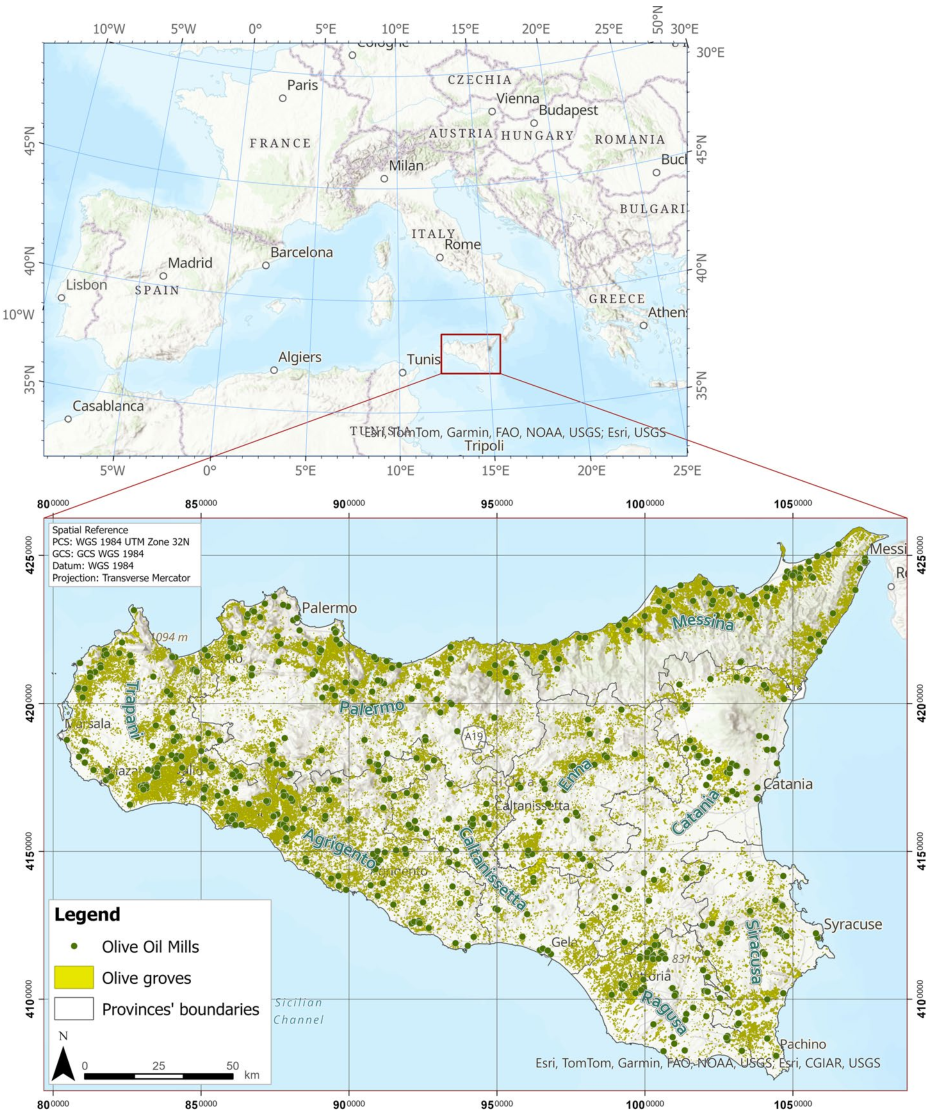

Fig. 1 Geolocation of the study area, Sicily region. The map below shows the geographical distribution of the 603 olive oil mills (OOM) surveyed across the Sicily region. It also illustrates the spatial distribution of olive groves according to the official land use and land cover (LULC) map released in 2008 by the Sicilian Region. The boundaries of Sicily's nine provinces are shown in light grey

mated coefficient of vegetation water per unit of crushed olives, considering the different extraction technologies employed. By processing the 2022 data provided by the olive oil portal of the National Agricultural Information System (SIAN) at the provincial level, we calculated the olive-to-oil yield percentage, and the average quantity of olives milled, and oil produced per hectare. The dataset includes the total olive-growing area, the quantity of milled olives, and the OMWW produced by the mills.

2.4 Mapping suitable areas for olive mill wastewater (OMWW) spreading

2.4.1 Flowchart of the proposed methodology

The spatial analyses required for mapping OMWW spreading suitability involved a comprehensive review of relevant regional, national, and European regulations. Simultaneously, we collected and integrated cartographic data necessary to evaluate the regulatory, agronomic, hydropedological, and economic aspects associated with OMWW applications on agricultural lands. This process required the acquisition of diverse geographical, environmental, and production datasets, which constitute the foundational layers of our analysis (Fig. 2). The sources of the collected data and the GIS-based implementations are detailed in the supplemental materials (Tables S1 and S2).

The proposed methodology consists of four distinct phases for identifying and mapping areas suitable for OMWW field application based on the following parameter categories:

I – Regulatory compliance (*Ope legis* suitability): identification of areas that meet existing legal requirements for OMWW application).

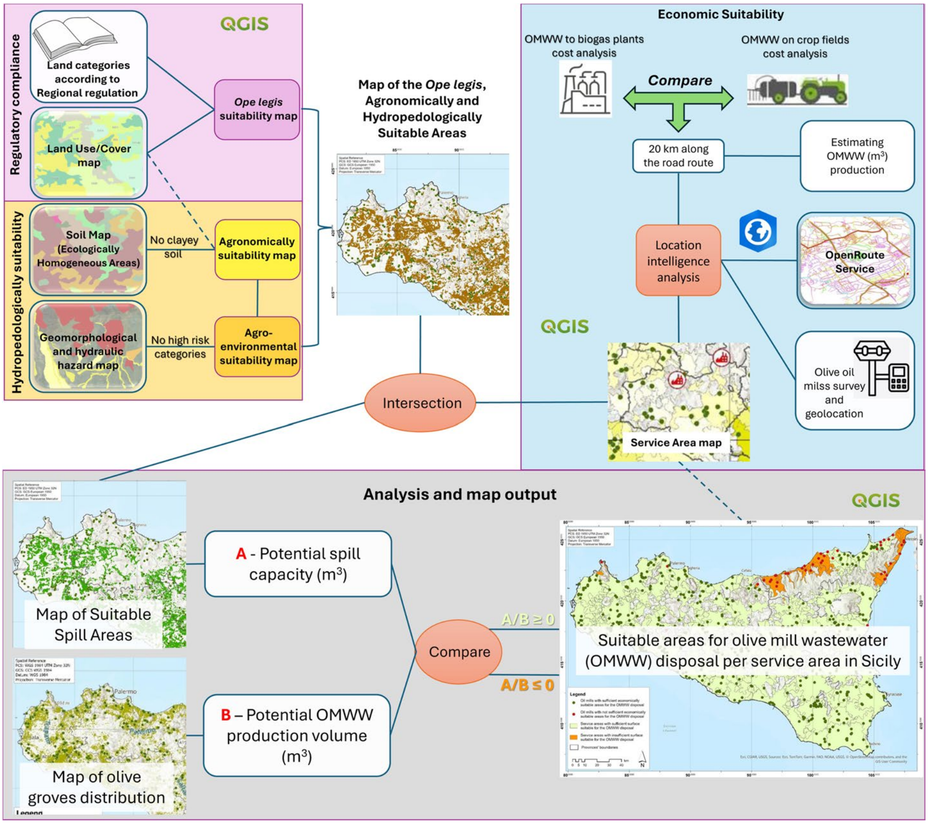

Fig. 2 Flow chart of the proposed methodology for mapping suitable areas for OMWW disposal in Sicily

II - Agro-environmental suitability: Assessment of agronomic and hydropedological characteristics to determine the feasibility of OMWW application.
III - Economic suitability: identification of areas where OMWW application is economically viable.
IV - Final Suitability Mapping: identification and spatial analysis of olive oil mills with sufficient available land for OMWW field disposal.

The proposed methodology was implemented in four successive phases within a GIS environment. This approach allowed the creation of a series of intermediate thematic maps. By intersecting these maps, we identified areas economically suitable for OMWW field application. This process led to the final phase, focused on identifying Sicilian olive oil mills with sufficient land for the effective disposal of OMWW in the field. These mills are located within a specified distance from the plant and possess sufficient land area to absorb the total quantity of OMWW produced. Conversely, we also identified mills that lack the necessary suitable lands for OMWW field application. A more circular approach to sustainability is required for these mills, addressing both technical and economic considerations.

