



## Article

# Strategies for Wine, Orange Processing and Olive Oil By-Product Valorisation Based on GIS Spatial Analysis

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## Abstract

Waste valorisation has become a key strategy for applying circular economy principles in the agro-industrial field. This study investigated the territorial implementation of the waste composting on a territorial scale. The wastes considered were the post-processing orange waste, spent olive oil pomace, and spent wine grape pomace. Their potential use as soil amendments across the provinces of Sicily was assessed through a GIS-based analysis, taking into account nitrogen (N) application constraints. Moreover, a cascade valorisation scheme was also evaluated: post-processing orange waste was first used as animal feed, and the remaining fraction was directed to composting; olive pomace was first sent to pomace oil extraction mills, and the residual material was subsequently used for composting. Results indicate that N inputs derived from composted residues remain below legal thresholds in all provinces, with relative contributions ranging from 38% to 92% of the regulatory limits. Spatial variability in nitrogen availability reflects the territorial distribution of agro-industrial activities, highlighting the importance of localised management strategies. These findings demonstrate that composting, combined with cascade valorisation, is an effective pathway to close nutrient cycles, reduce waste generation, and support sustainable biomass management in regional agri-food systems.

**Keywords:** circular economy; composting; GIS; cascade valorisation; animal feed

## 1. Introduction

The climate instability of recent years, coupled with the scarcity of fertile soils and soil deterioration, poses a serious threat to food security, especially in a context of a steadily increasing world population [1]. It is essential to consider the impact of the agri-food system, which is responsible for producing a large amount of waste, with significant effects on both human health and the environment [2]. Efficiently managing these wastes has recently become a priority issue internationally, given that the European agricultural sector alone generated around 21 million tonnes of waste in 2020 [3]. Such wastes represent an opportunity within circular economy (CE) models [4], which promotes sustainable development by replacing the traditional concept of the “end of life” of products with practices that reduce, reuse and recycle materials throughout the production, distribution and consumption cycle. In the Mediterranean basin, the predominant crops are citrus fruits, grapes, olives and stone fruits [5]. In 2021, the total production of these products in the Mediterranean region was approximately 13, 28.3 and 10 million tonnes respectively [6].

In Sicily, in particular, citrus production reached 1.47 million tonnes in 2021, with about 88,000 hectares cultivated, of which 58,000 hectares were dedicated to oranges, 21,000 ha



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to lemon, and 5000 ha to mandarin [7]. Notably, there was a substantial increase in orange cultivation in this region compared to 2022, particularly in the provinces of Catania (i.e., +500 hectares) and Agrigento (i.e., +200 hectares) [8]. Conversely, vine cultivation in Sicily covers around 95,760 hectares, and the region is renowned for its viticultural biodiversity and leading position in organic viticulture, with approximately 70 native grape varieties. In fact, 32,787 hectares of vineyards in Sicily are cultivated by using organic methods, representing around a quarter of the national organic wine-growing area [9]. Furthermore, the region is one of Italy's leading areas for the production of olives and olive oil. In 2024, it produced over 100,000 quintals of oil, ranking third nationally. However, the sector's competitiveness and investment capacity are limited by the prevalence of medium-sized olive farms, which average only 1.3 ha in size. At the same time, demand for exports to foreign markets is growing, particularly in the United States, Canada and Japan.

While the processing of these products yields high-value goods, it also generates a considerable amount of organic waste. If not properly managed, this waste presents an environmental challenge. The focus of recent research studies and industrial innovations is to transform this challenge in an opportunity for the sustainable exploitation of by-products [10–12].

Castagna et al. [13] conducted a review analysing the main strategies for the valorisation of citrus, grape and olive wastes, typical of the Mediterranean area. While acknowledging that many of these solutions are still in the laboratory phase, the authors propose the integration of digital tools and multidisciplinary approaches to facilitate their industrial implementation. Another study by Negrea et al. [14] examined the sustainable use of citrus peel in jam production to enhance its nutritional and functional properties. This approach yielded high levels of bioactive compounds and antioxidant activity.

Furthermore, Hartinger et al. [15] suggested that citrus pulp could be valuable as feed for dairy cows. A meta-analysis evaluating the effect of different levels of citrus pulp in the diet showed that milk production increased with low levels of inclusion (0–10%) without affecting food intake.

In the context of the bio-circular economy, cascade valorisation refers to the sequential use of biomass and agro-industrial by-products through a hierarchy of processes that maximise their economic value, while minimising the environmental impacts, before their final return to the environment [16]. Rather than treating residues as a waste, they are initially directed toward higher value applications such as the production of animal feed, the extraction of bioactive compound or the energy generation. Only after these stages they are used for lower value purposes, including composting or soil amendment [17].