For the reference data on olive-growing areas (see Fig. 1), we used the official land use and land cover (LULC) map released in 2008 by the Sicilian region (Regione Siciliana, 2008). This map, created at a nominal spatial scale of 1:10,000, follows the Corine Land Cover classification system (https://land.copernicus.eu/en/products/corine-land-cover, last accessed December 20, 2024).

The four phases described above will be detailed in the following sections.

2.4.2 I - Regulatory compliance (Ope legis suitability)

On July 21, 2022, the Region of Sicily adopted Presidential Decree no. 256, which implemented Italian Legislative Decree 152 of 2006. This regulation specifically addresses the agronomic use of OMWW and the field spreading of olive mill waste in Sicily. Article 5 of this Decree outlines the categories of land where the spreading of OMWW is prohibited.

For the purposes of this study, we referred to the provisions outlined in the decree and the accompanying implementing rules. The processed layers and details are provided in Tables S1 and S2 of the supplemental materials.

After acquiring the basic layers, we proceeded with the intersection process. We excluded the territorial information layers classified as "prohibited for spillage" according to Presidential Decree 256/22. These layers were modified accordingly, taking buffer distances and attributes into account. The result was the creation of a final layer representing the areas suitable by law in the Region of Sicily.

According to Sicilian Legislative Decree no. 256/2022, the agronomic use of OMWW via field spreading is allowed as long as it adheres to the annual acceptability limits established by Law no. 574/9. These limits are as follows:

- m^3 hectare-1 year-1 for OMWW from conventional cycle plants
- m^3 hectare-1 year-1 for OMWW from continuous cycle plants\
- 50 m^3 hectare^{-1} year^{-1} for OMWW from mixed (conventional and continuous) plants, provided the OMWW is not managed separately but is mixed.

Indeed, given the complexity of the administrative procedures required by the implementing regulations of Law No. 574/9 (to be implemented in the municipalities where the concerned areas fall), it is necessary to obtain authorization for spreading on fields at a rate of 80 m^3 ha^{-1} $year^{-1}$. To ensure operational efficiency and adopt a precautionary approach that prioritizes environmental sustainability, this study consistently uses the lower limit of 50 m^3 $hectare^{-1}$ $year^{-1}$ when calculating the amount of OMWW that can be spread over the available suitable areas. This standardization ensures precise and consistent results.

After identifying eligible areas in accordance with current regulations, we removed polygons with areas less than 1 hectare, as these were deemed unsuitable for OMWW spreading operations. This process resulted in the final map of areas suitable by law.

2.4.3 II - Agro-environmental suitability

In addition to regulatory constraints limiting the field spreading of OMWW, it is important to consider agronomic evaluations regarding the suitability of areas with land uses other than olive groves. Similarly, soils with pedological characteristics that hinder OMWW absorption or those affected by unfavorable hydrogeological and geomorphological conditions must be excluded, with particular attention to:

Hydraulic hazard (areas at risk of flooding).
Geomorphological hazard (areas prone to slope failures and landslides).

From an agronomic perspective, all agricultural land classified as Class 2 in the Corine Land Cover classification scheme is considered suitable for OMWW field spreading. However, greenhouse and open-field vegetable crops are explicitly excluded from this classification as per Presidential Decree 256/22. We extracted the relevant zones from the previously described land use map to identify agronomically suitable areas, ensuring compliance with the established selection criteria.

The areas identified as hydropedologically unsuitable for OMWW field spreading were excluded after assessing their intersection with the clayey soil layer. These areas exhibit low permeability and are prone to surface stagnation or runoff, making them inappropriate for OMWW application. To identify clayey soils, specifically clay and sandy-clay complexes, we used the “Ecologically Homogeneous Areas” dataset derived from the soil map of Sicily. This map, provided by the Sicilian region, is available in vector format at a nominal scale of 1:250,000.

Additionally, areas with a high risk of slope failures and landslides were excluded from consideration. The georeferenced data on hydraulic and geomorphological hazards was obtained from the vector shapefiles of the Hydrogeological Plan (PAI, Piano per l’Assetto Idrogeologico della Regione Sicilia) (https://www.sitr.regione.sicilia.it, last accessed December 14, 2024).

Hazard refers to the likelihood of a potentially destructive event of a specific intensity occurring within a given time frame and geographic area. It is typically expressed in terms of annual probability or return period. In the PAI, hazard is classified into four risk classes: R1 (low), R2 (medium), R3 (high), and R4 (very high). In this study, areas classified as R3 and R4, which correspond to active or reactivated landslides, were deemed unsuitable for OMWW field spreading.

The hydraulic hazard was assessed based on water draughts level and the recurrence intervals of flood phenomena (50, 100, and 300 years). The extent of water draught influences potential damage severity, which, in turn, affects land use and the overall hazard level.

To identify areas unsuitable for OMWW field spreading, we excluded regions with a Hydraulic Hazard Index (PI, Pericolosità Idraulica) classified as PI3 and PI4 (high and very high hazard). These areas have a hydraulic head exceeding 1 m and return periods shorter than 100 years, making them prone to severe flooding events. Conversely, areas categorized as PI1 (low hazard) and PI2 (medium hazard) were retained in the analysis, as they pose a lower risk.

This phase (II) involved identifying areas suitable from an agro-environmental perspective by overlaying zones that are agronomically suitable with those that are hydropedologically unsuitable. The resulting dataset was then compared with regions deemed legally suitable, as determined in phase I (Regulatory compliance - *Ope legis* suitability). The output of this step serves as input data for the subsequent phase (III – Economic suitability).

2.4.4 III - Economic suitability

Economic suitability refers to evaluating the financial viability and efficiency across different production processes. Through an economic assessment, various alternatives can be compared to identify the most cost-effective and sustainable solution (Blanc et al., 2018; Di Vita et al., 2014; Mancuso et al., 2019).

In the case of OMWW disposal in Sicily, the economic assessment must take into account how to dispose of alternative solutions beyond field spreading. One viable option is the transport of OMWW to biogas plants, where an anaerobic digestion process can convert its organic content into biogas within specialized reactors.

To evaluate the economic feasibility of these two approaches -field application vs. biogas conversion- it is essential to outline the costs that olive oil mill operators will incur for each alternative.

In the case of OMWW delivery to a biogas plant, the miller is responsible for transporting the wastewater to the nearest disposal facility, covering the related costs, and hiring a tanker truck of the appropriate size. On the other hand, if the OMWW is spread in the field, the farmer must cover the transportation costs as far as the road network allows. Additionally, the farmer is responsible for labor costs associated with field application and ensuring that at least one tanker truck is used safely to transfer and distribute the OMWW in the designated area.

To estimate transportation costs, we first calculated the barycentres of both olive oil mills (see Fig. 1) and biogas plants (see Fig. 4). Using these coordinates, we calculated the average distance between the types of facilities. The distance analysis was performed using OpenStreetMap's (OSM) open-source road network (www.openstreetmap.org, last accessed December 20, 2024). The shortest safely navigable route was identified, ensuring compatibility with a tanker truck of at least 12 m^3 capacity. The average distance between an olive oil mill and the nearest biogas plant was 60.8 km.

To estimate the costs of OMWW transportation by wheeled vehicle, we referred to the official cost tables provided by the Italian Ministry of Transport for 2023 (see Tab S4 of the supplemental material). For road transport, we selected a 12 m^3 tanker truck (classified as a C-class vehicle, with a capacity between 12 and 26 tonnes). This truck was estimated to make four return trips to transfer approximately 50 m³ of OMWW for disposal. The minimum tabular rates for this vehicle class were applied as cost items. For on-farm operations, including loading, transport within the farm, and field application, we selected a 2 m³ company wagon (classified as a Class A vehicle weighing up to 3.5 tonnes). The average tabular values for this class of vehicles were used for cost estimation. Additionally, labor costs were calculated based on the daily wage of a specialized worker, including taxes and contributions, according to the fixed-term agricultural worker wage rates in Sicily, effective June 1, 2023 (see Tab S5 in the Supplemental Material).

Finally, the estimated time required to spread 50 m³ of OMWW in the field amounted to 4.45 working days (with 7-hour workdays). This estimate was based on a loading and transfer time of 75 min per trip for the company's tanker truck, accounting for loading, transport, spilling, and returning to the reloading point. The truck's travel speed was assumed to range between 3 and 4 km h^{-1}. Additionally, it was considered that the specialized worker would need to reach the spreading site, located an average distance of 1 km from the stationary tanker truck, following the company's access road (Strano et al., 2004). This detailed analysis aimed to identify the specific distance at which the costs of these two waste management options become comparable, offering valuable insights for decision-making regarding waste disposal and resource allocation.