The current national regulatory framework is mainly regulated by Legislative Decree No 75 of 29 April 2010 [18], which reorganised and revised the subject of fertilisers, including soil improvers. In Article 2, the latter are defined as materials added to the soil <<to preserve or improve its physical or chemical characteristics or biological activity>>. A crucial update was introduced by the Decree of 2 February 2022, which added a new and specific category to Annex 2 of Legislative Decree 75/2010: <<Composted soil improver from agrofood chain waste>>. Among the requirements, a minimum 25% organic carbon content in dry matter, a minimum 7% humic and fulvic carbon content, and at least 80% of the total nitrogen (N) must be in organic form. On the other hand, at the European level, Regulation (EU) 2019/1009 [19] harmonises the standards for fertiliser products with CE marking.

In the literature, many studies [20,21] evaluated the sustainable reuse of agricultural by-products at a territorial scale. Geographic Information Systems (GIS) are an effective way of integrating and analysing georeferenced data. They allow residual biomass distribution to be mapped, areas under greater environmental pressure to be identified, and sustainable management strategies to be supported [22].

Studies carried out in Sicily have already demonstrated the effectiveness of these tools. For example, Beccali et al. [23] used GIS models to quantify residual resources and plan energy plants, and Valenti et al. [24] developed a spatial index to identify locations suitable for biogas production, thereby reducing logistics costs and environmental impact. More recently, Catalano et al. [25] applied GIS techniques and predictive ecological models to estimate the potential of citrus biomass in the province of Syracuse. This study identified over 184,000 tonnes of exploitable biomass, providing concrete support for spatial planning.

These examples confirmed the central role of geospatial technologies in the valorisation of by-products and the promotion of a circular agricultural economy. To the authors' knowledge, the GIS-spatial analysis has not been applied to a cascade valorisation approach for the citrus, olive oil and wine sectors in Sicily.

This research aims at assessing the feasibility of composting agricultural by-products and using them as a soil amendment within the same areas where the primary agricultural production occurs. The proposed approach is based on a spatial assessment that integrates the distribution of residual biomass, the location of major cropping areas, and key environmental constraints across the provinces of Sicily, about the levels of nitrogen that can be applied to the soil. By leveraging GIS-based spatial analysis, the research introduces an innovative territorial perspective on bio-circular economy strategies, in which resource use is optimised through cascade valorisation pathways and by-products are reintroduced into the production cycle. In this study, the cascade valorisation approach was applied to agro-industrial residues from the citrus, olive oil and wine sectors in Sicily. Specifically, orange-processing residues were first used as livestock feed, olive pomace was initially processed for oil extraction, and the resulting material was subsequently composted, while wine pomace was directly used for composting. This closed-loop framework reduces waste generation, enhances soil fertility, and promotes local resource cycling. Ultimately, the study provides a decision-support tool for policymakers and stakeholders to design territorially grounded strategies for sustainable biomass management and circular agri-food systems.

## 2. Materials and Methods

In this study the potential for adding value to by-products from the production of wine, citrus-processed products and olive oil is assessed. The analysis integrates agricultural activities, agro-industrial production data and territorial analysis tools with GIS support. The main methodological steps are as follows:

- data collection: acquisition of quantitative data on regional agricultural production (wine, orange-processed products, and olive oil) from official statistical sources and sectoral databases.
- estimation of by-products: calculation of quantities of by-products generated using specific yield coefficients validated in the literature;
- analysis of potential uses: assessment of the potential use of by-products for animal feed and composting, with reference to animal nutritional parameters and fertilisation needs.
- spatial analysis with GIS involves georeferencing the collected data and integrating it into a GIS environment to identify areas with the greatest by-product availability and possible logistical connections with recovery plants.

### 2.1. Data Collection

The collection of production and cultivated area data for olive trees, citrus fruits and viticulture at a provincial level in Italy was based on data provided by the National Institute of Statistics (ISTAT) between 2020 and 2024. For each species and province, the production/area ratio for each year, the average value, and the standard deviation over five years were calculated. This analysis enabled the consistency of these indicators over time to

be assessed, in order to highlight any trends or anomalies. Specifically, it was verified that the ratio of production (in quintals) to area (in hectares) remained substantially constant for each province over the considered period. The input data for each species (i.e., olives, citrus fruits and viticulture) were processed based on the average production over the last five years in each Sicilian province.

However, the use of advanced GIS technologies, thanks to the ability to manage and analyse geospatial data at different levels of detail, has improved understanding of agricultural sustainability and supported the development of more effective policies and decisions [26].

In Italy, the management of by-products from the processing of olive oil and orange fruits is governed by Legislative Decree No. 152 of 3 April 2006, known as the “Consolidated Environmental Act” [27]. This regulatory framework is of crucial importance as it allows certain olive oil by-products to be classified as “plant materials from agricultural activities used in agricultural activities”, thus distinguishing them from hazardous waste. This recognition allows them to be managed as a resource rather than as waste, provided that the relevant regulations are complied with and no negative impact on the environment or human health is generated.

### 2.1.1. Grape By-Products

Grape marc is a highly degradable organic material, accounting for around 20–25% of the total weight of grapes. It consists mainly of skins (43%), seeds (23%) and stalks (25%). Incorrect disposal can have negative effects on the environment, crop health and human health, so its management requires particular attention [28]. In the EU, pomace is often sent to distilleries where it is processed to extract residual ethanol for use in producing spirits. This results in exhausted grape pomace being obtained [29].

Around 75% of grapes are used for wine production, with 20–30% of these representing waste products with significant potential for valorisation, such as grape pomace and wine lees [30,31].

On average, the process of pressing grapes yields approximately 74% wine, 13% virgin pomace and 2.2% stalks and other waste. About the 13% of the total weight, representing virgin pomace, only 2% is recovered immediately, while the remaining 11% is used for distillation. Ultimately, 42% of the 11% of the total grape weight becomes spent pomace [32]. Therefore, the formula used for calculating reusable *grape pomace* was the following:

$$\text{grape pomace} = (0.11 \times 0.42) \times \text{Yearly wine grape production}.$$

### 2.1.2. Olive By-Products

On average, olive pressing yields 15–20% oil, 30–35% virgin pomace, and 55–60% physiological water. Further processing of the virgin pomace yields around 50% exhausted pomace, with the remainder being pomace oil and physiological water. The variability depends on:

- extraction technology (i.e., two- or three-phase system);
- cultivar (e.g., Sicilian varieties such as Nocellara or Biancolilla have different yields);
- state of ripeness of the olive;
- moisture content of the fruit.

The *exhausted pomace* has been computed with the following formula:

$$\text{exhausted pomace} = 0.5 \times 0.325 \times \text{Yearly olives for oil production}$$

### 2.1.3. Orange-Processing By-Products

Valenti et al. [33] highlighted that approximately 30% of total citrus production is destined for processing by the juice industry. Of this, 56% consists of solid waste, including

peel, membranes, vesicles and seeds. Based on these data, the annual quantity of *orange waste* generated can be estimated using the following formula:

$$\text{orange waste} = 0.3 \times 0.56 \times \text{Yearly Orange Production}$$

## 2.2. Estimation of Biomass Uses, for Bovine Nutrition

Orange wastes are supposed to pass through a cascade valorisation process. Firstly, it is given priority to intensively feed beef, dairy and mixed cattle in Sicily. The number of animals for each province has been acquired from the National Zootechnical Registry of the Italian Ministry of Health (IZS) ([https://www.vetinfo.it/j6\\_statistiche/#/](https://www.vetinfo.it/j6_statistiche/#/) accessed on 24 May 2025). The study by Gulisano et al. [34], advocated the use of fresh orange waste in dairy cow diets at doses ranging from 6 to 10 kg per cow per day. Specifically, an average of 8 kg per day was used over a period of six months from December to May, based on the assumption that the orange waste would be used as cattle feed within the same province. The remaining part of the orange waste in each province would be used in the same province agricultural lands as soil amendment.

## 2.3. Estimating the N from Biomasses Residues of Agro-Industrial Activities

Accurately estimating the N content of biomass residues from agro-industrial activities is essential for evaluating their agronomic and environmental potential for valorising them through composting. Orange waste contains an average of 1.39% N on a dry basis, while grape marc has a N content ranging from 1% to 2% by fresh weight [32]. The content of N in exhausted olive pomace is  $1.397 \pm 0.199\%$  [35].

Based on these coefficients, the total N content of each residue can be calculated as:

$$\begin{aligned} \text{N (spent olive pomace)} &= \text{spent olive pomace} \times \frac{1.397}{100} \\ \text{N (orange waste)} &= \text{orange waste} \times \frac{1.39}{100} \\ \text{N (spent grape pomace)} &= \text{spent grape pomace} \times \frac{1.50}{100} \end{aligned}$$

The composting process reduces N percentage in biomass [36]. A study by Zhao et al. [37] found that N losses amounted to around 31.4%, comprising 17.2% ammoniacal nitrogen ( $\text{NH}_3\text{-N}$ ) and 1.4% nitrous oxide ( $\text{N}_2\text{O-N}$ ).  $\text{NH}_3\text{-N}$  represents the most significant fraction of total nitrogen losses, contributing 55% to the overall decline. The main factors influencing these losses are the composting method, the type of biomass, and the duration of the process. In this study, the N content of each biomass after the composting process has been calculated by applying a reduction coefficient of 0.686% (i.e.,  $1 - 0.314\%$ ).