2.4.5 IV – Mapping olive oil mills suitable for OMWW field disposal

In this final phase, we defined a service area for each surveyed and geolocated olive oil mill. This service area was determined using the methodology described in the previous section and detailed further in Table 3. The service area extends along the road network from each mill's location. To delineate these areas, we conducted a location intelligence analysis, which identified the polygon representing the road network accessible within a defined distance for a specific vehicle. This analysis was performed using the Location Lab plugin (https://gis-box.com/location-lab-qgis-plugin, last accessed October 15, 2025, for QGIS. This plugin enables location intelligence analyses by integrating third-party APIs from road network providers, such as OpenRouteService (ORS, https://openrouteservice.org, last access December 15, 2024). ORS is based on the free collaborative project Open Street Map (OSM, www.openstreetmap.org, last access December 15, 2024). For this study, we calculated the service areas using a maximum distance of 20 km (based on the economic break-even point shown in Table 3) along the road network from each olive oil mill (Fig. 3). This threshold ensures that only mills within a feasible range are considered for OMWW field disposal. To assess whether these areas can effectively accommodate the disposal of OMWW generated by olive oil mills, it is necessary to compare the suitable areas with the olive groves located within the service area of each of the 603 surveyed mills. Once the hectare values for these two parameters have been obtained for each service area, the olive grove area within each polygon was multiplied by 1.25, representing the regional average yield of milled olives per hectare (as shown in Table 2). This result was then multiplied by 0.8, an estimate of the average volume of OMWW produced per ton of milled olives. Finally, the calculated value was compared to the potential spreading capacity of the service area, determined by multiplying the hectares of suitable land by the maximum allowable application rate of 50 m³ ha^{-1}.

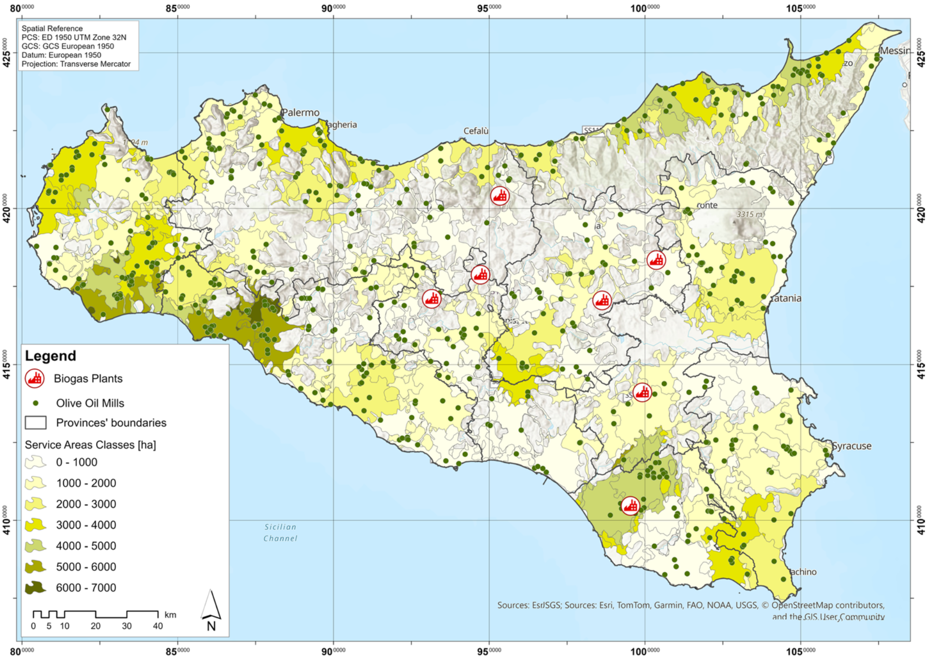

Fig. 3 Map of biogas plants locations together with the map of the service areas calculated for each of the 603 surveyed and geolocated olive oil mills (OOM)

In cases where the difference between the two values was higher than or equal to zero (≥0), service areas were identified where the ratio of economically suitable available land to olive groves is sufficient to accommodate the complete field spreading of OMWW produced by the nearby olive mills. Conversely, negative results (<0) indicate that the service areas associated with these olive oil mills lack adequate capacity for the complete disposal of OMWW.

3 Results

With an extensive olive grove area of 39,428 ha, Messina ranks as the leading province in terms of cultivated surface, followed closely by Palermo (37,367 ha) and Agrigento (32,296 ha) (Table 2). In contrast, with just over 10,000 ha, Ragusa has the smallest olive-growing area, primarily concentrated along the southwestern slopes of the Hyblaean hills. In terms of olive milling and oil production, Agrigento leads with an average of 65,614 tons of crushed olives, producing 52,491.20 m³ of OMWW and achieving the highest oil yield percentage (15.75%), followed by Trapani and Palermo.

The total area eligible for OMWW field application in Sicily, as defined by Legislative Decree 256/2022 and detailed in Table S1, was refined by excluding areas smaller than one hectare. As a result, the total eligible area amounts to 650,822.06 hectares, corresponding to 25.19% of the entire regional surface. The suitable spraying areas are fairly evenly distributed across most of the island, except for the northeastern region, which includes the Etna, Nebrodi, and Madonie mountain ranges. These areas are characterized by steep terrain, pro-

Table 2 Olive groves surface across the nine Sicilian provinces, along with data on crushed olives, oil production, and OMWW generation for the reference year 2022

Province	Olive groves surface		Total crushed olives	Oil yield	Total olive oil mill's wastewater		Average crushed olives	Average olive oil production
	[ha]	[%]	[t]	[%]	[m^3]	[%]	[$t\ ha^{-1}$]	[$t\ ha^{-1}$]
Agrigento	32,295.67	16.61	65,614.00	15.75	52,491.20	31.08	2.03	3.20
Caltanissetta	11,406.35	5.87	9,439.67	14.85	7,551.73	4.47	0.83	1.23
Catania	12,389.50	6.37	15,970.33	13.10	12,776.27	7.56	1.29	1.69
Enna	13,995.81	7.20	7,456.33	13.98	5,965.07	3.53	0.53	0.74
Messina	39,428.41	20.28	9,218.33	15.16	7,374.67	4.37	0.23	0.35
Palermo	37,366.89	19.22	30,803.67	15.33	24,642.93	14.59	0.82	1.26
Ragusa	10,333	5.32	14,111.33	12.60	11,289.07	6.68	1.37	1.72
Siracusa	11,702.83	6.02	8,899.33	12.46	7,119.47	4.22	0.76	0.95
Trapani	25,485.12	13.11	49,619.67	15.04	39,695.73	23.50	1.95	2.93
Sicily	***194,404.04***	**100**	***211,132.67***	***14.85***	**168,906.13**	**100**	***1.25***	***1.86***

tected natural reserves, and extensive forested zones, making them less suitable for OMWW application due to environmental conservation requirements and the constraints imposed by the rugged landscape.

After integrating agronomical and hydropedological suitability criteria (Fig. 4), the total suitable area for OMWW application was further reduced to 216,368.98 hectares, representing 8.38% of the entire region. These areas comply with both national and regional regula-

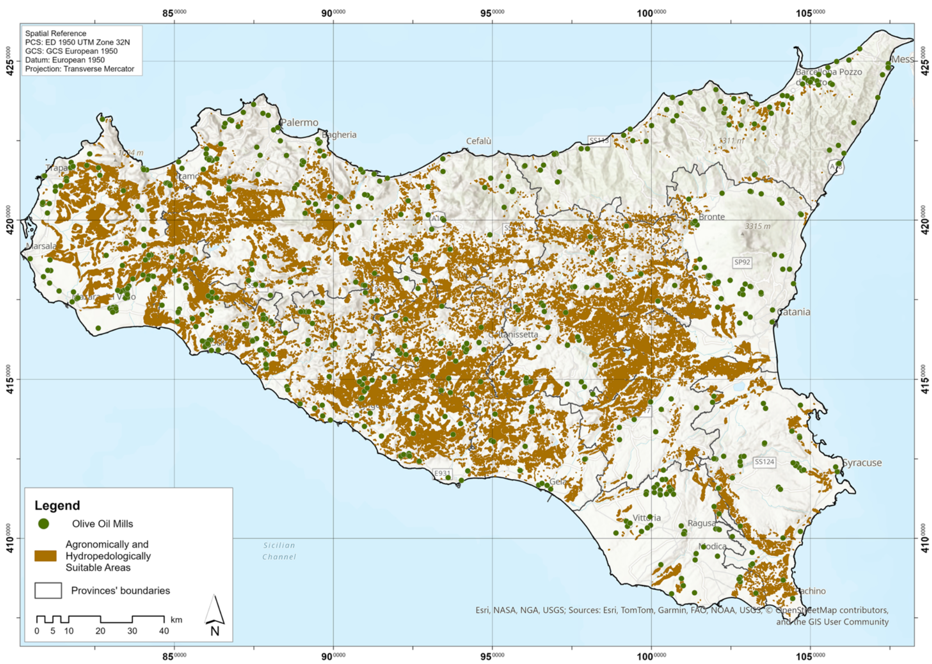

Fig. 4 Map showing the *ope-legis*, agronomically and hydropedologically suitable areas for the spreading of olive mills' wastewaters (OMWWs) in Sicily

tions and meet the agronomic and hydropedological requirements established in phases I and II of the proposed methodology.

The cost of transporting 50 m³ of olive mill wastewater (OMWW) to the biogas plant is equivalent to the cost of applying that same OMWW volume to a field 20 km away from the processing plant (Table 3). This finding implies that for distances shorter than 20 km, spreading OMWW to a field is more cost-effective for the miller than transporting it to the biogas plant.

The areas that are agronomically and hydropedologically suitable for OMWW spillage and fall within the defined service areas also represent the region economically viable for field spreading. For this analysis, areas smaller than 1 ha were excluded, resulting in the final map of OMWW-suitable areas for field application (see Fig. 5).

The areas suitable for the field application of OMWWs cover 166,401.94 hectares, representing 6.44% of the entire regional surface area. These correspond to Sicilian lands suitable for the field application of OMWW produced by the olive oil mills operating on the island.

Table 3 The table compares the unit costs of delivery [€ m^{-3}] for the biogas plant with those of applying olive mill wastewater (OMWW) in the fields [€ m^{-3}]

Cost of delivery to biogas plants (distance between centroids)				Cost of field application (distance 20 km)		
	Tanker truck (12 m³)		€/km		Tanker truck (12 m³)	€/km
	Vehicle purchase		0,1051		Vehicle purchase	0,1051
	Vehicle maintenance		0,0409		Vehicle maintenance	0,0409
A	Vehicle tires		0,0841	***A***	Vehicle tires	0,0841
	Vehicle tax		0,0012		Vehicle tax	0,0012
	Vehicle depreciation		0,0432		Vehicle depreciation	0,0432
	Salary		0,4344		Salary	0,4344
	Energy		0,3698		Energy	0,3698
	TOTAL		**1,0787**		**TOTAL**	**1,0787**
					Small tanker (2 m³)	**€/km**
					Vehicle purchase	0,1098
					Vehicle maintenance	0,0584
				B	Vehicle tires	0,0187
					Vehicle tax	0,0076
					Vehicle depreciation	0,0456
					Energy	0,1757
					TOTAL	**0,4156**
		€	**Km**			**€**
				C=A*(20*8)	Cost of 4 round trips with a 12 m³ tanker truck	172,59
B	Average distance between mills and biogas plants		60,80	**D**=B*50	Cost of 25 round trips with a 2 m³ small tanker	20,78
C=B*8	Truck trip for 4 round trips		486,40	**E**=74,59*4,45	Labor costs for 4.45 workdays	331,93
D=A*C	Total delivery cost	524,68		**F**=C+D+E	Total field application cost	525,30
E=D/50	**Cost per unit of OMWW delivered (€/m³)**	**10,49**		**G**=F/50	**Cost per unit of OMWW applied in fields (€/m³)**	**10,51**

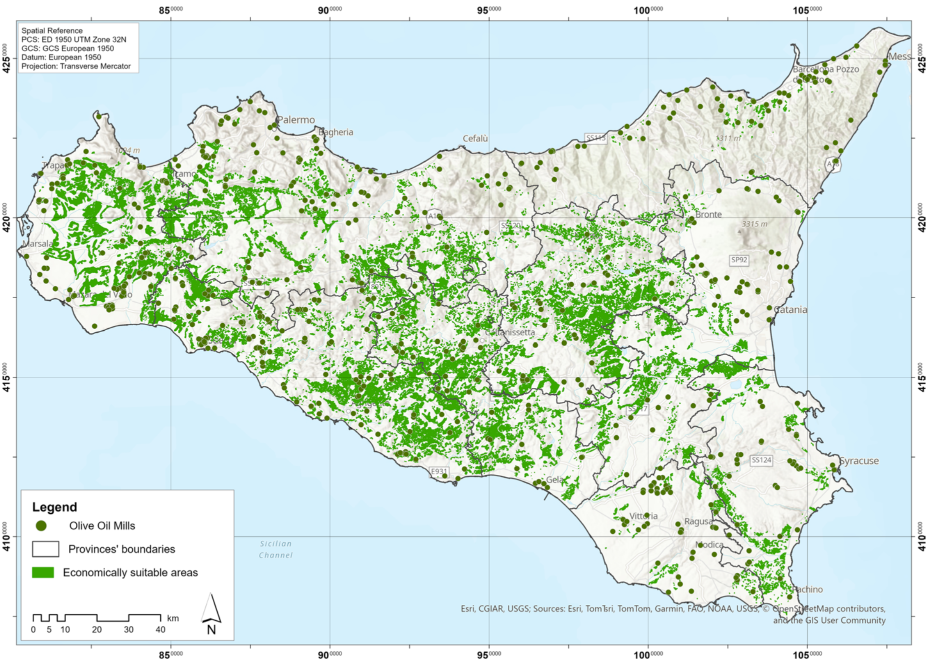

Fig. 5 Map of areas economically suitable for the field application of olive mill wastewater (OMWW) in Sicily, with a minimum area of 1 ha

Region-wide, economically suitable areas are mainly found in plains and low hills, while mountainous and protected districts remain constrained—patterns consistent with previous Mediterranean studies (Aydi et al., 2016; Issaoui et al., 2021). As shown in Fig. 6, suitable areas are primarily located in low hills (42.02%) and plains (29.33%), with only 1.67% of the total area in low mountainous regions (≥800 m a.s.l).

The map analysis (Fig. 6) reveals a significant concentration of economically suitable areas for olive oil production, especially in the southwestern and central parts of Sicily, where extensive olive-growing areas align with high potential for efficient waste management strategies. Notably, the southwestern part of the island has the highest density of suitable areas, highlighting the need for targeted strategies to improve environmental sustainability while ensuring cost-effective OMWWs treatment. The classification of surface area suitability shows a progressive increase in economic feasibility, with zones exceeding 7,500 hectares of suitable land mainly found in the southern and western provinces. On the other hand, less suitable areas, mostly in the northeastern and some inland zones, indicate a lower economic viability for large-scale processing, which may require tailored approaches for waste disposal and resource management optimization.

An analysis of the classification of suitable areas based on their current land use (Fig. 7) shows that nearly 71% (118,102.41 ha) of the identified land consists of arable crops. Additionally, 16.16% (26,886.43 ha) is occupied by vineyards, while only 8.33% (13,862.48 ha) is occupied by olive groves. Therefore, the olive groves classified as suitable for OMWW application account for just over 7% of the total olive grove area on the island.

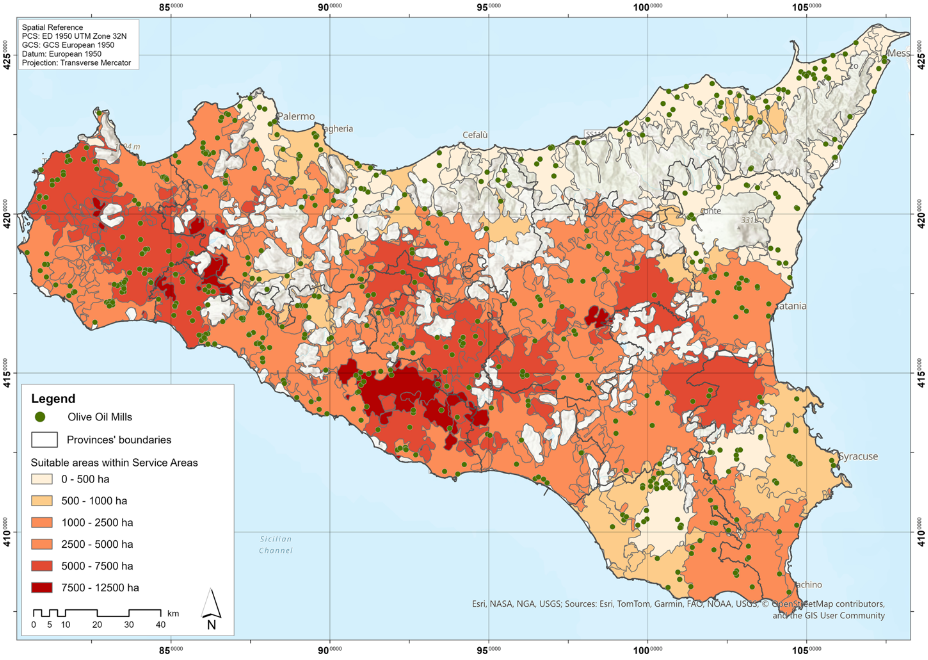

Fig. 6 Map of the distribution of suitable areas of field application of olive mill wastewaters (OMWWs) in Sicily within each service area

Out of the total number of olive oil mills, 50 (8.29%) are estimated to lack suitable areas for the field application of OMWW generated during the olive processing (Fig. 8). In contrast, the remaining 553 mills (91.71%) have enough suitable areas within their service zones to manage this wastewater effectively.