## 2.4. Study of Nitrate Vulnerable Zone (NVZ)

The Nitrates Directive (91/676/EEC) [38] requires Member States to identify polluted or at-risk waters and designate 'Nitrate Vulnerable Zones' (NVZs) within their territories. In Italy, this directive has mainly been transposed into national legislation through Legislative Decree No. 152 of 3 April 2006 [27] and subsequent emendations, as well as the Ministerial Decree of 19 April 1999 [39]. While these regulations allow for exceptions, they generally establish specific limits for the application of N in NVZs, such as a maximum of 170 kg of N per hectare per year from livestock manure.

For this reason, it is essential to identify these areas in order to adapt agricultural practices. The following analysis considered the NVZ shapefiles for the Region of Sicily [40], which enabled subsequent processing.

In this study, the NVZ shapefiles had been loaded and projected in QGIS environment.

The percentage of NVZ area for each crop in each province (NVZp) were calculated as the NVZ of the area ( $Pa$ ) divided by the total area ( $Ta$ ).

$$NVZp = \frac{Pa}{Ta} \times 100 \text{ [%]}$$

The same  $NVZp$  value for each crop in each province was also assumed for the agricultural production areas. Therefore, for each province it was assumed a limitation for the amount of N to be used in the crop of the total agricultural land.

### 2.5. Estimation of N Max to Be Spread on Agricultural Land for Every Province: Law Limitations

In order to assess the N limits in every province, the regional regulations, in particular the Sicilian plan on water safeguard [41] have been considered. For agricultural firms situated in non-vulnerable zones, the maximum limit for N input is  $340 \text{ kg ha}^{-1}$  (named  $N_{\max}$  hereafter). Conversely, in areas designated as Vulnerable Zones due to agricultural Nitrates (NVZ), a maximum N input of  $170 \text{ kg ha}^{-1}$  (named  $N_{\max NVZ}$  hereafter) is established.

## 3. Results

### 3.1. Input Data Collected and By-Product Calculation

In Table 1, the average value of the production/surface ratio between 2020 and 2024 it is shown for each province and for each fruit.

**Table 1.** Average value of production/area ratio for each species of fruit and for each province considered between 2020 and 2024.

Production (100 kg)/Area (ha)	Wine Grapes	Citrus	Olive for Oil
Agrigento	58	179	15
Caltanissetta	81	156	10
Catania	70	175	34
Enna	70	300	50
Messina	81	196	17
Palermo	51	188	26
Ragusa	77	311	49
Syracuse	78	214	21
Trapani	53	96	23

Table 1 and Figure 1 provide a quantitative basis for understanding the spatial variability of agricultural productivity across Sicilian provinces for the main fruit species considered. Table 1 reports the average production-to-area ratios for the period 2020–2024 and highlights clear differences in crop performance among territories. Provinces such as Ragusa, Enna, and Syracuse show notably higher citrus productivity, while Catania and Enna display comparatively high yields for olives. Conversely, provinces like Trapani and Agrigento exhibit lower production densities for specific crops. This heterogeneity is essential for estimating the potential generation of biomass and by-products, which depend directly on local production efficiency.

Figure 1 visually complements Table 1 by illustrating the magnitude of these differences through a graphical comparison of yield ratios. The bar lengths immediately allow to identify high-performing and low-performing provinces for each crop. This visualisation enhances the interpretability of the numerical data and supports the identification of spatial clusters where by-product availability may be significant. Together, Table 1 and Figure 1 provide the foundational input for calculating the annual amounts of citrus waste and other by-products considered in the subsequent stages of the assessment. Their combined use