4 Discussions

The findings of this study highlight significant spatial and quantitative variability in olive oil production and associated wastewater generation across Sicilian provinces. Messina, with the largest olive grove surface (39,428.41 ha, 20.28% of the regional total), paradoxically records one of the lowest average crushed olive values (0.23 t ha^{-1}) and oil production (0.35 t ha^{-1}). This suggests that extensive cultivation in Messina is characterized by traditional or low-intensity management practices, possibly influenced by fragmented land ownership and mountainous terrain, which limit mechanization and yield optimization. Conversely, Agrigento and Trapani emerge as the most productive provinces. Agrigento, despite ranking third in olive grove surface (32,295.67 ha), leads in total crushed olives (65,614 t) and achieves the highest oil yield (15.75%), producing 3.20 t ha^{-1} of olive oil. Trapani follows closely with 49,619.67 t of crushed olives and an oil yield of 15.04%, reflecting efficient processing systems and favorable agro-climatic conditions. Palermo, with a large cultivated area (37,366.89 ha), shows intermediate performance (0.82 t ha^{-1} crushed olives), indicating potential for improvement through modernization and irrigation strategies. OMWW gen-

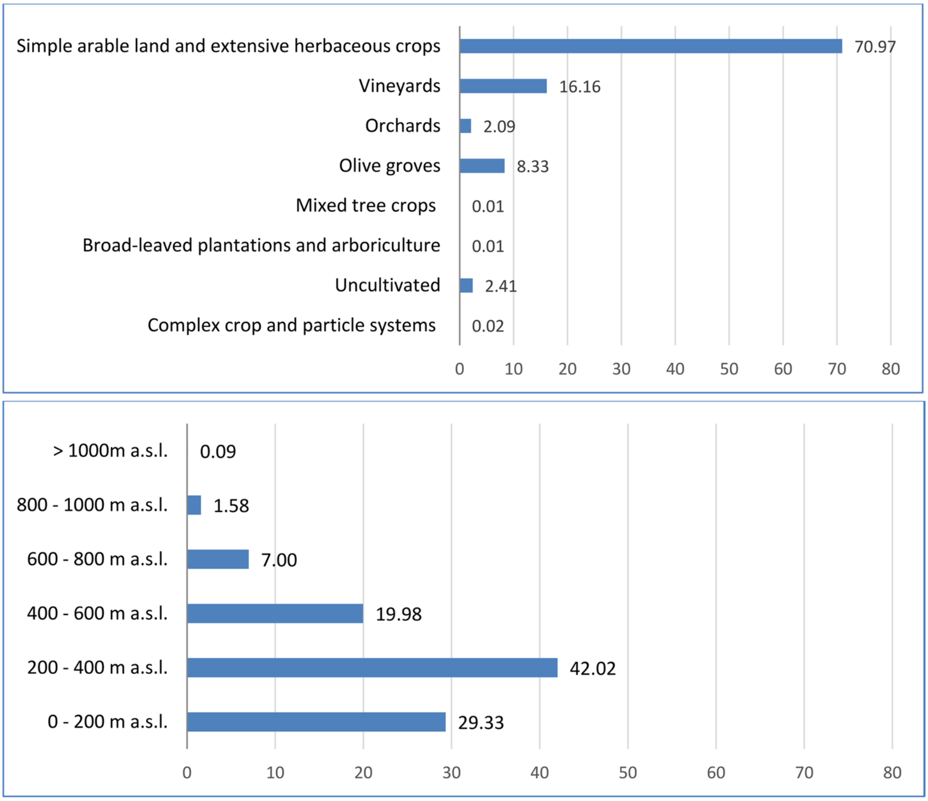

Fig. 7 The graph at the top illustrates the percentage distribution of economically suitable areas based on the current land-use classes (CLC), while the bottom shows their distribution according to the elevation zones

eration is directly proportional to processing volumes, and Agrigento and Trapani contribute 31.08% and 23.50% of regional production, respectively. This concentration of waste in high-production areas underscores the urgency of implementing localized management solutions to prevent environmental risks associated with uncontrolled disposal. This contrast between cultivated surface and productive output highlights the structural heterogeneity of the Sicilian olive sector. These differences are crucial for interpreting the spatial concentration of olive mill wastewater (OMWW) generation and underline why waste management strategies must be territorially differentiated rather than uniformly applied across the region.

The analysis of OMWW disposal options reveals critical implications for environmental management and economic sustainability. The findings presented in this study provide valuable insights for optimizing OMWW management in Sicily and in other Mediterranean regions with similar characteristics. By integrating GIS analysis, previously applied in studies on olive mills (Modica et al., 2024), with agronomic and hydropedological evaluations, we have identified key factors influencing the economic and environmental sustainability of OMWW field application. This comprehensive approach addresses the broader waste management challenges in the Mediterranean, where the absence of unified EU legislation

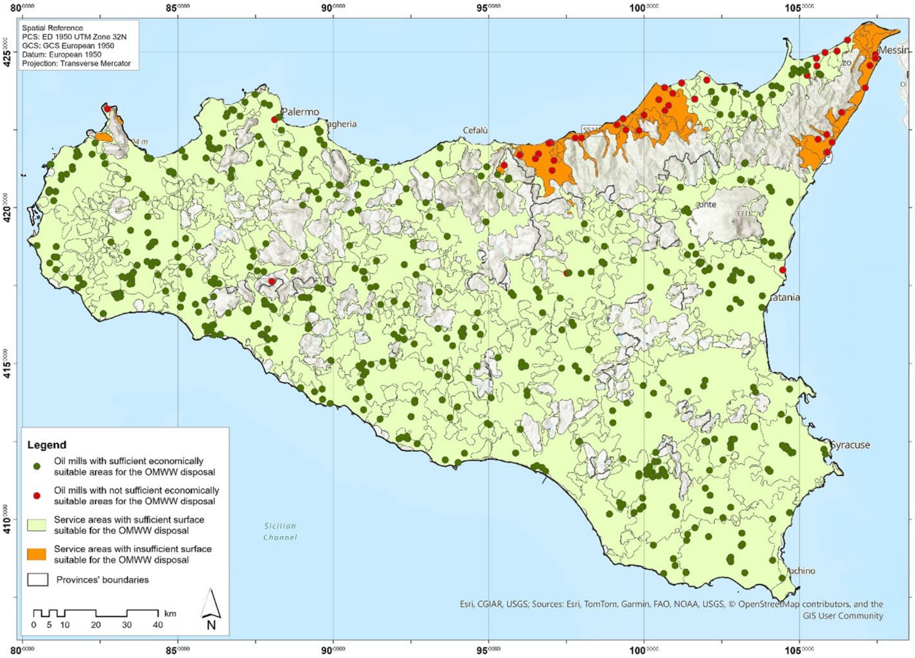

Fig. 8 Availability of suitable areas for olive mill wastewater (OMWW) disposal per service area in Sicily

has led individual countries to establish their own standards and limits for OMWW disposal (Koutsos et al., 2018).