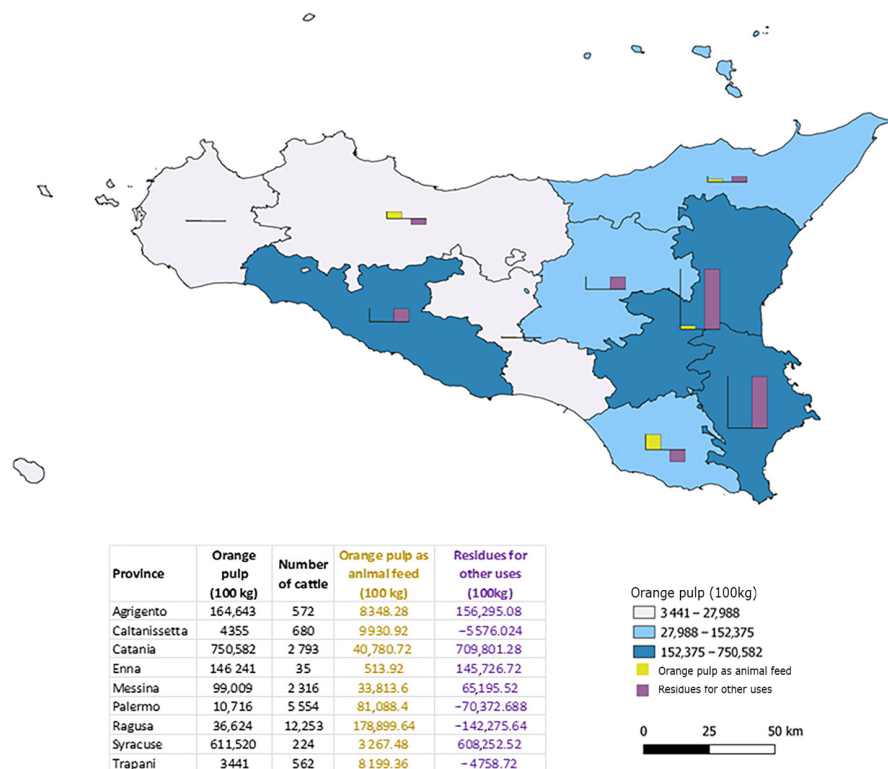
ensures that the by-product estimation is based on empirical, region-specific production data rather than uniform or averaged assumptions.

Province	Exhausted grape pomace (100 kg)	Olive pomace (100 kg)	Orange waste (100 kg)
Agrigento	18250	52064	164643
Caltanissetta	3350	13201	4355
Catania	1232	73050	750582
Enna	182	91236	146241
Messina	1368	97988	99009
Palermo	6571	90665	10716
Ragusa	776	22490	36624
Syracuse	1604	30063	611520
Trapani	23641	68331	3441
<b>Total</b>	<b>56976</b>	<b>539086</b>	<b>1827130</b>

**Figure 1.** Biomass residues from agro-industrial activities (in purple exhausted grape pomace, in green exhausted olive pomace, and in orange the orange post processing waste).

Based on these results and following the equation presented in Sections 2.1.1–2.1.3, the residues from orange processing, olive oil and wine production were quantified. Figure 1 shows the quantity of exhausted grape pomace, exhausted olive pomace after pomace oil extraction, and orange post-processing waste that can be obtained in each province.

In particular, for the orange post-processing waste, the bio-circular economy hypothesis was to use orange waste for animal feed, then the remaining part, if any, for composting. Therefore, after calculating the total amount of citrus waste, the amount of citrus waste needed for feeding them was estimated as 8 kg by day. Figure 2 shows a thematic map of the total production of orange waste (blue shades). Moreover, based on animal presence in each province, and citrus waste used as animal feed (yellow bar), Figure 2 shows the province in which there is a residue useful for composting (positive purple bar) and the provinces in which there are not (negative purple bar).



**Figure 2.** Thematic map of citrus pulp production for each province, and bar graphs of the amount used as animal feed (yellow) and the remaining amount for composting (purple).

### 3.2. Estimating the Amount of N from Biomass Residues from Agro-Industrial Activities

Following the formulas presented in Section 2.3, Table 2 shows the amount of N available from each agro-industrial waste in each province. As can be seen in the Caltanissetta, Palermo, Ragusa and Trapani provinces, the amount of N from orange should be considered 0 kg as the whole amount of orange post-processing waste was considered for animal feeding.

**Table 2.** Amount of N estimated from agro-industrial wastes.

Province	Olive Pomace (100 kg)	Exhausted Grape Pomace (100 kg)	Orange Waste (100 kg)
Agrigento	727	1506	2173
Caltanissetta	184	276	0
Catania	1021	102	9866
Enna	1275	15	2026
Messina	1369	113	906
Palermo	1267	542	0
Ragusa	314	64	0
Syracuse	420	132	8455
Trapani	955	1950	0

After that, the amount of N finally available after composting for the agricultural activities has been quantified for each province (Table 3).

**Table 3.** Amount of N estimated from composted agro-industrial wastes.

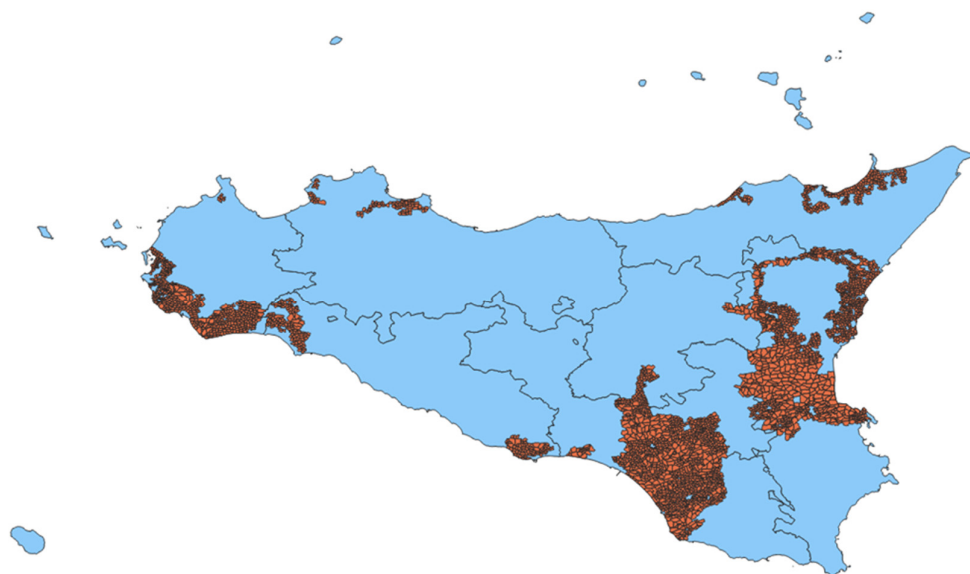
Province	Olive Pomace (100 kg)	Grape Pomace (100 kg)	Citrus Pulp (100 kg)
Agrigento	499	1033	1490
Caltanissetta	127	190	0
Catania	700	70	6768
Enna	874	10	1390
Messina	939	77	622
Palermo	869	372	0
Ragusa	216	44	0
Syracuse	288	91	5800
Trapani	655	1338	0

### 3.3. N Management in Agricultural Lands Under NVZ Restriction

In order to evaluate the real amount of hectares affected by NVZ, the official shape file from the Sicilian region repository has been analysed (Figure 3). Then, the NVZp was calculated for each province. The data used and the results are shown in Table 4.

**Table 4.** Percentage of NVZ area (NVZp) for each province.

Province	NVZ (ha)	Area (ha)	NVZp [%]
Agrigento	24,235	305,590	7.9
Caltanissetta	38,258	213,421	17.9
Catania	159,419	357,536	44.6
Enna	13,696	257,292	5.3
Messina	25,346	326,606	7.8
Palermo	5115	500,506	1.0
Ragusa	53,831	162,360	33.2
Syracuse	47,059	212,181	22.2
Trapani	49,950	246,941	20.2



**Figure 3.** NVZ in Sicily are showed in brown shades.

Based on the NVZp of each province, the maximum amount of nitrogen that can be applied to agricultural land was calculated for each province and for each crop considered ( $N_{\max \text{ tot}}$ ). Therefore, for each agro-industrial by-product considered the amount of N available after composting (N available) was calculated. The third column of Table 4 shows the amount of N that might be added in the agricultural land to achieve the maximum amount of N that is possible to add according to law constraints (N residual). As it can be seen in the Table, the limit is not overcome in any of the provinces.

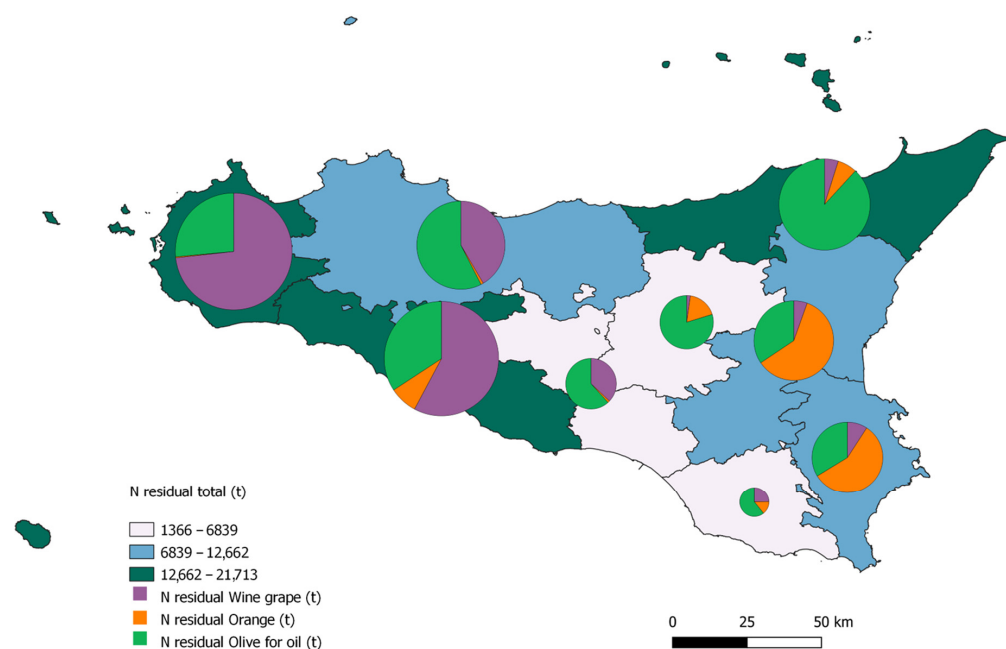
Based on the NVZp values identified for each Sicilian province, the maximum quantity of nitrogen that can be legally applied to agricultural land was calculated both at the provincial scale and for the main crop types considered in the study. Subsequently, the nitrogen potentially available from each agro-industrial by-product after composting was estimated. The results, summarised in Table 5, compare these values with the regulatory limits established by the current legislation. As shown in the third column, the total nitrogen potentially added to soils remains consistently below the legal threshold in all provinces.