The map of *Ope legis*, agronomically and hydropedologically suitable areas (Fig. 4), serves as a critical tool for identifying zones where OMWW can be applied with minimal environmental risk. This analysis establishes a robust framework for aligning OMWW disposal practices with sustainable agricultural objectives by integrating soil type, topography, and crop compatibility data. Identifying nutrient-rich yet underutilized soils supports previous findings highlighting OMWW's potential to enhance soil fertility while simultaneously addressing waste management challenges (Brunetti et al., 2007). Furthermore, this study underscores the importance of managing soil-water interactions to mitigate the risk of groundwater contamination, a concern widely documented in the literature (Altieri & Esposito, 2010). The sharp reduction from legally eligible areas to agro-environmentally suitable land demonstrates that regulatory compliance alone substantially overestimates the real capacity for sustainable OMWW field application. Hydropedological constraints, slope instability, and flood risk emerge as the primary limiting factors, confirming that environmental suitability represents the true bottleneck in OMWW management. This finding reinforces the need to integrate soil and hazard information into regulatory frameworks, as neglecting these aspects may lead to environmentally unsafe disposal practices even within legally permitted zones.

Consistent with our spatial screening, economically suitable land is concentrated in plains and low hills, with ~71% currently under arable crops, 16.16% in vineyards, and only 8.33% in olive groves (Fig. 7), reinforcing the agronomic feasibility of short-haul field application. This suggests that OMWW application strategies should not be limited to olive groves but extended to other compatible cropping systems, provided that agronomic and hydropedological criteria are met. Such diversification could enhance resource recovery and soil fertility while mitigating disposal challenges.

Economic and environmental feasibility analyses further refine the potential for OMWW field application. Although 650,822.06 ha (25.19% of Sicily) are legally eligible for OMWW spreading, integrating agronomic and hydropedological criteria reduces this to 216,368.98 ha (8.38%). When economic constraints are considered, the suitable area drops to 166,401.94 ha (6.44%), predominantly located in plains (29.33%) and low hills (42.02%), whereas mountainous and protected zones remain largely unsuitable due to conservation requirements. These findings confirm that topography is a critical determinant of feasibility, as mountainous zones ($\geq$800 m a.s.l.) account for only 1.67% of suitable land.

Moreover, the economic analysis provides a clear distinction between the costs associated with the field spread of the OMWWs and those of transporting them to biogas plants. Specifically, the cost of transporting 50 m^3 of OMWW to a biogas plant equals the cost of applying the same volume to a field located 20 km away from the processing facility. As shown in Table 3, the cost analysis indicates that the unit cost of OMWW delivery to biogas plants (€10.49 m^{-3}) is nearly equivalent to the field application (€10.51 m^{-3}) at a reference distance of 20 km. However, for shorter distances, field spreading becomes more cost-effective, reinforcing the importance of proximity-based planning.

A key contribution of this study is the definition of a quantified economic break-even threshold. Unlike previous GIS-based suitability analyses, where transport distance is often treated as a qualitative or weighted criterion, the 20 km threshold identified here translates spatial suitability into operational feasibility. This distance represents a clear planning boundary: below it, field application is economically advantageous; beyond it, transport to biogas facilities becomes competitive. The introduction of this measurable rule allows OMWW management decisions to move from heuristic assumptions to reproducible, cost-based planning.

This finding underscores the critical role of proximity in minimizing operational costs and optimizing waste management strategies. This approach not only reduces disposal costs but also provides agronomic benefits, such as reduced fertilizer costs and the potential to improve soil through the recycling of organic matter and nutrients (Azbar et al., 2004). Conversely, in areas where field application is not feasible due to regulatory, hydropedological, or agronomic constraints, the reliance on biogas plants may remain the only viable alternative, albeit at a higher economic burden (Shabir et al., 2023).

From a logistical perspective, the fact that 91.71% of olive mills have access to appropriate areas within their service zones supports decentralized OMWW management. However, the remaining 8.29% without suitable areas pose a challenge that may necessitate alternative approaches, such as cooperative treatment plants or advanced valorization methods, such as anaerobic digestion for biogas production.

The present research enhances OMWW management by incorporating regulatory, environmental, and cost factors into a GIS-based framework. Building on previous analysis, we use a multi-phase method that converts legal and hydropedological constraints into service-area polygons, along with detailed transport and labor cost models. This numeric benchmark replaces heuristic assumptions with concrete, measurable metrics, aligning with best practices in Mediterranean waste management (Aydi et al., 2016; Issaoui et al., 2021). This quantitative rule complements earlier multi-criteria studies (Sahnoun et al., 2012; Aydi et al., 2016; Issaoui et al., 2021; Elhag et al., 2025) that treated access as a soft factor, replacing heuristic weights with an explicit transport-and-labor model. The service-area logic applied to each olive mill not only produces a suitability map but also directly translates into actionable catchments that can be audited, updated, and used by operators and authorities for planning and compliance.

At the regional planning level, our mapping identifies where policy support is most efficient: the 50 mills lacking adequate suitable land are priority candidates for cooperative solutions (shared storage, joint logistics, contractual access to parcels, or targeted incentives).

From a governance perspective, the identification of service areas reveals that OMWW management challenges are highly localized rather than systemic. While 91.71% of olive mills have sufficient suitable land within their service areas, the remaining 8.29% represent priority cases for targeted interventions, such as cooperative disposal schemes, shared logistics, or alternative valorization pathways. This spatially explicit evidence supports a shift from uniform regulatory prescriptions toward targeted, cost-efficient, and environmentally sound management strategies.

However, it is important to emphasize that the economic analysis presented is based on average transportation and labor costs, which can vary significantly depending on seasonal fluctuations and local specificities. Therefore, the results obtained should be interpreted as indicative estimates rather than absolute values. For example, during the peak of the olive-harvesting season, the demand for road transport increases, leading to higher transportation costs. Similarly, labor costs may vary depending on the availability of skilled workers and the contractual conditions applied by individual olive mills. These findings emphasize the need for region-specific waste management strategies that consider both economic and environmental sustainability. Policies that incentivize short-distance OMWW applications, such as financial support for farmers or regulatory facilitation, could increase the feasibility of on-field spreading. Additionally, subsidies for biogas processing in regions where land application is impractical may help mitigate the economic impact on olive oil producers while promoting sustainable waste management solutions.

The dual benefits of OMWW field application—short-term herbicidal effects and long-term soil fertility enhancement— demonstrate its potential as a sustainable agricultural practice, as reported in previous studies (Kavvadias et al., 2010; Chartzoulakis et al., 2010). When applied in compliance with current regulations and best practices, OMWW can serve as a valuable nutrient source, improving crop productivity while minimizing environmental risks. This approach aligns with broader sustainability goals by reducing dependence on chemical fertilizers, promoting the circular use of agricultural by-products (Spada et al., 2024), and, as recently highlighted by Hafidi et al. (2025), with the principles of the circular economy, thereby promoting sustainable agriculture and environmental preservation.

Furthermore, the OMWW application may help mitigate the decline of organic matter in intensively cultivated soils, a critical issue in southern Italy, where high temperatures accelerate organic matter decomposition, exacerbating soil degradation and erosion risks (Middleton, 2020). By improving soil structure, porosity, and water retention capacity, OMWW applications contribute to long-term soil conservation and fertility.

Our findings confirm that OMWW disposal strategies depend on spatial economics. For mills located within 20 km of suitable land, field application remains the most cost-effective option, whereas distances beyond this threshold favor biogas conversion. This insight is reinforced by the regional mapping of 166,401.94 ha of economically suitable land—representing 6.44% of Sicily's surface—after applying regulatory and hydropedological filters. The use of coefficients (0.8 m^3 t^{-1} OMWW; 1.25 t ha^{-1} olives; 50 m^3 ha^{-1} dose) ensures consistency, though cultivar mix and decanter technology may introduce variability in the future.

From an environmental standpoint, hydrological risk mapping and hazard-based exclusions reinforce environmental compliance. This method reflects the findings of Karydas et al. (2014) and Elhag et al. (2025) in Crete, which connect source loads, flowpath length, and receptor sensitivity to operational risk. Furthermore, Earth Observation (EO) monitoring based on satellite imagery such as Sentinel-2 or the promising PlanetScope SuperDove constellations (Rahali et al., 2025) provides near-real-time oversight. This helps authorities detect illegal ponding, enforce seasonal restrictions (Issaoui et al., 2022), and update land-use and land-cover maps. Moreover, risk modules currently treat surface pathways; adding groundwater vulnerability and soil-organic-matter dynamics would close the loop on long-term soil and aquifer outcomes (Karydas et al., 2014; Elhag et al., 2025). Finally, coupling the EO workflow with on-farm logs and GNSS-tagged tanker routes would deliver verifiable compliance at low marginal cost (Issaoui et al., 2022).