The spatial distribution of NVZ across Sicily further supports these results, highlighting that even in areas subjected to stricter environmental constraints, nitrogen inputs derived from composted by-products do not exceed regulatory limits. Table 5 shows that the nitrogen contribution deriving from each of the analysed waste is much less than the legal limit. Indeed, for each waste and for province there is a residual amount of N. These values confirm that the proposed composting strategy is environmentally compatible across diverse territorial conditions and can be implemented without the risk of nitrate accumulation.

Figure 4 illustrates the spatial distribution of the nitrogen potentially available from the composting of agro-industrial by-products across the provinces of Sicily. The map highlights significant variability in both the total nitrogen content and the relative contribution of different residue types, reflecting the geographical specialisation of local agri-food production systems. The highest amounts of residual nitrogen are concentrated in the provinces of Catania, Agrigento, and Trapani, where the large-scale cultivation and processing of citrus fruits, olives, and wine grapes generate substantial quantities of by-products. In contrast, provinces such as Enna and Caltanissetta show lower overall nitrogen availability, consistent with their smaller agro-industrial output.

**Table 5.** Residual nitrogen for each province.

	Province	Nmax Tot (t)	N Available (t)	N Residual (t)
Wine grape	Agrigento	12,142.2	103.5	12,038.7
	Caltanissetta	1529.1	19.0	1510.1
	Catania	557.7	7.0	550.7
	Enna	102.6	1.0	101.6
	Messina	653.6	7.8	645.9
	Palermo	5178.8	37.3	5141.5
	Ragusa	342.3	4.4	337.9
	Syracusa	740.6	9.1	731.5
	Trapani	16,044.7	134.1	15,910.6
Orange waste	Agrigento	1807.3	149.0	1658.2
	Caltanissetta	53.2	0.0	53.2
	Catania	6745.0	676.8	6068.2
	Enna	960.1	139.0	821.1
	Messina	980.4	62.2	918.3
	Palermo	115.0	0.0	115.0
	Ragusa	198.5	0.0	198.5
	Syracusa	5139.0	580.0	4559.0
	Trapani	61.1	0.0	61.1
Olive for oil	Agrigento	7175.2	49.9	7125.3
	Caltanissetta	2530.7	12.7	2518.0
	Catania	3537.6	70.0	3467.6
	Enna	3716.2	87.4	3628.8
	Messina	11,765.1	93.9	11,671.2
	Palermo	7205.0	86.9	7118.1
	Ragusa	850.9	21.6	829.4
	Syracusa	2720.7	28.8	2691.9
	Trapani	5806.7	65.5	5741.2



**Figure 4.** Spatial distribution of nitrogen (N) potentially available from the composting of agro-industrial by-products across the provinces of Sicily. Colours of the province indicate the total N availability. The pie graph represents N composition according to the main residue types considered reported in Table 5.

The composition of the nitrogen pool also differs across provinces. Orange-processing residues represent a major share of the available nitrogen in eastern Sicily, particularly in Catania and Syracuse, while wine grape residues are predominant in western areas such as Trapani and Agrigento. Olive-derived nitrogen is more evenly distributed but contributes significantly to provinces with a strong olive oil sector, such as Palermo and Messina. These spatial patterns have confirmed the importance of a territorial perspective for planning composting strategies, as the distribution of available biomass and its nutrient content are closely linked to local production dynamics.

Overall, the spatial distribution of nitrogen availability highlights the strong territorial dimension of composting potential in Sicily, confirming that effective biomass management strategies must be tailored to local production patterns and nutrient demands to maximise the environmental and agronomic benefits of agro-industrial by-product valorisation.

#### 4. Discussion

This study aimed to evaluate the potential of using agro-industrial wastes from key sectors in Sicily as soil amendment. The importance of this topic is due to the amount of agricultural production and the percentage of waste deriving from agro-industrial activity. In particular, more than 80% of olive weight and more than 50% of orange weight generate by-products after the agro-industrial activities and transformations. Many studies in the literature have assessed several valorisation strategies [10,42–45]. However, when considering the most environmentally sustainable way to valorise these by-products, it is strictly dependent on the territorial aspects such as industrial clusters, and the verticality of the supply chain included in the territory. In this study, it was proven that a cascade valorisation approach is possible for olive oil by-products and orange wastes. Firstly, olive pomace oil can be sent to olive pomace oil mills to obtain spent olive pomace. Secondly, orange post-processing waste can be sent to livestock farms as animal feed. According to the scientific literature, this approach may lead to the reduction in methane emissions in livestock barns [46], which is another topic of particular interest in the context of agriculture sustainability [47]. Moreover, the proposed cascade valorisation approach further advances the state of the art by showing that sequential use of by-products, such as the preliminary use of orange residues as animal feed and the extraction of pomace oil before composting, maximises resource efficiency and reduces waste generation. This finding aligns with recent studies emphasising the importance of multi-step valorisation pathways for achieving higher environmental performance and economic returns in circular bioeconomy models [16]. Moreover, the methodology aligns to the necessity of taking into account the soil fertility issue and the limits in nutrient addition [48].

By combining territorial analysis with cascade valorisation strategies, this study provides a replicable framework that can support regional planning and policy development aimed at enhancing sustainability in agro-industrial supply chains. Wine by-products are rich in nutrients for soil, and the amount of by-products available for composting is particularly significant in the Agrigento and Trapani regions. The relatively wide margin between the estimated nitrogen contributions and the legal threshold in most provinces indicates the possibility of further integrating composted residues into local fertilisation practices. This reinforces the feasibility and scalability of a territorial biomass reuse strategy that simultaneously meets agronomic requirements and complies with environmental protection objectives [48]. Such results demonstrate the potential of composting and nutrient recycling as effective tools for advancing bio-circular economy strategies, reducing reliance on synthetic fertilisers, and promoting the closed-loop use of agro-industrial by-products.

The results of this study are consistent with previous research on the valorisation of agro-industrial residues [10,45,48–50], yet they also provide new insights by adopting a

territorial and spatially explicit perspective. Several studies have highlighted composting as one of the most effective and low-impact strategies for managing organic residues from the agri-food sector [50], improving soil fertility and contributing to long-term soil carbon sequestration [51]. However, most of these works address composting practices at the plant or farm scale, without considering the spatial distribution of biomass sources, crop demand, and environmental constraints at a regional level. By integrating GIS-based spatial analysis into the assessment, the present study fills this gap and demonstrates how composting potential and regulatory compliance can vary significantly across territories depending on the availability of by-products, cropping patterns, and the extent of nitrate vulnerable zones.

The outcomes of this study have practical implications for both regional policymakers and stakeholders in the agro-industrial sector. By demonstrating the feasibility of integrating composting into a territorial bio-circular economy framework, the results provide a valuable evidence base for designing policies that promote nutrient recycling, reduce dependence on synthetic fertilisers, and support the sustainable management of agricultural soils. The spatially explicit approach adopted here can serve as a decision-support tool for planning the localisation of composting facilities, optimising biomass transport, and aligning nutrient supply with crop demand at the provincial scale [48]. Furthermore, the cascade valorisation model highlights the importance of fostering cooperation among different sectors of the agri-food system, such as livestock farming, olive oil production, and citrus processing, to create synergies that enhance resource efficiency and minimise waste generation.

Future research should build on these findings by integrating additional environmental and economic parameters into the spatial analysis, such as greenhouse gas emissions, energy use, and cost-benefit assessments, to provide a more comprehensive evaluation of the sustainability potential. More in deep environmental analysis would assess whether to redesign the valorisation strategies, accounting for the energy valorisation approach or whether it is more efficient to compost biomass and use other renewable energy resources such as sun and wind [52,53].

Expanding the analysis to include other types of agro-industrial residues and exploring different regional contexts would also strengthen the generalisability of the proposed framework and support the broader transition toward circular and regenerative agri-food systems.

From a spatial analysis perspective, further research should focus on in-depth analysis of the transportation phase and on investigating the solution at a municipal level.

## 5. Conclusions

The results showed the potential of using agro-industrial residues from the main agricultural products in a circular economy approach. In particular, a cascade valorisation strategy was applied for each of the wastes. Based on the outcomes of this study, this approach has been proven to be very effective, particularly when the processes involved are well-integrated within the industrial context of the territory. In this sense, GIS studies play a key role in assessing the sustainability of a valorisation strategy. As it was demonstrated, this was the case of composting agro-industrial residues and using the compost as a soil amendment. Moreover, the other agricultural activities, namely, olive pomace oil extraction and feeding animals with orange wastes, are very widespread sustainable practices in Sicily.

Future research in this field should focus on including additional environmental impacts and economic analyses, by integrating other industrial and agronomic phases. Moreover, the applicability of the methodology to other by-products should be investigated as well as additional cascading valorisation processes, including a waste-to-energy approach.

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