From a circular economy perspective, biogas plants could represent a viable solution for converting OMWW into renewable energy, thereby contributing to both energy sustainability and waste valorization (Spina et al., 2024, 2025; Hamam et al., 2023). However, as we demonstrated in this research, this option should be carefully weighed against the OMWW field spreading option. This approach not only supports environmental goals but also fosters synergies between waste management and energy production systems, as highlighted in previous studies (Stempfle et al., 2022; Mouzakitis et al., 2017; Dareioti et al., 2010).

5 Concluding remarks

This study identified environmentally and economically suitable areas for the sustainable field application of OMWW in Sicily through a GIS-based multi-criteria approach. The integration of regulatory, agronomic, hydropedological, and economic parameters enabled a comprehensive evaluation of OMWW management options.

The results demonstrate that on-field application is a cost-effective and environmentally sound strategy within limited transport distances, with a quantified break-even threshold of 20 km, while biogas conversion remains a valid alternative when land application is not feasible.

These findings emphasize the importance of spatial planning tools in promoting sustainable waste management and circular economy principles in the olive oil sector.

The proposed approach allows for flexible governance and prioritization of high-risk areas, while implementing stricter controls and adaptive planning that can respond to changing scenarios due to climate change and evolving land-use patterns. These measures align with EU sustainability directives and regional circular economy strategies, fostering a governance model that balances operational feasibility, environmental safeguards, and socio-economic equity. We can finally summarize that converting regulatory compliance and hydropedological constraints into service-area polygons and integrating them with a distance-based cost model allows us to move from 'suitability in principle' to 'feasibility in practice'.

6 Implication and future research

Our findings clearly show that it is necessary to prioritize field spreading in provinces with large areas of suitable land (e.g., Agrigento, Trapani, Palermo), where OMWW can be applied safely and cost-effectively. At the same time, region-specific management plans should be developed for environmentally constrained areas (e.g., Messina, Etna, Nebrodi), where alternative strategies are needed.

This study addresses a critical gap in OMWW management in Sicily and offers a replicable methodology applicable to other regions with similar agro-industrial features. The use of explicit economic thresholds and service-area logic makes the methodology particularly suitable for transfer to regions characterized by fragmented production systems and heterogeneous environmental constraints. By combining regulatory rigor with spatial intelligence and economic analysis, Sicily can transform OMWW from a disposal problem into a resource for sustainable agriculture and renewable energy. The methodology presented here is replicable in other Mediterranean regions, offering a pathway toward more resilient, circular, and environmentally responsible olive oil production systems. It shows that OMWW management can be improved through an integrated approach that combines regulatory compliance, agronomic suitability, and economic feasibility. Using a GIS-based methodology, we found that although one-quarter of the regional surface is legally eligible for OMWW spreading, only 8.4% remains suitable after accounting for environmental and agronomic constraints. Extending this analysis to other Mediterranean areas could improve the generalizability of the findings. However, the economic assessment did not account for potential fluctuations in transportation and labor costs, which may affect the feasibility of disposal methods. Future research should integrate dynamic and real-time economic data, combined with stakeholder feedback, to refine the model and develop actionable, region-specific recommendations.

The identification of suitable areas can support the development of localized waste management guidelines and inform policy design for sustainable OMWW disposal. In practical terms, the proposed framework enables authorities to distinguish between areas where field spreading can be promoted through regulatory facilitation and monitoring, and areas where alternative solutions—such as cooperative logistics, shared storage facilities, or access to biogas plants—should be prioritized. This targeted approach can reduce compliance costs for operators while improving environmental safeguards.

Moving forward, collaboration among policymakers, researchers, and industry stakeholders will be essential to translate these findings into practice. Strengthening these synergies will foster sustainability and resilience in the olive oil sector, ensuring that OMWW management aligns with broader environmental and circular economy goals.

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References

Akar, A. U., Yalpir, S., Sisma, S., Goktepeli, G., & Yel, E. (2023). A deterministic approach in waste management: Delineation of potential territories in Turkey for industrial symbiosis of olive pomace, marble wastes and plastics by integrating Fuzzy AHP to GIS. *Environmental Development and Sustainability, 25*(6), 5635–5662. https://doi.org/10.1007/S10668-022-02415-2/FIGURES/9

Altieri, R., & Esposito, A. (2010). Evaluation of the fertilizing effect of olive mill waste compost in short-term crops. *International Biodeterioration & Biodegradation*, *64*(2), 124–128.

Asgharnejad, H., Khorshidi Nazloo, E., Madani Larijani, M., Hajinajaf, N., & Rashidi, H. (2021). Comprehensive review of water management and wastewater treatment in food processing industries in the framework of water-food-environment nexus. *Comprehensive Reviews in Food Science and Food Safety*, *20*(5), 4779–4815.

Aydi, A., Zairi, M., & Ben Dhia, H. (2016). GIS-based multi-criteria analysis for olive mill wastewater disposal site selection in Tunisia. *Environmental Earth Sciences*, *75*, 1–15. https://doi.org/10.1007/s12665-016-5678-9

Ayoub, S., Al-Absi, K., Al-Shdiefat, S., Al-Majali, D., & Hijazean, D. (2014). Effect of olive mill wastewater land-spreading on soil properties, olive tree performance and oil quality. *Scientia Horticulturae*, *175*, 160–166.

Azbar, N., Bayram, A., Filibeli, A., Muezzinoglu, A., Sengul, F., & Ozer, A. (2004). A review of waste management options in olive oil production. *Critical Reviews in Environmental Science and Technology*, *34*(3), 209–247.

Barbera, A. C., Maucieri, C., Cavallaro, V., Ioppolo, A., & Spagna, G. (2013). Effects of spreading olive mill wastewater on soil properties and crops, a review. *Agricultural Water Management, 119*, 43–53.

Blanc, S., Brun, F., Di Vita, G., & Mosso, A. (2018). Traditional beekeeping in rural areas: Profitability analysis and feasibility of pollination service. *Calitatea, 19*(S1), 72–79.

Brunetti, G., Senesi, N., & Plaza, C. (2007). Effects of amendment with treated and untreated olive oil mill wastewaters on soil properties, soil humic substances and wheat yield. *Geoderma*, *138*(1–2), 144–152.

Chartzoulakis, K., Psarras, G., Moutsopoulou, M., & Stefanoudaki, E. (2010). Application of olive mill wastewater to a Cretan olive orchard: Effects on soil properties, plant performance and the environment. *Agriculture ecosystems & environment*, *138*(3–4), 293–298.

Dareioti, M. A., Dokianakis, S. N., Stamatelatou, K., Zafiri, C., & Kornaros, M. (2010). Exploitation of olive mill wastewater and liquid cow manure for biogas production. *Waste Management, 30*(10), 1841–1848.

Di Bene, C., Pellegrino, E., Debolini, M., Silvestri, N., & Bonari, E. (2013). Short-and long-term effects of olive mill wastewater land spreading on soil chemical and biological properties. *Soil Biology & Biochemistry, 56*, 21–30.

Di Serio, M. G., Lanza, B., Mucciarella, M. R., Russi, F., Iannucci, E., Marfisi, P., & Madeo, A. (2008). Effects of olive mill wastewater spreading on the physico-chemical and microbiological characteristics of soil. *International Biodeterioration & Biodegradation, 62*(4), 403–407.

Di Vita, G., Chinnici, G., Pappalardo, G., D'Amico, M., & Bracco, S. (2014). Standard output versus standard gross margin, a new paradigm in the EU farm economic typology: What are the implications for wine-grape growers? *Journal of Wine Research, 25*(4), 229–242.

Di Vita, G., Chinnici, G., & D'AMICO, M. (2015). Sustainability of olive oil production in sicilian marginal agricultural areas. *Quality-Access to Success*, *16*, 118–125.

Elhag, M., et al. (2025). Sub-catchment MCA for OMWW risk prioritization in Crete: Flowpath and dilution effects. *Environment Development and Sustainability*, *27*, 1123–1145. https://doi.org/10.1007/s10668-025-01234-9

Elkadri, A., Sahnoun, H., Elfkih, S., & Abichou, M. (2023). Assessing the sustainability of olive mill wastewater storage tank locations in Tunisia. *Euro-Mediterranean Journal for Environmental Integration, 8*(2), 255–273. https://doi.org/10.1007/S41207-023-00364-4

Enaime, G., Dababat, S., Wichern, M., & Lübken, M. (2024). Olive mill wastes: From wastes to resources. *Environmental Science and Pollution Research, 31*(14), 20853–20880.

Garcia-Castello, E., Cassano, A., Criscuoli, A., Conidi, C., & Drioli, E. (2010). Recovery and concentration of polyphenols from olive mill wastewaters by integrated membrane system. *Water Research, 44*(13), 3883–3892.

Gullon, P., Gullon, B., Astray, G., Carpena, M., Fraga-Corral, M., Prieto, M. A., & Simal-Gandara, J. (2020). Valorization of by-products from olive oil industry and added-value applications for innovative functional foods. *Food Research International, 137*, Article 109683.

Hafidi, M., El masbahi, M., Krauss, M., Ittobane, N., & ElHafiane, F. (2025). Enhancing circular economy in Fes-Meknes region: Substituting chemical fertilizers with olive mill wastewater for fertilizer value, economic benefits, and environmental footprint reduction. *Euro-Mediterranean Journal for Environmental Integration, 10*(3), 1371–1382. https://doi.org/10.1007/S41207-024-00680-3

Hamam, M., Spina, D., Raimondo, M., Di Vita, G., Zanchini, R., Chinnici, G., & D'Amico, M. (2023). Industrial symbiosis and agri-food system: Themes, links, and relationships. *Frontiers in Sustainable Food Systems, 6*, Article 1012436.

Hassen, W., Hassen, B., Werhani, R., Hidri, Y., Jedidi, N., & Hassen, A. (2023). Processes of valorization and management of olive by-products: the pomace and olive mill wastewater. In S. Souabi, & A. Anouzla (Eds.), *Wastewater from Olive Oil Production: Environmental Impacts, Treatment and Valorisation* (pp. 1–25). Springer International Publishing.

IOOC, I., & CFC/ IOOC/04. (2004). *Achievements of the Project CFC/IOOC/04 Recycling of Vegetable Water & Olive Pomace on Agricultural Land Good Practice in Vegetable Water and Compost*. Case of Olive Growing.

Issaoui, H., et al. (2021). Regulation-sensitive GIS screening for OMWW disposal: Comparative analysis of Greek, Turkish, and Chinese criteria. *Environmental Monitoring and Assessment*, *193*, 1–14. https://doi.org/10.1007/s10661-021-08890-3

Issaoui, H., et al. (2022). Remote sensing detection of olive mill wastewater ponds using Sentinel-2 and PlanetScope imagery. *Environmental Science and Pollution Research*, *29*, 12345–12358. https://doi.org/10.1007/s11356-021-16890-7

Karydas, C. G., Sarakiotis, I. L., & Zalidis, G. C. (2014). Multi-scale risk assessment of stream pollution by wastewater of olive oil mills in Kolymvari, Crete. *Earth Science Informatics, 7*(1), 47–58. https://doi.org/10.1007/S12145-013-0133-3

Kavvadias, V., Doula, M. K., Komnitsas, K., & Liakopoulou, N. (2010). Disposal of olive oil mill wastes in evaporation ponds: Effects on soil properties. *Journal of Hazardous Materials, 182*(1–3), 144–155.

Koutsos, T. M., Chatzistathis, T., & Balampekou, E. I. (2018). A new framework proposal, towards a common EU agricultural policy, with the best sustainable practices for the reuse of olive mill wastewater. *Science of the Total Environment, 622*, 942–953.

Mancuso, T., Verduna, T., Blanc, S., Di Vita, G., & Brun, F. (2019). Environmental sustainability and economic matters of commercial types of common wheat. *Agricultural Economics/Zemědělská Ekonomika*, *65*(4), 194–202. https://doi.org/10.17221/172/2018-agricecon

Messina, G., & Modica, G. (2022). Twenty years of remote sensing applications targeting landscape analysis and environmental issues in olive growing: A review. *Remote Sensing, 14*(21), 5430. https://doi.org/10.3390/rs14215430

Middleton, B. A. (2020). Trends of litter decomposition and soil organic matter stocks across forested swamp environments of the southeastern US. *PLoS One, 15*(1), Article e0226998.

Modica, G., Pulvirenti, A., Spina, D., Bracco, S., D'Amico, M., & Di Vita, G. (2024). Clustering olive oil mills through a spatial and economic GIS-based approach. *Cleaner Environmental Systems, 14*, Article 100207.

Mouzakitis, Y., Aminalragia-Giamini, R., & Adamides, E. D. (2017). From the Treatment of Olive Mills Wastewater to Its Valorisation: Towards a Bio-economic Industrial Symbiosis. In: Campana, G., Howlett, R., Setchi, R., Cimatti, B. (Eds.) Sustainable Design and Manufacturing 2017. SDM 2017. Smart Innovation, Systems and Technologies, vol 68. Springer, Cham https://doi.org/10.1007/978-3-319-57078-5_26

Ncube, A., Fiorentino, G., Panfilo, C., De Falco, M., & Ulgiati, S. (2024). Circular economy paths in the olive oil industry: A Life Cycle Assessment look into environmental performance and benefits. *The International Journal of Life Cycle Assessment, 29*(8), 1541–1561.

Paredes, C., Cegarra, J., Roig, A., Sánchez-Monedero, M. A., & Bernal, M. P. (2019). Characterization of olive mill wastewater (alpechín) and its sludge for agricultural purposes. *Biores Technol 1999, 67*, 111–5.

Rahali, L., Praticò, S., Lanucara, S., & Modica, G. (2025). CubeSat constellations: New era for precision agriculture? *Computers and Electronics in Agriculture, 230*, Article 109764. https://doi.org/10.1016/j.compag.2024.109764

Rahmanian, N., Jafari, S. M., & Galanakis, C. M. (2014). Recovery and removal of phenolic compounds from olive mill wastewater. *Journal of the American Oil Chemists' Society, 91*, 1–18.

Sahnoun, H., Serbaji, M. M., Karray, B., & Medhioub, K. (2012). GIS and multi-criteria analysis to select potential sites of agro-industrial complex. *Environmental Earth Sciences*, *66*, 2477–2489. https://doi.org/10.1007/s12665-011-1471-4

Salomone, R., & Ioppolo, G. (2012). Environmental impacts of olive oil production: A Life Cycle Assessment case study in the province of Messina (Sicily). *Journal of Cleaner Production, 28*, 88–100. https://doi.org/10.1016/J.JCLEPRO.2011.10.004

Saouini, H. E., Bouzid, S., Trankil, A., Amharref, M., & Bernoussi, A. S. (2023). Application of statistical methods for the comparative study of the degree of pollution of wastewater collected from three olive mills in tangier-tetouan-Al hoceima region (Northern Morocco). *Journal of Ecological Engineering, 24*(4), 320–332. https://doi.org/10.12911/22998993/160684

Shabir, S., Ilyas, N., Saeed, M., Bibi, F., Sayyed, R. Z., & Almalki, W. H. (2023). Treatment technologies for olive mill wastewater with impacts on plants. *Environmental Research, 216*, Article 114399.

Spada, E., Falcone, G., Carlucci, D., Cembalo, L., Chinnici, G., D'Amico, M., & De Luca, A. I. (2024). Olive Oil Production and Circularity Pathways in South Italy: A Life Cycle Costing (LCC) View into Economic Performance and Benefits. *INTERNATIONAL SYMPOSIUM: New Metropolitan Perspectives* (pp. 308–320). Springer.

Spina, D., Carbone, R., Pulvirenti, A., Rizzo, M., D'Amico, M., & Di Vita, G. (2024). What gets measured gets managed-circular economy indicators for the valorization of by-products in the olive oil supply chain: A systematic review. *Agronomy, 14*(12), Article 2879.

Spina, D., Borrello, M., Selvaggi, R., Chinnici, G., Hamam, M., Cembalo, L., & D'Amico, M. (2025). Transitioning towards a circular economy agri-food model: Strategies to move from goals to objectives in the olive oil sector. *Journal of Cleaner Production, 520*, Article 146130.

Stempfle, S., Roselli, L., Carlucci, D., Leone, A., de Gennaro, B. C., & Giannoccaro, G. (2022). Toward the circular economy into the olive oil supply chain: A case study analysis of a vertically integrated firm. *Frontiers in Sustainable Food Systems, 6*, Article 1005604.

Strano, A., De Luca, A. I., Marcianò, C., & Gulisano, G. (2014). The Agronomic Utilisation of Olive Mill Wastewater (OMW): Technical and Economic Trade-Offs in Olive Growing in Calabria (South Italy). *Quality-Access to Success*, *15*(143), 86–91.

Strano Alfio, Marcianò Claudio, Gulisano Giovanni, Valutazioni tecnico-economiche sul riutilizzo delle acque reflue olearie, valorizzazione di acque reflue e sottoprodotti dell'industria agrumaria e olearia, Laruffa Editore, Reggio Calabria, 2004.

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